Improving Energy Supply and Use in the Rice Value Chain using Rice Husk Energy Systems

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This thesis is dedicated to my Aunt, Margaret Ebela Kwofie, whose greatest desire was to see me become a PhD holder, but could not live long enough to see the realization of this dream.

May she rest in Perfect Peace!

Abstract

Rice is the most rapidly growing source of food in Africa with profound implication for food security and welfare of poor urban and rural households. Its production within rural communities besides being laborious and energy intensive, raises concerns on issues such as energy efficiency, deforestation, rice husk disposal, greenhouse gas emission and smoke related health impact. With farmers' health and the environment at stake, a simple but effective and environmentally friendly system may be required to improve both rice quality and overall livelihood of rural rice processors. This project is part of McGill's contribution in providing such solution within the region using rice husk energy systems. The primary objectives of this work were to provide an alternative biomass energy supply through efficient rice-husk-fired systems and to improve energy use through an integrated steaming and drying system (ISDS).

The study began with investigation of the thermal characteristics of rice husk and its briquette together with the evaluation of their potential of meeting the local parboiling energy demand. A thermogravimetric approach was used to study the devolatilization characteristics, reactivity, kinetics and ignition performance of rice husk and its briquette produced with different local starch binders. The devolatilization activation energies and frequency factors were within the range of 53.39 and 65.38 $kJmol^{-1}$ and $2.1 \times 10^5 - 20.6 \times 10^5$ min^{-1}, respectively. It was found that, the current available rice husk could effectively and efficiently replace wood, achieving up to 67% wood savings, 63% greenhouse gas emission reduction and an annual parboiling energy expenditure reduction of 73%.

Based on the evaluation results, two thermochemical biomass conversion systems (TBCS) were developed and evaluated. A bottom lit downdraft gasifier designed to operate continuously was first developed and evaluated. The results indicated a fivefold improvement in efficiency (58.85%) over the three-stone fire (TSF) stove currently being used. A thermochemical equilibrium model was developed to understand the gasification principle and to estimate the gasifier's performance under different operating conditions. A second continuous TBCS was developed for direct combustion of rice husk. Experimental evaluation of the improved rice parboiling stove (IRPS) showed a thermal efficiency, fire power and specific energy consumption of 29±3%, 16±3kW and 0.14kg/kg rice husk, respectively.

Having provided alternative energy supply systems, the next step was to improve energy use which was achieved in a two-step process. The first step was to improve the heat transfer process and generate a continuous stream of steam for parboiling. A fire tube heat exchanger extension was made to achieve the energy use improvement which in addition to the continuous steam production, increased thermal efficiency from current 11.4±2.5% to 46.4±0.43 (a 407% improvement). Emission test conducted on the system revealed that CO and CO_2 emission factors for rice husk combustion were in the range of 10.6-12 and 785-793 g/kg rice husk, respectively. These were much lower than fuel wood (36.3 – 42.7 and 1519-1531 g/kg wood) implying a reduction of up to 10.4 kg of CO and 227.4 kg of CO_2 per tonne of paddy processed when compared with the TSF stove. The second step was a waste heat recovery process where hot air heat exchanger was built and added to the steam production unit for the generation of hot air for drying. To complete the integrated steaming and drying system (ISDS), a recirculating dryer with a pneumatic recirculation unit was designed and fabricated. A thermodynamic performance evaluation of the complete system gave overall system energetic and exergetic efficiencies of 47.81 and 10.93%, respectively. To enable quick evaluation of rural parboiling systems, an excel-based energy and exergy assessment framework was developed.

Finally, to ascertain the environmental impact reduction and economic viability of the ISDS, a comparative life cycle analysis (LCA) and techno-economic analysis (TEA) were performed. Using a functional unit of one tonne of paddy processed, and four impact categories, the normalised result demonstrated that overall, rural parboiling system (RPS) impact the environment five time more than the ISDS, implying that up to 80% of the present environmental impact can be eliminated by replacing the existing process with ISDS. For the economic viability, a financial analysis was used to examine the systems' cost-effectiveness from a potential buyer's perspective using four financial criteria while an economic analysis was used to evaluate the systems' worth from societal point of view. The profitability evaluation shows that even without subsidy/grants, the system is attractive with a net present value of $9900 and a profitability index of 2.25. The cost-benefits analysis which considered benefits from wood saving, income generation, environmental damage cost reduction, and forest preservation in addition to profits from the system use, showed a benefit-cost ratio of 1.74 – 6.5 at different discount rates (5-25%).

Résumé

On assiste présentement à une explosion de la production de riz à titre de culture vivrière en Afrique. Cette nouvelle production permet d'améliorer la sécurité alimentaire et le bien-être des populations à faibles revenus. Sa production au sein des communautés rurales en plus d'être laborieuse et consommatrice d'énergie, suscitent des inquiétudes sur les questions d'efficacité énergétique, de déforestation, de la balles de riz élimination, des émissions de gaz à effet de serre et l'impact sur la santé a la fumée lié. Avec la santé des agriculteurs et de l'environnement en jeu, un système simple mais efficace et respectueux de l'environnement peut être nécessaire pour améliorer à la fois la qualité du riz et la subsistance globale de transformateurs de riz rurals. Cette étude a permis de développer de nouveaux systèmes des transformation qui combinent à la fois le procédé d'étuvage à celui du séchage (ISDS) en utilisant comme source d'énergie les résidus de balle de riz. Cette approche est bien adaptée aux besoins des transformateurs de riz d'Afrique rurale.

La première partie de l'étude a permis d'établir les caractéristiques thermiques de la balle de riz et de briquettes faites à partir de ces dernières. Elle a aussi permis d'évaluer leur potentiel à satisfaire la demande d'énergie d'étuvage à l'échelle locale. Une approche thermogravimétrique a été utilisée pour étudier les caractéristiques de dégazage, la réactivité, la cinétique, et les performances à l'allumage de la balle de riz et des briquettes produites avec différents liants. Les valeurs E et A de dégazage étaient entre 53,4 et 65,4 $kJmol^{-1}$ et entre 2,1 à 20,6 $(10)^5$ min^{-1}, respectivement.

A partir des résultats obtenus, deux systèmes de conversion thermochimique de la biomasse (TBCS) ont été construits, évalués et comparés. Le premier système était un gazéificateur à courant descendant conçu pour fonctionner en continu. Les résultats ont indiqué une amélioration de l'efficacité énergétique de l'ordre de 58,85% lorsque comparé au poêle traditionnel sur feu à trois pierres (TSF). Un modèle thermochimique a été développé pour représenter le processus de gazéification et pour prédire la performance du gazéificateur.

Le deuxième système de conversion de la biomasse en continu était un poêle à combustion pouvant utiliser directement les résidus de balle de riz. L'évaluation expérimentale de l'étuvage sur ce type de poêle amélioré (IRP) a permis d'établir l'efficacité thermique, la puissance et la consommation d'énergie spécifique. Ces valeurs étaient de 28,7 ± 2,7%, 15,9 ± 3,2 kW et de 0,14 ± 0,01 kg / kg de balle de riz, respectivement.

La partie suivante a consisté à améliorer l'utilisation de l'énergie dans ce procédé. La première étape était d'améliorer le processus de transfert d'énergie. Une extension de l'échangeur de chaleur à tubes à flamme a été ajoutée pour améliorer l'efficacité tout en maintenant la production en continu de la vapeur. Cette modification a permis d'augmenter l'efficacité thermique de 11,37 ± 2,5% à 46,4 ± 0,4% soit une augmentation de près de 407%. Les tests d'émission réalisés sur le système ont indiqué que les émissions de CO et CO_2 étaient de l'ordre 10,6 à 12, et de 785 à 793 g/kg de combustible lorsque les balles de riz étaient utilisées. Ces émissions étaient nettement inférieures à celles obtenues avec le bois de chauffage qui étaient de 36,3 à 42,7 et de1 519 -1 531 g / kg de bois dans un poêle traditionnel TSF. On observe donc une réduction nette de 10,4 kg de CO et de 227,4 kg de CO_2 par tonne de riz brut transformé.

Par la suite, un système de récupération de chaleur à air chaud a été ajouté à l'unité de production de vapeur afin d'utiliser cette énergie pour le séchage. Une unité de recirculation pneumatique a été ajoutée au système ISDS pour en compléter l'intégration. L'évaluation du rendement thermodynamique du système ISDS complet a démontré que les efficacités énergétiques et exérgétiques étaient de 47,8 et 10,9%, respectivement. Pour permettre une évaluation rapide des systèmes d'étuvage rurales, un programme basé sur Excel a été développé pour l'evaluation de l'energie et de l'exergie.

Une analyse comparative du cycle de vie (ACV) et une analyse technico-économique (TEA) ont été effectuées pour valider l'impact bénéfique sur l'environnemental et la viabilité économique de l'ISDS. L'analyse était basée sur l'utilisation d'une unité fonctionnelle d'une tonne de riz étuvé, et quatre catégories d'impact. Les résultats normalisés ont démontré que dans l'ensemble, l'impact du système IRPS sur l'environnement était de cinq fois plus élevé que pour l'ISDS. Le remplacement du procédé actuel par l'ISDS permettrait donc une réduction de près de 80% de l'impact environnemental. Une analyse financière a été utilisée pour examiner de coût/efficacité du système du point de vue d'un acheteur potentiel et une analyse économique a permis d'évaluer le système du point de vue sociétal. L'évaluation de la rentabilité basée sur une valeur nette actuelle du système de 9900 $ a montré que même sans aides financières que le système était attrayant puisque son indice de rentabilité était de 2,25. L'analyse coûts-bénéfices a tenu compte des impacts sur la diminution de la demande en bois, la génération de revenus, la réduction des coûts environnementaux, la préservation de la forêt, et les profits résultant de l'exploitation du système

ISDS. Les résultats obtenus ont démontré un rapport bénéfice/coût de 1,7 à 6,5 lorsque les coûts/bénéfices sont actualisés à des taux allant de 5 à 25%.

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Contribution of Authors

Ebenezer Miezah Kwofie is the principal author of this work, supervised by Dr. Michael Ngadi from the Department of Bioresource Engineering, McGill University, Sainte Anne-de-Bellevue, Quebec, Canada. The entire fabrication and performance evaluation was done at the Technical Service Unit (Machine shop) of the Bioresource Engineering Department.

Dr. Michael Ngadi, the supervisor and director of the thesis, co-authored all manuscripts, and provided scientific guidance in the planning and execution of the work as well as co-editing and reviewing manuscripts.

Dr. Samson Sotocinal co-authored the fifth and sixth chapters and also provided technical assistance during fabrication and testing of equipment. He also made contribution in reviewing some of the manuscript.

Details of the papers accepted and submitted are provided below:

A. Journal papers

1. **Kwofie, E. M** and Ngadi, M. (2016). A review of rice parboiling concept, systems, energy supply and use. *Renewable and Sustainable Energy reviews*, (under revision)
2. **Kwofie, E. M** and Ngadi, M. (2016). Sustainable energy supply for local rice parboiling in West Africa: The potential of rice husk. *Renewable and Sustainable Energy Reviews, 56*, 1409-1418. doi:http://dx.doi.org/10.1016/j.rser.2015.12.030
3. **Kwofie, E. M** and Ngadi, M. (2016). Reactivity, kinetics and ignition performance of rice husk and its briquette produced with different local binders. *Fuel Processing Technology*, (under revision)
4. **Kwofie, E. M** and Ngadi, M. (2016). Development and Thermochemical Equilibrium Analysis of a rice husk gasifier stove for rural rice processing. *Energy Conversion and Management*, (under revision)
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B. Papers presented at Conferences

1. **Kwofie E.,** and Ngadi M., (2015).Development and Performance Evaluation of an Integrated Paddy Steaming and Drying System. Oral presentation at the 2015 *International Annual Meeting of the ASABE*, July 26-29, New Orleans, LA, USA
2. **Kwofie E.,** and Ngadi M., (2015). Technoeconomic assessment of an integrated steaming and drying unit for local rice processing. Oral presentation at 2015 *NABEC Meeting,* July 12-15, Delaware, DE, USA **[Received Outstanding oral presentation – first Place Award]**
3. **Kwofie E**., and Ngadi M., (2015). Life Cycle Assessment of an integrated rice steaming and drying unit fuelled with rice husk. Oral presentation at the *2015 CSBE/SCGAB Technical Conference & AGM,* from July 5 – 8, 2015, Edmonton, AB, Canada.
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5. **Kwofie E**., and Ngadi M., 2014. Development of an Excel-Based Energy Efficiency Assessment Framework for Local Parboiling Systems. Oral presentation at the *4th International Rice Congress, Bangkok International Trade & Exhibition Centre, (BITEC)* from 27 October – 1 November 2014, Bangkok, Thailand

6. **Kwofie E.,** and Ngadi M., 2014. Sustainable Thermal Energy Production for Rice processing in Africa: The potential of Rice Husk. *Oral presentation at 2014 NABEC Meeting,* July 27-20, Kemptville, ON, Canada **[Received Outstanding oral presentation – Second Place Award]**
7. **Kwofie E.,** and Ngadi M., 2014. Thermochemical Equilibrium Modelling of rice husk Gasification. Oral presentation at the *International Annual Meeting of the ASABE*, July 13 – 16, Montreal, QC, Canada.
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Nomenclature

AEE	Annual Energy Expenditure
ASABE	American Society for Agricultural and Biological Engineers
ASTM	American Society for Testing and Materials
BCR	Benefit-Cost Ratio
BOT	Burnout Temperature
CaB	Briquette made with cassava starch binder
CC	Climate Change
CCT	Controlled Cooking Test
CE	Combustion Efficiency
CoB	Briquette made with corn starch binder
COPD	Chronic Obstructive Pulmonary Disease
DTGA	Derivative Thermogravimetric Analysis
FAOSTAT	Food and Agriculture Organization Statistics
GHG	Greenhouse Gases
GWI	Global Warming Index
GWP	Global Warming Potential
HHV	Higher Heating Value
HRY	Head Rice Yield
IRPS	Improved Rice Parboiling Stove
IRR	Internal Rate of Return
IWA	International standard organization's international workshop agreement
KPT	Kitchen Performance Test
LCA	Life Cycle Analysis
LCIA	Life Cycle Impact Assessment
LHV	Lower Heating Value
LMTD	Logarithmic Mean Temperature Difference

LSU	Louisiana State University
MASLOC	Microfinance and Small Loans Centre
MoFA	Ministry of Food and Agriculture
MRY	Milled Rice Yield
NPV	Net Present Value
PAHs	Polycyclic Aromatic Hydrocarbons
PBP	Payback Period
PI	Profitability Index
PMF	Particulate Matter Formation
POF	Photo-oxidant Formation
RCaB	Briquette made with rice-cassava starch binder
RPS	Rural Parboiling System
SDI	Smoke Development Index
SPC	Specific Fuel Consumption
SR	Safety Ratio
TA	Terrestrial Acidification
TBCS	Thermochemical Biomass Conversion System
TEA	Technoeconomic Analysis
TGA	Thermogravimetric Analysis
TNMHC	Total Non-Methane Hydrocarbon
TRACI	Tool for Reduction and Assessment of Chemical and other environmental Impact
TSF	Three Stone Fire
VITA	Volunteers in Technical Assistance
WBT	Water Boiling Test
WHO	World Health Organization

CHAPTER 1 Introduction

1.1 Background

Rice is the most rapidly growing source of food in Africa with profound implication for food security and welfare of poor urban and rural households. Africa currently accounts for a third of global rice imports and this is expected to rise (Kula & Dormon, 2009; Seck et al., 2013). In response to reducing the burden of rice importation while ensuring food availability, several national and internationally supported efforts were under taken in the past decade across the continent towards local rice production. This has been reflected in the increasing rate of rice production (6% per annum) recorded in recent years within the region (Somado et al., 2008). However, 70% of this increase in production is attributed to land expansion and the rest due to increase in productivity. The continuous increase in consumer preference for imported rice is mainly due to the poor quality of locally produced rice (Demont et al., 2012). For instance, as at 2009 there were no grade 1 quality in local rice in Ghana, only 4.3% were of grade 2 and 82.6% were of the worst grade, 5 (Kula & Dormon, 2009). This probably explains why local rice costs less than the cheapest imported rice (Rutsaert et al., 2013). There is therefore an urgent need for a corresponding effort in rice processing to make Africa's dream of self-sufficiency in rice production a reality. One way of achieving this quality improvement in the rice value chain is parboiling of paddy.

Rice parboiling is a hydrodynamic process which enhances the physical, chemical and organoleptic quality of rice. It increases milling yield, improves nutritional value, extends storage life, reduces rice stickiness and increases hardness of cooked rice (Araullo et al., 1985; Lapcharoensuk & Sirisomboon, 2014; Luh & Mickus, 1991; Oli et al., 2014; Parnsakhorn & Noomhorm, 2008). Parboiling has the potential to increase not only product quality but also process efficiency as well as enhance competitiveness of local rice. Generally, local parboiling is energy intensive requiring about 1659 - 2758 MJ/tonne of paddy (Roy et al., 2006) depending on the parboiling process. In most of the rice producing countries within the region, the thermal energy requirement for parboiling is usually met by woody biomass which are bought from wholesale wood vendors or locally collected and carried over long distances to processing centres. Reliance on fuel wood has become a serious problem in most African countries. For example, in

Ghana, tropical forest area has been reduced to a quarter in less than 50 years with an annual forest depletion rate of 22,000 hectares (Duah-Yentumi & Klah, 2004). Therefore with the current wood consumption rate of 640 kg per capita coupled with forest growth dropping to less than half the demand (Duah-Yentumi & Klah, 2004) wood use cannot be a sustainable energy option for rice processing. Furthermore, the use of wood as energy in traditional stoves and small hand-crafted cookstoves is considered responsible for several cases of respiratory illness and death, as well as burns, cuts, and scalds (Desai et al., 2004; Johnson & Bryden, 2012a; Johnson & Bryden, 2012b; Wickramasinghe, 2003).

Rice processing is characterised by large quantities of rice husk, an agro-industrial residue. The husk is removed as a by-product during rice milling. For each kilogram of rice paddy, 200 – 330 grams of rice husk is generated (Lim et al., 2012). The husk generated is considered as waste material and usually burnt in open fields without energy recovery. This inefficient burning results in air pollution releasing carbon dioxide (CO_2), carbon monoxide (CO), un-burnt carbon (with trace amount of methane) as well as NOx and trace amount of sulphur dioxide (SO_2) (Lim et al., 2012). The burning process also contributes to particulate matter emissions and introduces several compounds including carcinogenic/mutagen mainly polycyclic aromatic compounds (PAHs) (Yang et al., 2006). As climate change is extensively recognized as a threat to development, there is a growing interest in alternative uses of agro-industrial residues for energy applications. In this context, rice husk would be a potential source for meeting future energy needs not only for rice processing but also for residential use.

Energy from rice husk may be harnessed through a thermochemical (direct combustion, briquette combustion, pyrolysis or gasification) or biochemical (biogas or bioethanol production) pathway. Biochemical processes are typically capital intensive and require skilled operators (Verma et al., 2012) so may not be suitable for local rice processing. Therefore, a simple and efficient thermochemical process with higher energy and operational efficiency is required for the desired switch from wood. Direct combustion of rice husk has successfully been employed in Asia for rice parboiling although smoke from such operations raises health concerns. Gasification of rice husk is another promising thermochemical process used for energy generation. It has been used for heat and electricity generation in large rice farms (Akgün & Luukkanen, 2012; Bhat et al., 2001; Yoon et al., 2012). Although, small scale rice husk gasification for direct thermal application has not been extensively reported (Belonio, 2005; Jain, 2006), its viability and prospect in local energy supply depends on the development of simple, reliable and efficient equipment that requires minimum biomass pre-treatment (Pérez et al., 2012). In recent times, small unit rice husk gas stoves for rural utilization have been developed in the Philippines and are being used for domestic application but these are usually batch systems making refuelling difficult and raise lots of safety concerns such as burns during operation. To enhance parboiling energy supply for small scale rice processing in Africa, an improved biomass combustion system which allows the use of both agro waste and wood may be essential. Improving energy supply without the corresponding enhancement in the parboiling systems may result in a marginal overall growth, hence both energy supply and use improvement should be targeted for any substantial change in rural rice processing.

In sub Saharan Africa, traditional steaming is done by pouring paddy rice into a pot containing water and precooking for 20 - 30 minutes on a three-stone fire (TSF) stove (Houssou & Amonsou, 2004). The TSF is known to be inefficient with efficiency of 10 -15% (Alakali et al., 2011; Bhattacharya et al., 2002a; Bhattacharya & Abdul Salam, 2002). This process, besides rendering some paddy fully cooked and others uncooked, results in poor rice quality and also requires long hours of travelling for wood collection. Recently, Zossou et al. (2009) reported an improved steaming process in Benin, West Africa under a collaboration between the National Agricultural Institute of Benin Republic, AfricaRice Centre and local artisans. The improved process prevents direct contact of paddy with water by placing a perforated steel container with soaked paddy rice over boiling water. Steam generated is then used for starch gelatinization. Although, the process is an improvement over the traditional method, it is still operationally inefficient and energy intensive. This is because (1) it requires addition of water after each batch to ensure there is enough water for steam generation, (2) it is difficult to monitor the amount of water left in the vessel, posing a safety risk, (3) it still requires the long hours of wood collection, and (4) it uses the inefficient three stone fire (TSF) stove.

In an effort to achieve energy economy for rice processing in Africa, this project aims at providing a sustainable energy alternative by harnessing thermal energy from rice husk. This is achieved through the development of continuous rice husk combustor and gasifier systems to replace the existing low-efficiency “wood for energy practices” and improving energy use. This will not only improve parboiling process in the region but will also reduce parboiling fuel cost, reduce total greenhouse gas emission, reduce deforestation and improve the well-being of rice producing farmers.

1.2 Objectives

The overall objective of the project was to improve energy efficiency through enhanced thermal energy supply and use with an integrated steaming and drying system powered by rice husk. The specific objectives of the research have been developed based on four key research questions whose answers will lead to the achievement of thermal energy economy for rice processing as shown in the objective formulation diagram (Fig. 1.1).

The Specific Objectives

The specific objectives of the research are as follows:

1. Thermogravimetric characterization and evaluation of the potential of rice husk as a local parboiling fuel.
2. Development, performance evaluation and thermochemical equilibrium modelling of a continuous rice husk gasifier system.
3. Energy efficiency and emission assessment of a continuous rice husk combustion stove.
4. Thermodynamic performance evaluation of an integrated steaming and drying system (ISDS) for rice parboiling.
5. Techno-economic analysis and lifecycle assessment of an integrated parboiling system.

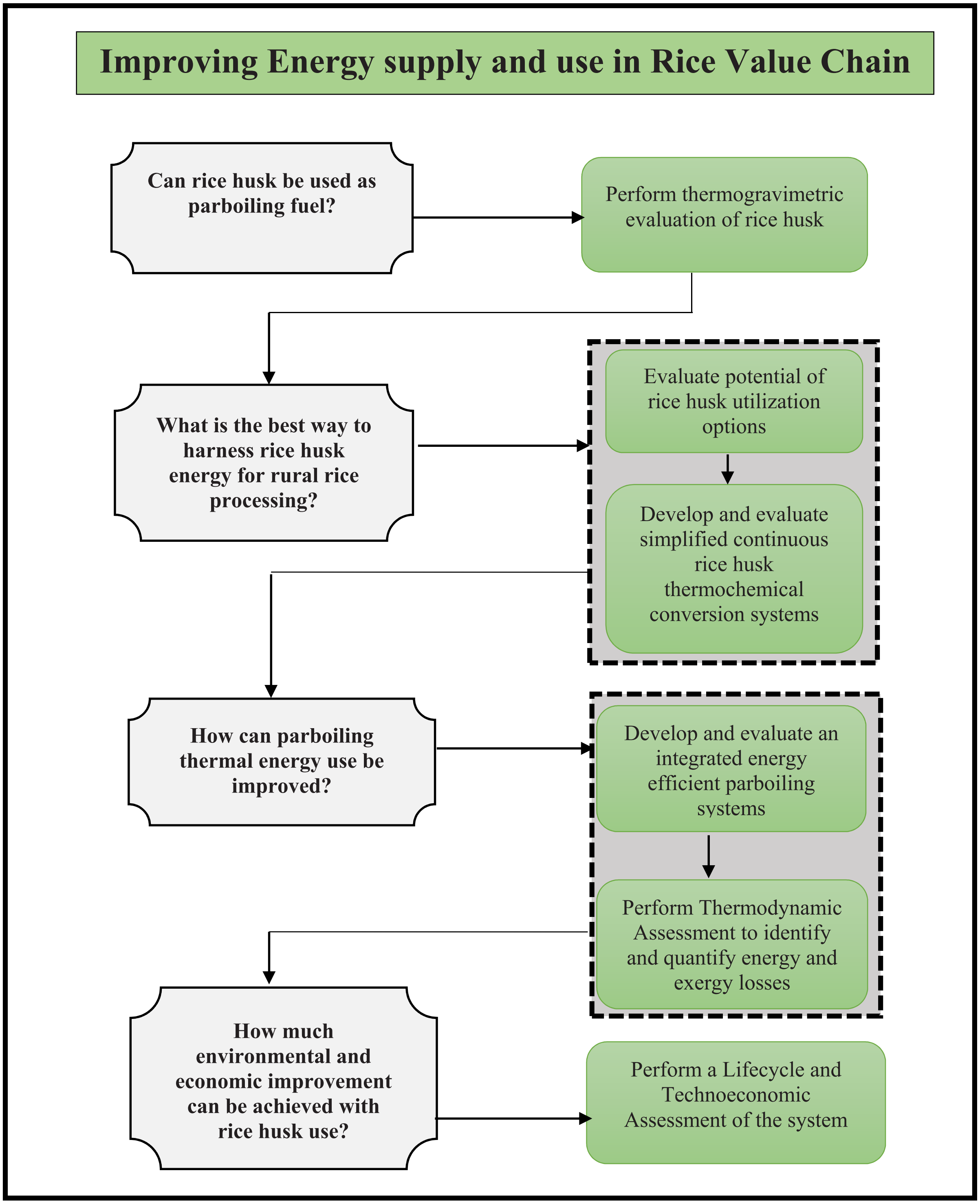

Figure 1.1: Thesis objectives formulation diagram

CHAPTER 2 Literature Review

2.1 Introduction

The review of literature has been conducted with the aim of understanding and appreciating previous work done pertaining to parboiling energy supply and use. The review covers three broad areas. Firstly, an understanding of the parboiling concept within the value chain, the different parboiling systems used in local rice processing, the types of fuel and the energy consumption. Secondly, the characteristics of rice husk and the pathways for harnessing its energy is reviewed, since rice husk use as a primary energy source for parboiling is the focus of this work. Finally, the evaluation of thermochemical biomass systems (combustion and gasification systems) is also presented with particular interest in their design and evaluation methods.

2.2 Parboiling concept, systems and energy

2.2.1 The concept of rice parboiling

Rice parboiling is a hydrothermal process which gelatinize starch in the grain to reduce breakage and improve rice quality. It involves three steps – soaking, steaming and drying. Rice grains are mainly composed of polygonal starch granules in their endosperm. The endosperm has inter-granular spaces which are filled with air and moisture. During maturity of the grain, fissures and cracks are developed that cause breakage of the grain during milling. To reduce the breakage, the grains are parboiled during which the starch are gelatinized, filling the void and cementing the fissures and cracks (Araullo et al., 1985; Thakur & Gupta, 2006).

During soaking, water penetrates into the starch granules and forms hydrates through hydrogen bonding which causes swelling. This swelling is less when soaking is done in cold water due to the limited water absorbing capacity of the starch granules. However, in hot soaking, heat energy disrupts the hydrogen bonds and weakens the granule structure which gives more surfaces for water absorption and allows further hydration and swelling as temperature increases. The process of gelatinization is completed with heat from moist steam supplied during the steaming stage. Generally, soaking increases paddy moisture up to 45-50% (wb) hence the need for drying before milling (Thakur & Gupta, 2006)

Parboiling rectifies the problem of cracks and incomplete grain filling thereby leading to many favourable changes including easy shelling, higher head rice yield, fewer broken, increased resistance to insect, nutrient retention (Igathinathane et al., 2005) and reduced disintegration and solubilisation of kernels during cooking (Priestley, 1976). Rough rice or dehusked rice may be used for parboiling. Local rice processors use rough rice whereas brown rice is mainly used in modern industrial parboiling process (Buggenhout et al., 2013; Luh & Mickus, 1991; Thakur & Gupta, 2006). The choice of processing dehusked rice in modern processes is typically based on avoidance of husk associated natural contaminant (Thakur & Gupta, 2006), avoidance of colour and odour transport during soaking (Luh & Mickus, 1991), reduction in processing time, energy consumption and handling cost (Kar et al., 1999).

2.2.2 Parboiling systems

Several parboiling systems have been developed with the aim of improving rice quality and reducing energy consumption. A parboiling system includes soaking, steaming and drying components. The success of parboiling systems is determined by the quality of the parboiled paddy through parameters such as milled rice yield (MRY) or head rice yield (HRY). Parboilers give priority to any system which increases the HRY since broken rice are worth 60% of full grains (Patindol et al., 2013). Overall, parboiling systems which increase HRY and reduce the parboiling duration and energy are considered to be the best (Igathinathane et al., 2005).

Soaking is the most time consuming step of the parboiling process lasting about 12 - 48 hours in the traditional parboiling process and 2 - 6 in modern processes (Igathinathane et al., 2005). As the soaking water temperature increases from 25 to 80ºC, soaking duration decreases from 60 to 1.5 hours (Kapur et al., 1996c). Traditional soaking may be carried out in vessels or concrete masonry tank. Improvement in soaking process have been achieved with the combined soaking procedure proposed by Igathinathane et al. (2005). In this process, paddy is soaked above the gelatinization temperature at 80 ºC for 45 minutes and then re-soaked below the gelatinization temperature for 3 hours and 15 minutes. An intermediate moisture content of 35.0 wt% d.b is reached in the first stage before the final moisture content of 42.7 wt% d.b. This two-step soaking prevents husk splitting which unreasonably increases water absorption.

Steaming of soaked paddy is brief, yet energy intensive. In traditional steaming in sub-Saharan Africa, paddy rice is directly poured into a pot with small water and pre-cooked on a three-stone fire (TSF) stove. This process renders grains at the bottom over cooked while the upper portion is still uncooked resulting in low milling yield and poor rice quality. This method also increases drying time and rate of cracking hence lower yield (Houssou & Amonsou, 2004). Recently, the National Agricultural Research Institute in Benin and the Africa Rice Center collaborated with local artisans to develop an improved parboiling system (Demont et al., 2012; Zossou et al., 2009; Zossou et al., 2010). In this improved system, already soaked paddy is transferred to a perforated container placed over a boiling water pot and is pre-cooked with steam, without the paddy touching the water.

In Asia, local steaming systems include indigenous single boiling or double vessel parboiling system (Kapur et al., 1997), small-boiler systems (2 - 4 tonne/batch) used for commercial rice processing and medium-boiler systems with capacity of 5 -10 tonne/batch that are also used for commercial parboiling (Roy et al., 2006).

To enhance efficiency in paddy gelatinization, other improved systems have been developed. These include the thermic fluid systems (Pillaiyar et al., 1996), hot humid air steaming, and continuous flow steamer. In the thermic-fluid system, paddy is soaked for 4-5h (depending on variety) at 65^{o}C. In the case where short soaking tempering method is used, the paddy is soaked for 60 - 75 min before steaming. During steaming, the thermic fluid (e.g. Servotherm medium) is circulated in a cylindrical drum made of stainless steel while the paddy is kept in stainless steel tubes. Gelatinization is achieved through heat transfer from the fluid to the paddy. The thermic-fluid steaming system is reported to give a better milled rice whiteness compared to the traditional open-steaming process. The use of hot humid air for steaming may lead to leaching of solids or discoloration in rice.

Several commercial batch and continuous parboiling process have been developed. These include the Schule, CFTRI, Judavpur University, Crystal rice and Malek systems with either medium or high temperature water systems (Luh & Mickus, 1991). A summary of rice parboiling technologies is shown in Table 2.1.

Table 2.1: Summary of rice parboiling Systems

Process	Soaking	Steaming	Drying	Source
Schule	Batch system in medium temperature water followed by a second stage in high temperature water under pressure in same tank.	Steaming is not required. Starch gelatinization obtained by soaking in high temperature water under pressure.	In high-temperature air followed by medium-temperature air.	(Luh & Mickus, 1991)
CFTRI	Batch system in hot water 70-75°C for 2-3.5 hr.	Steam is pressure-injected through perforated pipes.	Sun drying or mechanical drying by medium-temperature air	(Luh & Mickus, 1991)
Judavpur University	Batch system in hot water 60-70°C for 2.5-3 hr.	Steam is pressure injected through perforated pipes. Alternatively continuous system with steam at ambient pressure in autoclave equipped with screw conveyor	Cooling before drying. This is done by using high temperature air followed by medium temperature air	(Luh & Mickus, 1991)
Avorio	Continuous system in medium-temperature water	Continuous steaming under pressure in an autoclave Equipped with mechanical conveyors	Cooling before drying. This is done by using medium temperature air	(Luh & Mickus, 1991)
Crystal rice	Batch system in high-temperature water under vacuum, followed by hydrostatic pressure	Continuous system in a rotary autoclave under steam pressure	Under vacuum in the same autoclave. Final drying may be done after milling	(Luh & Mickus, 1991)
Malek	Batch system in high-temperature water	Continuous steaming under pressure in a medium vertical Stationary autoclave	By high-temperature air, followed by medium temperature air	(Luh & Mickus, 1991)
CRGA parboiling	Batch system in medium-temperature	Continuous system in a horizontal cooker under	In high-temperature air, followed by	(Luh & Mickus, 1991)

	water, medium followed by higher-temperature water	high steam pressure for a short time	medium temperature air	
Thermic Fluid Parboiling	Batch system in hot water soaking (65 - 75ºC)	Paddy are stored in tubes place in a cylinder with a circulating heated thermic fluid.	Air drying in shade	(Pillaiyar et al., 1996)
Infrared Heating System	Batch system in hot water soaking (55ºC)	No steaming	Simultaneous parboiling and drying with IR heating (2100W) and vibration	(Likitrattanaporn & Noomhorm, 2011)

Steamed paddy is primarily dried under the sun in local rice processing. In sun drying, the paddy is spread on concrete floor or tarpaulin to reduce the dirt contamination. Other drying methods used includes hot-air drying, vacuum drying, superheated-steam drying, fluidized bed drying (Swasdisevi et al., 2010) and particulate medium drying (Khan et al., 1974). The fluidization technique has received attention due to its effectiveness. In fluidization, there is vigorous mixing of air and solid particles while the drying medium, hot-air or superheated steam, is used to carry the evaporated water and particles. Particulate medium heat transfer drying is known for its superior heat transfer process. This superiority, results from much higher heat capacities of solid materials compared with air. During this particle drying, heat loss is reduced due to the retention of heat hence overall system efficiency is improved. In this process, the particles are heated, mixed with the paddy, separated after the heat transfer and then recirculated before cooling the paddy. Several materials have been used including sand, salt, zeolite, silica, and molecular sieves of varying sizes.

Industrial parboiling in developed countries such as the United States is fully mechanised with built-in steaming coils in soaking vessels. Paddy is soaked with hot water at 80-90 ºC circulated for 15 minutes and maintained at 65 ºC for 4-5 hours. At the end of the soaking period the water is drained off and the steam is introduced through in-built steaming coils for 10-20 minutes after which it is transported on conveyor belts to the drier. The driers used are usually rotary-drum type with steam heat-exchangers or husk-fired furnaces; rotary hot-air driers or bin driers (Luh & Mickus, 1991).

2.2.3 Parboiling energy supply

Biomass is the main source of energy for traditional parboiling in most developing countries with rice husk and wood as the major biomass energy source. Biomass combustion and gasification are the main thermochemical conversion processes used.

Wood is the primary fuel used for small scale rice parboiling in Sub-Saharan Africa. It is usually collected and carried over long distances to processing centres by women and children either by foot or bicycle. Some parboilers collect wood over a period of time and when large amounts have been gathered they are then transported by truck. In communities where wood is scarce, wood wholesalers transport wood from other districts in trucks to be sold across villages. These are usually not for domestic use but for industrial purposes. The rice husk generated during milling is usually not used but burnt in open fields without energy recovery. The burning process also contributes to particulate matter emissions and introduces several compounds including carcinogenic/mutagenic substabces mainly polycyclic aromatic compounds (PAHs) (Yang et al., 2006).

Combustion of wood occurs in three-stone fire (TSF) stoves, improved brick stoves (Demont et al., 2012; Houssou & Amonsou, 2004; Perera & Sugathapala, 2002) or improved metal stoves (Jetter & Kariher, 2009; Jetter et al., 2012a) to generate heat for parboiling. Although, the three-stone stove is known to be inefficient with an efficiency of 9% -15% (Alakali et al., 2011; Ayoub & Brunet, 1996; Bhattacharya et al., 2002b) it is the most widely used stove due to its lower cost. Improved natural draft brick stoves with higher efficiency of 11-53% have also been introduced for both domestic and economic activities. These stoves cost between US$5 and US$300 depending on the complexity (Bank, 2011) and can also reduce fuel use by 33%, CO emissions by 75% and particulate matter (PM) emissions by 46%, when compared with the TSF stove (MacCarty et al., 2010b).

Sustainability has been a major concern of wood use. Wood stoves' inefficiency and health impact have been implicated in deforestation and regional climate change (Bond & Sun, 2005; Manibog, 1984; Ramanathan & Carmichael, 2008). In addition, the use of wood as energy in traditional TSF and small hand-crafted cookstoves is considered responsible for several cases of respiratory illness and death, burns, cuts, and scalds (Desai et al., 2004; Johnson & Bryden, 2012b; Wickramasinghe, 2003). National and regional institutions in Africa such as the AfricaRice Centre in collaboration with other academic institutions (e.g. McGill University, Canada) have made efforts to improve energy supply and use within the region through the development of sustainable alternative energy systems like briquetting and gasification as well as new parboiling systems (Demont et al., 2012).

Contrary to the practice in Sub-Saharan Africa, rice husk is the main source of energy for rural rice processing in most parts of Asia (Kapur et al., 1998; Roy et al., 2008; Roy et al., 2003; Roy et al., 2006). The stoves used are specially designed with either fixed or movable grate systems to allow continuous feeding of the fuel. The husk is supplied directly from the rice mills which may be situated close to the parboiling centres. For large scale production, (>10 tonnes/hour) electrical energy may be used.

In terms of paddy drying, the sun has been the primary source of energy. Parboiled paddy is normally dried on the floor for several hours. Paddy may intermittently be shuffled to ensure uniform drying. The platforms used are generally a cemented floor or a tarpaulin laid on the floor. The tarpaulin may be made of plastic cement sacks sewn into a bigger material for use. Drying of the steamed paddy is very important for reduction of moisture content to suitable limits for proper milling and storage. However, this type of drying is different from raw paddy (with moisture content of 25-30%) drying because steamed paddy is expected to have a moisture content of about 45 -50% (Araullo et al., 1985). In medium scale local processing, combined sun and mechanical drying may be employed (Ahiduzzaman & Sadrul Islam, 2009). The mechanical dryers may be powered with diesel generators or grid electricity.

2.2.4 Parboiling energy consumption

Parboiling is generally an energy intensive process. The intensity of the energy consumption is influenced by the quantity of rice being processed, parboiling method used, the variety of rice, the state of rice (rough or dehusked) and the parboiling conditions such as the soaking temperature, steaming time and pressure (Kapur et al., 1996a). The state of rice is reported to have a huge influence on the energy consumed. For instance, parboiling of dehusked rice reduces the energy consumption by 42.8 and 46.6% using traditional and modern methods, respectively (Kar et al., 1999). The energy consumed is usually estimated based on the amount and heating value of the fuel used. Choosing a pressure parboiling system over a conventional hot soaking system will increase the energy consumption. For example, a 4 tonne/hour system will incur an additional 48kWh each day (Sridhar & Manohar, 2003). The different methods of parboiling practiced differ mainly in the time-temperature combinations for both soaking and steaming (Kapur et al., 1997). The net thermal energy consumption for processing a tonne of paddy rice has been reported in literature in different units. Islam et al. (2004) measured the parboiling energy requirement through residual gelatinization enthalpy with a differential scanning calorimeter (DSC) and reported energy consumed as the difference between the enthalpy of the untreated sample and the residual gelatinization enthalpy, expressed in mJ/mg. The International Development Research Center, Canada also reported the net energy requirement for hot soaking, steaming and drying as 360, 105.5 and 547 MJ, respectively (Araullo et al., 1985).

Different thermal energy requirements for indigenous single boiling, and hot soaking and steaming parboiling methods have also been reported as 241 MJ/tonne and 425 MJ/tonne, respectively (Kapur et al., 1997). These energy intensities were based on a theoretical framework of hot soaking and steaming. The energy for soaking was estimated as the heat required to raise the soaking water from ambient to a desired temperature. The steaming energy on the other hand was estimated as the heat gained by the dry mass of paddy and that gained by moisture inside the paddy grain (Kapur et al., 1997). While these information are relevant for the estimation of the minimum heat and fuel requirement as well as optimum achievable efficiency, they differ widely from field measurements.

Field measurement of energy consumption for rice processing using direct combustion of rice husk has been found to be 1680 MJ/tonne for parboiling and 1,540 MJ/tonne for mechanical drying (moisture reduction from 32 to 14% under hot air temperature range of 65 - 130ºC) (Ahiduzzaman & Sadrul Islam, 2009). Traditional parboiling energy consumption at laboratory scale has also been also found to be 1400 – 2441 MJ/tonne (Roy et al., 2003) depending on the treatment time. This was found to be lower than small boiler and vessel parboiling system and that was attributed to the type of energy and equipment. Roy et al. (2006) also measured energy consumption using rice husk as energy in direct combustion systems for total parboiling (pre-steaming and steaming) and reported 2583, 2758 and 1659 MJ/tonne for vessel, small-boiler and medium-boiler processes, respectively. Table 2.2 presents a summary of soaking and steaming energy consumption.

Table 2.2: Summary of soaking and steaming energy consumption

Parboiling system	Parboiling conditions	Energy consumption	Energy type	Source
Water bath soaking and rice cooker steaming	Soaking @65ºC for 6 h; Steaming @ 90-100 ºC for 5-60 min; Drying @ room temperature for 18 – 24 h	4.0 – 5.5 mJ/mg	Electrical	(Islam et al., 2004)
Single steaming	Soaking@ room temperature for 72 h; Steaming @ 85-90 ºC for 3-8 min;	241MJ/t	Rice husk	(Kapur et al., 1996b; Kapur et al., 1997)
Double steaming/ Open drum	Soaking@ room temperature for 36 h; Steaming @ 85-90 ºC for 3-8 min;	391 MJ/t	Rice husk	(Kapur et al., 1996b; Kapur et al., 1997)
Hot soaking and steaming	Soaking @65ºC for 3-4 h; Steaming @ 85-90 ºC for 15-20 min;	425 MJ/t	Rice husk	(Kapur et al., 1996b; Kapur et al., 1997)
Pressure	Soaking @ room temperature for 0.5-1 h; Steaming @ 85-90 ºC for 20-30 min;	270 MJ/t	Rice husk	(Kapur et al., 1996b; Kapur et al., 1997)
Hot soaking and steaming	Soaking @ 70 Steaming @ 100ºC for 10 min	276MJ/t	Electrical	(Sridhar & Manohar, 2003)
Pressure	Soaking @ 60 ºC followed by 196 kPa pressure	251MJ/t	Electrical	(Sridhar & Manohar, 2003)
Hot soaking and steaming	-	1680 MJ/t	Rice husk	(Ahiduzzaman & Sadrul Islam, 2009)

2.3 Fuel characteristics of rice husk

This section reviews the characteristics of rice husk as a potential fuel for rice parboiling. The fuel classification, physical and chemical properties in addition to thermal characteristics reviews have been presented.

2.3.1 Rice husk fuel classification

Fuel classification is a means of assessing the properties of fuel. To consider rice husk as a parboiling fuel, it is important to check its characteristics and then based on the known properties understand its conversion potential. From the ultimate analysis from Table 2.3, the O/C atomic ratio of rice husk can be estimated as 0.95 and the H/C atomic ratio calculated from Eq. 2.1 as 1.84. The high oxygen content would result in high volatiles and may also consume hydrogen to produce water.

$$(H/C) = 1.4125\ (O/C) + 0.5004 \qquad 2.1$$

Also, a plot of the hemicellulose to lignin ratio against the cellulose to lignin ratio indicates rice husk is within the general biomass range of 0.5-2.7 for cellulose to lignin ratio and 0.5-2.7 for hemicellulose to lignin ratio, which lies slightly above woody biomass (Basu, 2010a). This shows that rice husk will behave as other woody biomass during combustion and gasification.

2.3.2 Physical and chemical characteristics

The important physical properties of biomass that characterize its use as fuel are density, moisture content and angle of repose (Jain, 2013). The density of the fuel is expressed as bulk density. The bulk density is the weight of bulk biomass divided by the volume occupied. Rice husk bulk density ranges from 98 – 106.3 kg/m^3 (Jha & Singh, 2007). Moisture content cited in the literature usually refers to the inherent moisture (found in fuel's capillary opening) and surface moisture (moisture at surface of fuel) and not the decomposition moisture. The fraction of moisture in the fuel influences the overall heat output of fuels. In this context, higher moisture content of rice husk will impair the heat budget of the combustion and gasification reaction (Jain, 2006). In rice husk gasification, moisture content above 15% will result in poor performance of gasifier (Jain, 2013). Angle of repose expressed in degrees, is the angle made by biomass from the horizontal to the side of a pile under free falling conditions. It is useful in determining the angle for feeding hopper and ash hopper designs. Rice husk has an angle of repose in the range of 35-42 (Olivier, 2010) degrees depending on the moisture content.

Rice husk is a ligno-cellulosic material i.e. a non-starch, fibrous part of the rice plant. On an ash free basis it is composed of hemicellulose, cellulose and lignin as well as extractive matter such as proteins, oil, sugar etc (Williams & Nugranad, 2000) as shown in Table 2.3. Though the ultimate analysis does not give information about the suitability of a biomass fuel for combustion or gasification, the information about elemental composition for the biomass fuel is useful in the determination of stoichiometric formula, stoichiometric air fuel ratio, gas composition, temperature limits and gas production rate through a mass and energy balance over the thermochemical conversion process (Jain, 2013). The combustion efficiency of any biomass may be influenced by its chemical composition. Melting temperature of rice husk ask for example, is lower due to the high alkali content and presence of phosphorus. This low melting temperature may lead to fouling and corrosion during combustion or gasification and the possibility of agglomeration in a fluidized bed. However, due to the high ash content (>16%) of rice husk which results in a low multi fuel fouling (MFF) index, it has been classified as a low fouling fuel (Skrifvars et al., 2005a; Skrifvars et al., 2005b).

2.3.3 Thermal characteristics

The important thermodynamic property of a fuel relevant to thermochemical conversion is the heating value. The heating value, expressed as higher heating value (HHV) or lower heating value (LHV), is the amount of heat released under ideal combustion. HHV takes into account the latent heat of vaporization. Combustion or gasification operations occur at constant pressure and the vapor leaves with flue gas without being condensed. Under such conditions, the heating represents the LHV and it is usually 10 - 15% lower than the HHV (Jain, 2013). The proximate analysis which provides an initial indication of the fuels quality determines the moisture, volatile matter fixed carbon and ash. The volatile matter represents the condensable and non-condensable gases released when the fuel is heated. The amount of these gases may be used in estimating the thermodynamic properties of fuel including heating value and specific heat.

Table 2.3: Characteristics of rice husk

Characteristics	Unit	Value	Source
Composition			
Hemicellulose	wt%	28.6	(Park et al., 2004; Williams & Nugranad, 2000)
Cellulose	wt%	28.6-34.4	(Park et al., 2004; Williams & Nugranad, 2000)
Lignin	wt%	24.4	(Park et al., 2004)
Extractive matter	wt%	18.4	(Park et al., 2004)
Physical Properties			
Bulk Density	kg/m^3	98-106.5	(Jha & Singh, 2007)
True density	kg/m^3	1009-1054	(Jha & Singh, 2007)
Angle of repose	º	35-42	(Olivier, 2010)
Proximate Analysis			
Volatile matter	%	60.0	(Yoon et al., 2012)
Fixed Carbon	%	20.1	(Yoon et al., 2012)
Moisture	%	3.6	(Yoon et al., 2012)
Ash	%	16.3	(Yoon et al., 2012)
Ultimate Analysis			
Carbon	%	38.5	(Yoon et al., 2012)
Hydrogen	%	5.5	(Yoon et al., 2012)
Oxygen	%	36.6	(Yoon et al., 2012)
Nitrogen	%	0.4	(Yoon et al., 2012)
Sulfur	%	0.2	(Yoon et al., 2012)
Thermodynamic Properties			
HHV	MJ/kg	14.9	(Parikh et al., 2005)
Specific heat	kJ/kg.K	1.098-2.754	(Jha & Singh, 2007)
Thermal Conductivity	J/s.m.K	0.024-0.099	(Jha & Singh, 2007)

2.4 Harnessing rice husk energy

Rice husk energy can be harnessed through a biochemical or thermochemical conversion pathway. Biochemical routes include production of ethanol, hydrogen and methane. Thermochemical conversion processes range from simple direct combustion of the husk to technologies such as pyrolysis and gasification.

2.4.1 Bioethanol production

Rice husk cellulose and hemicellulose like other biomass can be converted to glucose and several pentose and hexoses during enzyme hydrolysis. The glucose is finally fermented into ethanol by elected microorganisms (Lim et al., 2012). Several studies to establish the feasibility of rice husk in ethanol have been published. These include the fermentation of hydrolysated rice husk powder to ethanol (Tian-xia & Zhang, 2005), the effects of lime pretreatment, enzymatic saccharification on rice husk cellulose and hemicellulose to monomeric sugars (Saha & Cotta, 2008), diluted sulphuric acid pretreatment and fermentation of rice husk to monomeric sugars (Saha et al., 2005), and microbial pretreatment and fermentation of rice husk (Patel et al., 2007). Kaylen et al. (2000) also evaluated the financial feasibility of converting lignocellulosic biomass into ethanol and suggested that by considering the co-production of higher-value chemicals, ethanol production can be competitive with gasoline. Abbas and Ansumali (2010) examined the global potential of rice husk for bioethanol production and concluded that about 20.9-24.3 billion liters could be produced per annum. This is equivalent to $37 \pm 4\%$, $19 \pm 2\%$ and $7 \pm 1\%$ of global demand of E5, E10 and E25, respectively. Although this is promising, fermentation of cellulosic biomass like rice husk to second generation ethanol is a great technical hurdle requiring consistent biomass source, advanced equipment, distribution/collection network and highly skilled labour (Verma et al., 2012). Hence its potential as local rice processing energy alternative is very unlikely.

2.4.2 Biogas production

Anaerobic digestion involves the microorganism conversion of rice husk to biogas, a mixture of methane and carbon dioxide, in the absence of oxygen. Very little literature exists on rice husk conversion to biogas as most research on rice biomass for biogas has been on rice straw (Lianhua et al., 2010; Lim et al., 2012; Zhang & Zhang, 1999). Mussoline et al. (2013) provides a review on biogas production with rice straw. Okeh et al. (2014b) evaluated the potential of rice husk for biogas production using a 1 liter digester and reported that a maximum yield of 382 ml/day could be achieved for a feed to water ratio of 1:6 w/v. Biogas production from rice husk requires pre-treatment such as alkali pre-treatment, heat pre-treatment or size reduction to increase digestibility (Lim et al., 2012) and co-substrate such as cow dung (Iyagba et al., 2009) for substantial biogas production.

2.4.3 Rice husk combustion

Rice husk may be combusted directly in the presence of sufficient air in a combustion chamber for steam production. Combustion systems developed for such purposes are equipped with forced air from a blower into the combustion chamber where combustion takes place either on an inclined static grate or a moving grate and mechanical ash removal systems (Araullo et al., 1985). In such combustion stoves, biomass burns in a combustion chamber in the presence of excess air to release long chain hydrocarbon (volatiles product of pyrolysis) to produce heat. Several rice husk furnace have been developed for boiler operations (Kapur et al., 1996a). Singh et al. (1980) developed and tested a rice husk combustion system capable of drying a tonne of paddy from 35 to 14% moisture content. At a feed rate of 20 kg/h up to 80% efficiency was achieved. Tumambing (1984) also tested a cyclonic rice husk furnace and reported a 98% combustion efficiency. Recently, the International Rice Research Institute (IRRI) collaborated with the Nong Lam University to upscale the Hohenheim-type inverted draft automatic furnace for paddy drying (Gummert, 2010). The improved furnace consists of a hopper with holding capacity of up to an hour, an incline grate and an ash pit. To improve efficiency and reduce smoke and fly ashes, both primary air and secondary air are supplied to burn charred carbon and smoke, respectively. Direct combustion of rice husk on a larger scale has been reported to be economically feasible for electricity generation for rice mills using a steam engine (Sookkumnerd et al., 2007; Sookkumnerd et al., 2005) or internal combustion engine (Wibulswas et al., 1994).

2.4.4 Rice husk briquetting

The use of rice husk is faced with the challenge of handling, storage and transport due to its low bulk density (Kaliyan & Vance Morey, 2009). In most rice processing communities where the milling centres are further away from the parboiling centres, extra work is required to transport husk for use. To ease the labour and improve the energy density of rice husk, briquettes are produced and used. This process of densification generally increases the biomass bulk density from 40-200 kgm^{-3} to a final bulk density of 600 – 800 kg/m^3 (Holley, 1983; Mani et al., 2003; McMullen et al., 2005). Husk briquette has been found to be an alternative fuel for wood fuel in rice processing. They are sometimes seen as a semi-matured technology usually developed by local entrepreneurs with or without support from government or donor agencies. Besides being efficient, briquetting facilitates transportation, better handling and storage (Ahiduzzaman, 2006). The briquette are produced by piston or screw press. In most developing countries a screw extrusion processed called heated die screw press is used (Ahiduzzaman & Islam, 2013). Moral and Rahman (1999) made a comparison of briquette presses and reported that briquette made from screw press has advantage over piston press in terms of combustion. Rice husk briquettes are generally densified with a compaction ratio ranging from 2.5:1 to 8.25: 1(Ahiduzzaman, 2007; UNEP, 2009).

During the briquette formation, physical forces are applied to the husk which binds the particles together. Five main binding forces come into play to hold particles together (Behnke, 1994; Tabil

Jr, 1996). These include solid bridges; attraction forces between solid particles; mechanical interlocking bonds; adhesion and cohesion forces; and interfacial forces and capillary pressure. Solid bridges may be developed when high pressure and temperature are applied. These occur through inter-particle molecular diffusion, crystallization of ingredients, chemical reaction, hardening of binders and solidification of melted components (Kaliyan & Vance Morey, 2009). Husk briquettes may be produced with or without external binders. Rice husk has up to 42 % of lignin and extractives which is more than the 34% required for biomass internal binding during densification (Lim et al., 2012). External binders includes starch or molasses, however, Chin and Siddiqui (2000) reported that water other than molasses and starch were good binding agent. Briquettes have higher heating value due to their higher energy density (Moral & Rahman, 1999) and the energy content of a kilogram of rice husk briquette could replace 1.67 kg of wood (Miah et al., 1999). Although, rice husk briquetting is reported to be profitable with benefit cost ratio of 1.8 (Kamruzzaman, 2001), it may be saddled with challenges such as excess energy consumption, lack of skilled operators, frequent damage of screw and main bearing and unavailability of heating coil (Alam et al., 2002). The average energy consumption for rice husk briquette production has been estimated based on laboratory research to be 116 kWh/tonne and for commercial process to be 179 – 250 kWh/tonne (Hardman, 2001). The consumption could be reduced to 150kWh/tonne when feed material is heated up in a pre-heater resulting in a 10 % energy savings (Bhattacharya et al., 2002c).

Considering an effective use of rice husk utilization, briquette presents a better option than the direct combustion in terms of energy density and efficiency. Briquettes have about 3.3 MJ/kg energy more than the raw husk (Bhattacharya et al., 1985; Mai Thao et al., 2011) with stove efficiency of 17% (Svenningson & Hosier, 1987) compared with 12% (IE, 2001) for husk combustor. Although, briquette has a higher energy density the cost of its production limits its use in rice processing. In rice producing communities where briquettes are produced manually with hand press, the rate of briquette production does not meet the energy demand hence the use of briquettes become inconvenient and parboilers resort to fuel wood.

2.4.5 Rice husk gasification

Rice husk gasification is the partial combustion of the husk to combustible gases. It includes drying, pyrolysis, combustion and gasification or reduction. In the gasification process a gasifying medium such as steam, air or oxygen is needed to react with the solid carbon and heavier hydrocarbon to produce low-molecular-weight gases. Using air as the gasifying medium gives the lowest heating value (4-7 MJ/Nm^3) of producer gas compared to steam (10-18 MJ/Nm^3) or oxygen (12-28 MJ/Nm^3) (Basu, 2010b), but it offers the cheapest cost hence it is mostly employed in small scale gasification projects. The advantage of burning gasification producer gas over the direct combustion of rice husk as practiced in most rice processing units, is the ability to control heating, higher flame temperature and the production of seemingly smokeless blue flame and more importantly, higher thermal efficiency. Generation of thermal energy through rice husk gasification for rice parboiling has not been widely reported since most parboiling systems burn rice husk directly without any further conversion. However, there are many reports on gasification for electricity production (Ahiduzzaman & Islam, 2012; Bhattacharyya, 2014; Kapur et al., 1997; Yoon et al., 2012). Belonio (2005) reported several small gasifier stoves designed for domestic heating application and rice producing communities. A summary of available rice husk gasifier stove is shown in Table 2.4

Gasifier stoves are generally more efficient than direct combustion stoves due to the combustion of CO, H_2 and light hydrocarbons to liberate heat from the producer gas. Their efficiencies range from 35 to 50% with low emission levels and uniform flame (Sutar et al., 2015).

Table 2.4: Rice husk gasifier stoves

Rice husk gasifier stove	Developer and Year	Description	Stove performance	Reference
CPU Prototype-IDD/T-LUD	Developed by Paul Wendelbo and Dr. Tom Reed in 1985	It's a top-lit updraft gasifier. The design has a concentrator lid. Reactor dimensions -15 cm ID and 25 cm high and has a capacity of 600g of rice husk. It has a fan attached to an ash chamber situated beneath reactor. Secondary air is preheated.	Thermal efficiency - 12.28-13.83%, Stove power output is estimated to be 0.237-0.269 kW. Boils a liter of water in 9-9.5 minutes	(Belonio, 2005; Lockwood et al., 2010)
DA-IRRI	Developed by Dr. Robert Stickney and A. T. Belonio in 1986	Double-core downdraft type reactor. Producer gas is cooled by condensation before combusted in a burner	Stove is a batch systems and produces flammable bluish gas. Quick fuel reloading system.	(Belonio, 2005)
CPU single-burner	Developed by CPU in 1989	An improved version of DA-IRRI with a continuous rice husk feeding system. It uses an LPG-type burner and has a chimney to take away smoke from user. Producer gas is regulated with a gate valve.	Average operating time is 0.98-1.25 hours/ load. 1.2-4 liters of water can be boiled in 10-34 minutes	(Belonio, 2005)
CPU cross-flow type	Developed by the Asian Institute of Technology	Operates in a continuous mode. Uses a 3-W DC motor to provide air which move horizontally across the reactor. Cooking occurs on a side burner.	Produces lot of smoke which are directed towards the burner. Reactor capacity is 2 kg which is operated in 37-47 minutes. One liter can be boiled in 8-11 minutes	(Belonio, 2005)
San San	Developed in Myanmar by San San Industrial Cooperative in 2005	Burns husk in continuous mode.	Frequent tapping for ash removal is reduced, smoke emission is negligible	The stove is referenced in several internet publication but the site is no longer online

				(Lockwood et al., 2010)
Conical grate stove	Developed by Dr. Alexis Belonio at the Appropriate Technology Center of Central Philippine University	It is a quasi-gasification system where secondary air and the pyrolysis gas mixes and burn.	It's a smokeless system but requires regular tending to remove ash	(Lockwood et al., 2010)
Rice husk gas stove	Developed by Dr. Alexis Belonio at the Appropriate Technology Center of Central Philippine University (2005)	A bottom lit downdraft gasifier operating in a batch mode. Consists of a removable rice burner with pot support fitted onto a reactor, a fan with switch controller, a char chamber and a safety shield.	Thermal efficiency 0.749-0.909. Specific gasification rate at full load is estimated to be 56.81 kg/hr-m^2	(Belonio, 2005; Lockwood et al., 2010)

2.5 Design and evaluation of combustion and gasifier systems

2.5.1 Design parameters

Thermochemical biomass conversion systems have been the main source of heat generation for food preparation in developing countries. About 2.7 billion people rely on biomass using different types of biomass such as wood, charcoal, crop residue and animal dung. These biomass are combusted in such stoves named as *cookstoves* or *biomass cookstoves* (Sutar et al., 2015). Biomass stoves have evolved over the years from a primitive open fire and three-stone fires (TSF) to the advanced biomass stove (Sutar et al., 2015). Recent advancement of biomass stoves takes into consideration several design parameters to enhance thermal efficiency and emissions. These include material of construction, type of air input, and the use of grate, chimney and pot skirts.

Clay, bricks and cement have been the main material for stove construction. These stoves are usually heavy and have high thermal inertia. Stoves made of metal on the other hand, are light and portable, and exhibit low inertia. However, they are known for their high heat lost due to the high thermal conductivity of metals (Sutar et al., 2015).

The use of a grate has been found to significantly improve stove performance through the supply of air. Stoves with grate allow the flow of primary air both above and below the fuel bed, thus enhancing combustion quality and improving efficiency by 3-5% (Gussain, 1990). Another design consideration for improved stove performance is the air supply. The combustion process is sustained by the air supply to the combustion chamber either as primary or secondary air. The mode of air supply, either natural or forced draft, influences the performance of stoves. In natural draft, the air enters the combustion chamber through free convection so optimal volatile-air mixing is not achieved, hence an improved stove geometry and construction material will be required to ensure higher efficiency. Forced draft stoves on the other hand have better performance and lower emissions due to proper mixing of volatiles and air. Higher efficiency and emission reduction can also be achieved by preheating input air. This occurs as a result of higher combustion temperature within the combustion chamber. A chimney may be added to the stove design to reduce impact of emissions. Besides removing flue gas from stove user, it also offers draft for drawing air into the combustion chamber. Gussain (1990) observed that the diameter of a chimney influenced the stove performance more than its height. Larger area as a result of the diameter increases the air inflow and reduces the frictional pressure drop.

2.5.2 Performance evaluation

Biomass stove performance has been evaluated usually at the laboratory scale using different testing protocols such as Volunteers in Technical Assistance (VITA) protocol (VITA, 1985), Indian standard on biomass Chulha-specification (BIS) protocol (BIS, 1991), the Water boiling test (WBT) (Aprovecho Research Center, 2013; Bailis R et al., 2007) and the ETPT (L'Orange et al., 2012). These test protocols employ the use of different thermal performance parameters such as power, thermal efficiency, specific fuel consumption, and turn-down ratio in the evaluation of the stoves (Sutar et al., 2015). Due to the variation in laboratory and field results, other field testing protocols such as the Controlled Cooking Test (CCT) and Kitchen Performance Test (KPT) have been developed (Manoj et al., 2013).

The VITA protocol specifies the use of an air dried wood with a uniform size of 3 x 3 cm^2. It requires that the pot be filled with water up to two-thirds of its capacity and the water heated from ambient to boiling point. Estimation of thermal efficiency (termed as Percentage Heat Utilization) disregards heat absorbed by the pot but takes into account the mass of water lost while boiling. A repetition of the test for at least four times is recommended. The VITA protocol makes no mention of pot size, feeding rate or emission measurements.

The revised BIS protocol (version 2013) requires the use of *kali*, *deodar*, *mango*, *acacia* or *eucalyptus* at 5±1% moisture content with sizes 3 x 3 and 4 x 4 cm^2 for family size and commercial stove, respectively. Depending on the fire power, a provision of pot sizes and corresponding amount of water is given. Initial and final water temperatures of 23±5 and 95 ^oC, respectively is stated. For continuous feeding system, a 6 minutes interval is mentioned. Thermal efficiency calculation considers the heat absorbed by pot and heat released by kerosene during the start of the test. However, heat absorbed by the pot and char remaining after test are neglected. BIS protocol includes emission measurement and recommends a hood method and sensors for gas analysis.

The WBT (version 4.2.2:2013) specifies the use of wood with high calorific value (20-21 MJ/kg) with size of 1.1 x 1.5 cm^2 and moisture content of 6.5-10%. Based on the stove design and the fire power, a recommended standard pot of 7 or 5 litres may be used with 5 or 2.5 litres of water in the larger and smaller pot, respectively. A 15^oC initial water temperature, a local water boiling point and a temperature 3 ^oC below boiling point are recommended. Thermal efficiency estimation takes into account the amount of water evaporated and equivalent dry wood which account for the moisture in the fuel but not the heat absorbed by the pot. Hood method and sensors for gas analysis are also recommended for emission measurement.

Connecting Text

The literature review presented in chapter 2 provided an understanding of the parboiling concept within the rice value chain, and described the different parboiling systems, energy supply and use in local rice processing. It also provided information about rice husk characteristics and rice husk energy conversion pathways as well as the evaluation of combustion and gasification systems.

Chapter 3 establishes the basis for the rest of the work. The thermal behaviour, reactivity, kinetics and ignition performance of rice husk and briquettes made with different binders is examined to understand how devolatilization characteristics vary with the addition of binders and at different heating rates. The chapter further examines the different rice husk utilization options broadly, considering energy replacement potential, wood savings, greenhouse gas mitigation potential and annual energy expenditure. The information provided may be useful for local rice processing stakeholders in selecting the appropriate rice husk utilization options as well as providing basic information for future rural energy development.

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CHAPTER 3 Thermogravimetric characterization and potential of rice husk as a local parboiling fuel

Abstract

In this study, rice husk was considered as an alternative to wood for local rice processing. The thermal characteristics of rice husk and its briquette together with their potential of meeting the local parboiling energy demand were examined. The devolatilization characteristics, reactivity, kinetics and ignition performance of rice husk and its briquette produced with different local starch binders - cassava, rice, corn starch and mixed rice-cassava starch binders - were evaluated using a thermogravimetric approach. The activation energy (E) and reactivity index were used to evaluate the kinetics and reactivity during combustion. The devolatilization E and frequency factor (A) were within the range of 53.4 - 65.4 $kJmol^{-1}$ and 2.1 x 10^5 – 20.6 x 10^5 $min^{-,1}$ respectively. Rice husk potential was broadly examined under different utilization scenarios using energy replacement value based on a modified heating value, greenhouse gas reduction potential and annual energy expenditure. It was found that, rice husk use could effectively and efficiently replace wood achieving up to 67% wood savings, 63% greenhouse gas emission reduction and an annual parboiling energy expenditure reduction of 73%.

3.1 Introduction

Rice has become a traditional staple food in most parts of Africa with the fastest relative growth in its demand in the world (Balasubramanian et al., 2007). Ghana, like most West African countries has more than doubled rice consumption in the last decade, recording an increase in per capita consumption from 17.5 to 38.0 kg between 1999 and 2008. This value is expected to reach 63 kg by 2018 as a result of rapid population growth and urbanization (Ministry of Food and Agriculture, 2009). Although, milled rice production keeps increasing, it has been reported that local rice production cannot meet the increasing demand for rice in many African countries (Balasubramanian et al., 2007). This is evident in the increase rice importation within the West Africa region which is expected to reach 10.1 million tonnes in 2020 (Ministry of Food and Agriculture, 2009). With the self-sufficiency ratio of rice in Ghana declining from 38% in 1999 to 24% in 2006 (Ministry of Food and Agriculture, 2009) coupled with the declining global stocks and increase in prices, there are additional strains on rice importing countries to meet their projected consumption rate. Furthermore, 80% of local rice in Ghana is grown and processed by ultra-poor, marginal rice smallholders and small-scale rice farmers (Ministry of Food and Agriculture, 2009).

Increasing consumer's preference for local rice undoubtedly requires improvement in quality which can be achieved through improved processing. Parboiling is one such quality improvement technique currently being employed in local rice processing with the aim of improving both physical and nutritional quality. It is generally energy intensive and requires about 1659 - 2758 MJ/tonne of paddy (Ahiduzzaman & Sadrul Islam, 2009) depending on the parboiling process. In Ghana, like most African Countries where parboiling is practiced, thermal energy requirement for parboiling is usually met by woody biomass for small and medium scale rice processing units (Demont et al., 2012). Reliance on wood, in Ghana for example, has become a serious problem since the tropical forest area has been reduced to a quarter in less than 50 years coupled with an annual forest depletion rate of 22,000 hectares (Duah-Yentumi & Klah, 2004). With the current wood consumption rate of 640 kg per capita and forest growth dropping to less than half the demand (Duah-Yentumi & Klah, 2004), wood use cannot be a sustainable energy option. In addition to these, the use of wood as energy in inefficient (13% (Johnson & Bryden, 2012a; Johnson & Bryden, 2012b)) traditional three-stone and small hand-crafted cookstoves is considered responsible for several cases of respiratory disease and morbidity, burns, cuts, and scalds (Desai et al., 2004; Wickramasinghe, 2003). Meanwhile, the rice husk generated during milling process is heaped and openly burnt to dispose them.

In considering rice husk or its briquette as fuel in small scale rice producing communities, the combustion behaviour cannot be ignored because it may influence performance and acceptance. Knowledge of combustion dynamics, reactivity and ignition performance in fuel combustion are important features for flame and combustion stability, pollutant formation and combustion process control stability (Mortari et al., 2010) which in the case of briquette, can aid in the selection of the best locally available binder and improve rice husk use.

Combustion behaviour has been investigated under both oxygen and nitrogen environment using several thermogravimetric technique (TGA, DTGA, TGA-DTGA combination method) and infrared spectroscopy including TGA-FTIR. GC-MS, LC-MS or the laboratory-scale FBR method (Aghamohammadi et al., 2011; Matsuzawa et al., 2004; Otero et al., 2002). The TGA-DTGA combination method has been found to be more convenient with better repetitiveness compared with test results which is dependent on experimental conditions (Chao et al., 2013).

The two objectives of the study were firstly, to assess the thermal decomposition behaviour, kinetics, reactivity and ignition performance, and secondly, to examine the most effective thermochemical pathway for harnessing rice husk energy for local parboiling.

3.2 Materials and Methods

3.2.1 Fuel preparation

Rice husk used for the experiment were purchased from California, USA. The husk was milled using a hammermill with mesh size number 20 (841 μm). For briquette production, local materials within rice processing communities were simulated and used as binders. Residue from rice milling, '*gari'* (local food) processing and corn milling were simulated using rice flour, cassava flour and corn flour, respectively. The simulated starch binders were purchased from the local grocery store. Binders were prepared with hot water at 100ºC with water-flour ratio of 40:60. Briquettes were produced with milled rice husk and binder in a ratio 70:30. A mixture of rice husk and binder weighing 100 g were mixed thoroughly in a pyrex container and covered with a plastic film and heated in a microwave for 120 seconds. This was to enhance proper mixing of starch and the milled rice husk. Using a funnel the heated biomass was transferred into a mold and pressed beneath a 30 tonnes hydraulic press. A Futek sensor (model FSH00885, Thornhill, ON, Canada) was used to monitor and collect data on the hydraulic press pressure. The briquettes were dried for two hours in the sun and stored on a laboratory bench for a week before analysis. Three types of briquettes - cassava binder briquette (CaB), corn binder briquette (CoB) and rice-cassava binder briquette (RCaB) - were produced and used for thermogravimetric analysis.

3.2.2 Proximate and ultimate analysis

The proximate analyses of rice husk and briquettes produced were carried out. The moisture content of the fuels were determined according to ASABE Standard S358.2 by drying at 104 ºC for 24 hours in an oven (Fisher Scientific 750, USA). The proximate analysis was determined following ASTM E1131, standard test method for compositional analysis by thermogravimetry for volatile matter, ash and fixed carbon (ASTM, 2010). The higher heating value (HHV) and the ultimate analysis were determined from the proximate analysis using correlations proposed by Parikh et al. (2005) and Shen et al. (2010), respectively, as shown in Eq 3.1- 3.4.

$$HHV = 0.3536FC + 0.1559VM - 0.0078ASH \quad (MJ/kg) \tag{3.1}$$

$$C = 0.635FC + 0.460VM - 0.095ASH(wt.\%) \tag{3.2}$$

$$H = 0.059FC + 0.060VM + 0.010ASH(wt.\%) \tag{3.3}$$

$$O = 0.340FC + 0.469VM + 0.023ASH(wt.\%) \tag{3.4}$$

3.2.3 Thermogravimetric analysis

Thermal analysis was carried out using thermogravimetric analyser Universal V4.7A TA Instruments (TGA Q500). Non-isothermal combustion was performed in the furnace of the thermobalance under controlled temperature. Rice husk and dried briquettes (crushed with a mortar and pestle, and mixed thoroughly) were sampled for thermographic evaluation. Approximately 20 mg of samples were combusted under oxidative environment in continuous airflow of 60 ml/min at a gauge pressure of 101 kPa. The samples were heated from room temperature to 850 ºC at selected heating rate. To explore the kinetics of the thermal decomposition and ensure homogeneous ignition, low heating rates (5, 10, 20, 50 ºC/min) were used (Gentzis & Chambers, 1995). These lower heating rates may also reduce the temperature gradients throughout samples (Kneller, 1986). The tests were carried out in triplicates and the data was analysed using the TA Instruments Universal Analysis 2000.

3.2.4 Reactivity and kinetics of combustion

The iso-conversional (model-free) technique was used for the kinetic analysis. It was chosen over the model-fitting to tolerate change of mechanism during reactivity since it is sufficiently flexible and also allows the use of multiple heating rates (β) which will reduce the mass transfer limitation (Sima-Ella & J, 2005). This method calculates effective activation energy as a function of the extent of conversion of a chemical reaction (Mortari et al., 2010). The conversion is defined by Wang et al. (2012b):

$$\alpha = \frac{W_T - W_0}{W_f - W_0} \tag{3.5}$$

Where W_T is the weight of sample at a given temperature T ; W_0 and W_f refer to the weight at the beginning and the end, respectively.

Using a single step kinetic correlation, the kinetics of the heterogeneous reactions in the rice husk was expressed in terms of the rate of conversion (Mortari et al., 2010) as:

$$\frac{d\alpha}{dt} = k(T).f(\alpha) \qquad 3.6$$

By replacing $k(T)$ with the Arrhenius equation, the explicit dependence of the rate equation on temperature expressed in Eq 3.6 becomes

$$\frac{d\alpha}{dt} = A\exp\left(-\frac{E}{RT}\right).f(\alpha) \qquad 3.7$$

Where, A is the frequency factor. The rate equation was expressed in terms of $\frac{d\alpha}{dt}$ by including the variation of constant heating rate with temperature $\beta = \frac{dT}{dt}$. This gave

$$\frac{d\alpha}{dT} = \frac{1}{\beta}\left[A\exp\left(-\frac{E}{RT}\right)\right].f(\alpha) \qquad 3.8$$

Rearranging Eq 3.8 and integrating (Mortari et al., 2010; Sanchez et al., 2009; Wang et al., 2012b) up to conversion α resulted in Eq 3.9:

$$\ln\left[\frac{-\ln(1-\alpha)}{T^2}\right] = \ln\left(\frac{AR}{\beta E}\right) - \frac{E}{RT} \qquad 3.9$$

The slope obtained by plotting $\ln\left[\frac{-\ln(1-\alpha)}{T^2}\right]$ against $\frac{1}{T}$, was used to evaluate kinetic parameters A and E. The reactivity index for the briquette combustion was evaluated based on the Coats-Redfern equation. Higher reactivity index was taken as an indication of better reactivity (Wang et al., 2012b).

3.2.5 Rice husk utilization scenarios

Biochemical and thermochemical processes have been the main pathways for harnessing energy from biomass materials like rice husk. Biochemical processes such as biogas and bioethanol are typically capital intensive and require skilled operators (Verma et al., 2012) so they may not be suitable for local rice processing. Therefore, thermochemical systems namely direct combustion, briquetting and gasification, which could be simple, less expensive, requiring less skill for operation were considered for this study. In many parts of Asia, direct combustion and briquetting of rice husk has successfully been employed for rice parboiling and has been reported to be economically feasible on a larger scale not only for heat production but also for electricity generation for rice mills using steam engine (Sookkumnerd et al., 2007; Sookkumnerd et al., 2005) or internal combustion engine (Wibulswas et al., 1994). Gasification has also been used for heat and electricity generation in large rice farms (Akgün & Luukkanen, 2012; Bhat et al., 2001; Yoon et al., 2012). Though, gasification systems are known to be complex requiring high level skill for operation and maintenance (Ghani et al., 2009), development of small unit rice husk gas stoves for rural domestic application have been successful and operational in the Philippines and India (Belonio, 2005). These biomass gas stoves are both mini-gasifier heat generators and also effective structures for heat transfer into cooking pots (Vitali et al., 2013). They supply their own gas from dry solid biomass and are currently known to be the cleanest method to burn biomass (Mukunda et al., 2010). In addition to the aforementioned advantages of small unit gasifiers, they are simple to operate, requiring less expertise and less expensive and could be extended for small scale rural rice processing.

To ensure accurate evaluation of rice husk's potential in meeting parboiling energy demand, preliminary data from a baseline survey conducted on parboiling energy dynamics in the Northern region of Ghana was used. The data was initially collected by the author of this thesis in 2012 while working as a senior lecturer at the Department of Energy Systems Engineering, Koforidua Polytechnic, Ghana. The data was updated in 2014 by Mr. Anthony Modei Mainoo also of Department of Energy Systems Engineering, Koforidua Polytechnic. The complete results have subsequently been submitted for publication in the Energy for Sustainable Development Journal.

Although, the results of the survey are not included in this thesis, part of the data has been used for comparison purposes only to effectively determine the extent of the improvement achieved in this project.

Assessment of the selected rice husk utilization scenarios was based on energy replacement potential, wood savings, greenhouse gas reduction potential and annual energy expenditure. The annual paddy processed used was assumed to be 800 tonnes (Mainoo & Kwofie, 2014).

3.2.6 Energy replacement potential evaluation

The energy replacement potential was estimated based on modified heating value. The modified energy estimation that takes into account the fuel's heating value and the system's efficiency was used. For each fuel, the lower heating value and the combustion efficiency of a typical stove using such fuel were used and their product taken as the modified heating value. Using current wood energy demand as the baseline, the energy replacement potential was calculated as the ratio of the modified heating value of a selected rice husk scenario to wood. For gasification, the hot gas efficiency based on air gasification was used since the producer gas was used directly from the gasifier without further processes like scrubbing or filtering. A summary of the parameters used for the energy replacement assessment is shown in Table 3.1.

Table 3.1: Summary of parameters for energy replacement potential

Fuel	Stove Type	Lower Heating value [MJ/kg]	Efficiency [%]
Wood	Three stove stone fire	15.60 (Mai Thao et al., 2011)	13 (Johnson & Bryden, 2012b)
Rice Husk	Continuous rice husk combustor	14.35 (Jain, 2006)	23[b]
Briquette	Continuous rice husk combustor	16.3 (Miah et al., 1999)	23[b]
Gasifier producer gas	Continuous rice husk downdraft gasifier stove	4.2[a] (Jain, 2006)	61 (Jain, 2006; Mukunda et al., 2010)

[a]Estimated using gas density of 0.95kg/m^3 (Basu, 2013). [b]Efficiency based on authors' fabricated rice husk combustor.

3.2.7 Environmental evaluation

The environmental evaluation considered both wood saving and GHG emission reduction potential. Annual wood saving was estimated by calculating equivalent energy saving for various percent of rice husk in the energy mix. Energy savings were then converted to quantity of wood saved.

Emission evaluation took into account the emission due to (a) wood combustion, (b) vehicular transport of bulk wood for sale to parboilers, (c) current disposal of rice husk, (d) emission from a proposed rice husk scenario and (e) emission from fuel production (where applicable). The emissions due to wood transport have been included considering the fact that about 65% of parboiling energy is transported over 110 km from other districts (such as Kintampo and Yendi) to the processing centres. In estimating the number of trips per year, an average of 10 "seat" (the unit used for selling wood with the communities equivalent to 4050 kg) per trip was chosen resulting in 118 trips per year. Also, emission due to transport of rice husk was neglected since the rice mills (where the husk were heaped) were within walking distance from the parboiling centers and could be carried or transported by cattle. Total GHG emission reduction potential was estimated according to Eq. 3.10 – 3.13

$$\text{Emission reduction} = \left(\begin{array}{c} \left(\begin{array}{c}\text{Emission due}\\ \text{to wood}\\ \text{combustion}\end{array}\right) + \left(\begin{array}{c}\text{Emission due to}\\ \text{the wood}\\ \text{transportation}\end{array}\right) + \\ \left(\begin{array}{c}\text{Emission due}\\ \text{to uncontrolled}\\ \text{burning of rice husk}\end{array}\right) - \left(\begin{array}{c}\text{Emission due}\\ \text{to the Rice husk}\\ \text{use for parboiling}\end{array}\right) \\ - \left(\begin{array}{c}\text{Emission due to}\\ \text{rice husk}\\ \text{energy production}\end{array}\right) \end{array} \right) \qquad 3.10$$

$$\left(\begin{array}{c}\text{Emission due}\\ \text{to wood}\\ \text{combustion}\\ \left[tCO_2e/yr\right]\end{array}\right) = \left(\begin{array}{c}\text{Heating}\\ \text{value}\\ \text{of wood}\\ \left[TJ/yr\right]\end{array}\right) \times \left(\begin{array}{c}\text{Methane emission}\\ \text{factor for}\\ \text{wood combustion}\\ \left[tCH_4/TJ\right]\end{array}\right) \times \left(\begin{array}{c}\text{Approved GWP}\\ \text{of } CH_4 \text{ factor for}\\ \text{wood combustion}\\ \left[tCO_2e / tCH_4\right]\end{array}\right) \qquad 3.11$$

$$\left(\begin{array}{c}\text{Emission due}\\ \text{to rice husk}\\ \text{use}\\ \left[tCO_2e/yr\right]\end{array}\right) = \left(\begin{array}{c}\text{Heating value}\\ \text{(Rice husk/briquette}\\ \text{/producer gas)}\\ \left[TJ/yr\right]\end{array}\right) \times \left(\begin{array}{c}\text{Methane emission}\\ \text{factor for}\\ \text{wood combustion}\\ \left[tCH_4/TJ\right]\end{array}\right) \times \left(\begin{array}{c}\text{Approved}\\ \text{GWP}\\ \text{of } CH_4\\ \left[tCO_2e / CH_4\right]\end{array}\right) \qquad 3.12$$

$$\left(\begin{array}{c}\text{Emission due to}\\ \text{the wood}\\ \text{transportation}\\ \left[tCO_2/yr\right]\end{array}\right) = \left(\begin{array}{c}\text{Number}\\ \text{of truck}\\ \text{trips in a}\\ \text{year}\end{array}\right) \times \left(\begin{array}{c}\text{Average return trip}\\ \text{distance to rice}\\ \text{producing communities}\\ \left[km\right]\end{array}\right) \times \left(\begin{array}{c}CO_2 \text{ emission}\\ \text{factor for}\\ \text{trucks}\\ \left[tCO_2 / km\right]\end{array}\right)$$

3.13

Considering the fact that wood and rice husk are all outcomes of atmospheric carbon dioxide accumulated during their respective plant growth and are transformed into organic carbon substances, their carbon dioxide emissions are taken to be neutral and not included in the inventory (Tarnawski, 2004). Also for simplification, N_2O have been excluded from emission evaluation. A summary of the parameters used for the Greenhouse Gas reduction potential evaluation is shown in Table 3.2.

Table 3.2: Summary of parameters for Greenhouse Gas reduction potential evaluation

Parameter	**Unit**	**Value**	**Source**
GWP_{CH4}	tCO_2/cCH_4	25	(IPCC, 2007)
CH_4 EF for biomass combustion	tCH_4/TJ	0.0411[c]	(IPCC, 2006)
CO_2 EF for trucks	tCO_2/km	1.098×10^{-3}	(EPA, 2012)
CO_2 emissions per kWh	tCO_2/MWh	0.214767509	(Jenkins et al., 1991)
Briquetting machine energy consumption	kWh/tonne	179	(Hardman, 2001)

[c]Calculated assuming a conservativeness factor of 1.37 (UNFCCC, 2007)

3.2.8 Economic evaluation

Annual parboiling energy expenditure was evaluated using a modified version of the economic model . The model allows the estimation of the annual parboiling energy using different fuel and their relative stove technology. It takes into account the capital of stove spread over its lifespan, the annual stove maintenance cost and the fuel cost. The fuel cost is the product of fuel unit cost and fraction of gross energy need calculated using the modified heating value. The annual energy expenditure (AEE) is estimated using the expression:

$$AEE = \sum_{ij}\left[\frac{C_{Sj}}{L_{Sj}} + M_{Sj} + \left(\frac{ET \times f_i}{\eta_{ij} \times LHV_i} \times C_{fi}\right)\right], \qquad \text{(USD)} \qquad 3.14$$

Where ET is the total net energy required for parboiling paddy, LHV_i is the lower heating value for the fuel i, f_i is the share of parboiling energy needs covered by fuel i, η_{ij} is the transfer efficiency of the stove j using the fuel i, C_{fi} is the cost of the fuel i, C_{Sj} is the capital cost of the stove j, M_{Sj} is the annual maintenance cost of stove j and the L_{Sj} lifespan of the stove j.

The cost of gasifier, manual briquetting machine and rice husk combustor used in the economic analysis were based on actual cost of fabrication at McGill University, Canada. The rice husk combustor consists of a firebox (80 x 75 x 55 cm) made from 3/16 inch black iron plate, a 4.5 kg capacity feed hopper at rear end, a 20 x 20 cm^2 perforated gauge 16 steel plate inclined at 45^o, and a removable front end to allow for the use of alternative fuel like wood or briquette. The gasifier is a continuous feed bottom lit downdraft type made of a galvanized steel reactor column (30 x 120 cm), a movable conical grate powered by a 0.5HP motor for continuous ash removal and a 15W blower for air. Detailed design drawing of gasifier is hown in appendix A. A summary of the parameters used for the economic evaluation is shown in Table 3.3.

Table 3.3: Summary of parameters for Economic Evaluation

Item	**Capacity [kg fuel/h]**	**Power requirement [kW]**	**Cost of stove** [GHS]	**Maintenance cost** [GHS]	**Source**
TSF stove	variable	-	0	0	This study
Rice husk combustor	9.0	0.015	900	90	This study
Manual briquetting machine	1.8	-	300	50	This Study
Commercial briquetting machine[d]	180-210	4.4	3600	360	(GROUP, 2015)
Gasifier stove	12	0.015	1200	120	This study

1USD = 3.0 GHS (Ghana Cedis)

3.3 Results and Discussion

3.3.1 Characterization and thermal behaviour

The results obtained for the proximate analysis, ultimate analysis and heating value are shown in Table 3.4. They include the characterization of briquettes, rice husk and popular wood species used for parboiling in the West Africa region (Mainoo & Kwofie, 2014).

As can be seen, briquettes had similar characteristics and heating values but were generally lower than the wood species. TGA and DTGA curves obtained for the temperature controlled combustion of the samples at the heating rate of 20 ºC/min are shown in Fig 3.1. From the DTGA curves three distinct events can be observed. These events correspond to moisture removal, volatile matter decomposition and fixed carbon decomposition. Fig. 3.2 shows DTGA plots of rice husk at different heating rate (5, 10, 20 and 50 ºC/min). The results show that the devolatilization peak shifts slightly towards the right with an increase in the heating rate indicating a possible increase in ignition temperature.

Table 3.4: Proximate and ultimate Analysis

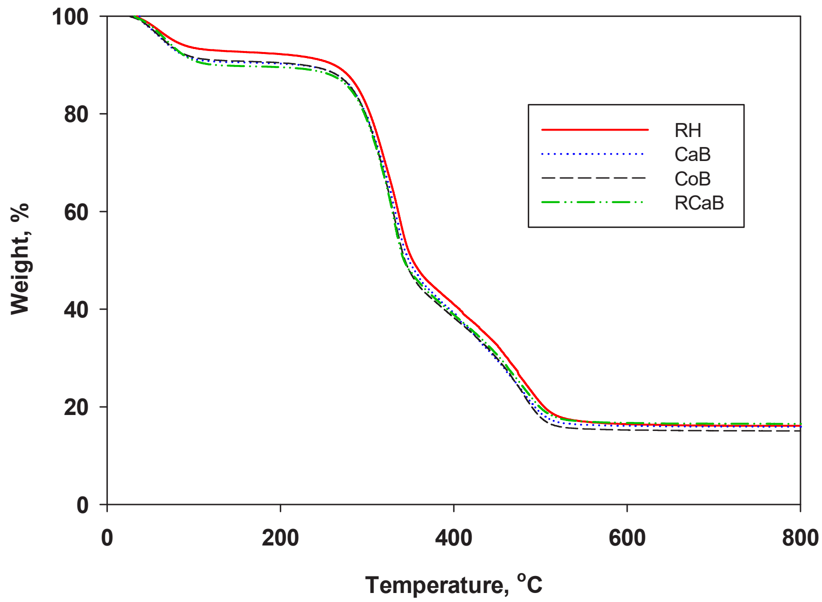
Biomass	Proximate Analysis (wt %), db			Ultimate Analysis (wt %), db			HHV[a] (MJ/kg)	Reference
	VM	FC	ASH	C	H	O		
RCaB	63.12	17.68	19.2	38.44	5.02	36.06	15.94	This work
CoB	62.89	16.51	21.6	37.36	4.96	35.61	15.47	This work
CaB	62.54	16.56	20.9	37.30	4.94	35.44	15.44	This work
Rice Husk	61.24	18.04	20.72	37.66	4.95	35.33	15.76	This work
Rice husk	61.81	16.95	21.24	37.18	5.2	34.61	15.46	(Channiwala & Parikh, 2002)
Neem wood	85.86	12.19	1.93	48.26	6.27	43.46	17.68	(Shen et al., 2010)
Wood chips	76.4	23.5	0.1	48.1	5.99	45.74	20.22	(Shen et al., 2010)
Mango wood	85.64	11.36	2.98	46.24	6.08	44.42	17.34	(Parikh et al., 2007)

RCaB = Briquettes made with rice cassava binder; CoB = Briquettes made with corn starch binder; CaB = Briquettes made with cassava binder; [a]Estimated from Eq 3.1

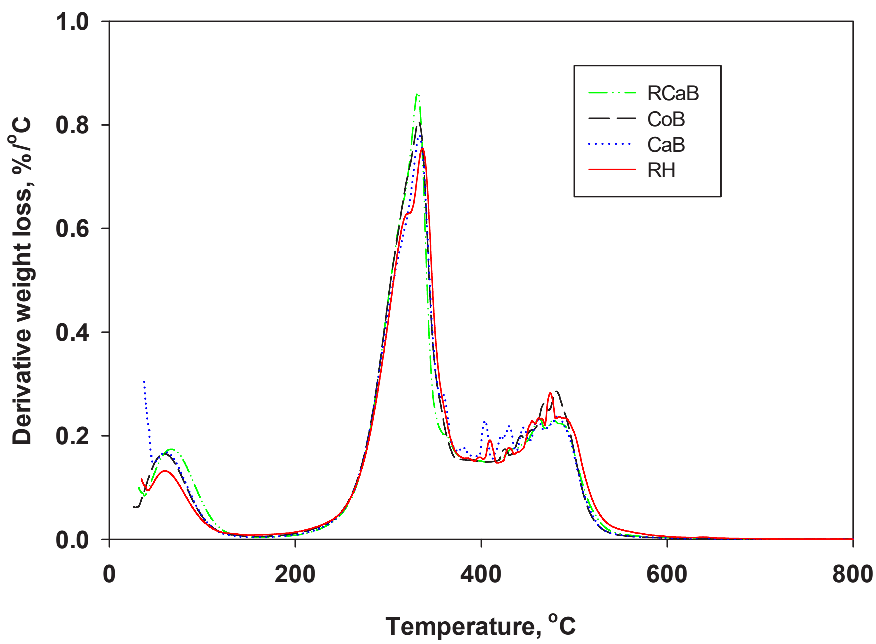
The characteristics of the briquettes displayed in Fig. 3.1 are indication that the addition of a binder does not significantly influence the heating value. This also explains the fact that binders are primarily added to improve mechanical characteristics and not thermal behaviour. The briquettes did not show superior heating value over rice husk or comparably to wood as expected (Bhattacharya et al., 1985; Mai Thao et al., 2011; Miah et al., 1999) perhaps it is because the samples were not in the densified form which increases the energy density (20 mg were used for thermogravimetric experiments).

Despite the difference in binders, the evolution profiles of weight change and the time derivative weight loss were not different. They were similar to general biomass degradation characteristics showing the three distinct combustion stages - moisture removal, volatile combustion and fixed carbon decomposition (oxidation of char) (El may et al., 2012). The moisture removal which began from room temperature to about 155 ^{o}C accounts for the weight loss (10.98-12.02% during this first stage of combustion. A greater percentage indicates a higher moisture content of the briquette. High moisture content implies that a higher mass of water has to be vaporized which leads to reduction in the maximum process temperature and the biomass consumption (Pérez et al., 2012; Xie et al., 2010; Xiong et al., 2013). Higher moisture content will therefore impair the heat budget of the combustion reaction. Therefore the percentage of water used in the binder formulation is critical as it has the potential of increasing briquette moisture content and reducing the available energy. The briquettes had a general volatile decomposition temperature range of 168 – 396 ºC that is similar to biomass devolatilization results reported by other researchers (López-González et al., 2013; Sait et al., 2012; Wang et al., 2012b). The burnout temperature (BOT) of the briquettes defined as the temperature where the weight loss reaches 1%/min at the terminal phase of the DTGA profile were found to be within the range of 543.9 – 551.9 ºC. The residual weight of briquettes after oxidation obtained was between 18.9 and 20.90 % and was similar to that of rice husk (20.72 %). During thermal degradation most starch undergoes a moisture removal process between 25 and 174 ºC as well as a depolymerisation and degradation between 274 and 374 ºC (Guinesi et al., 2006) releasing CO_2, CO, water, acetaldehyde and furan. Corn starch on the other hand releases mainly levoglucosan with other gases (Greenwood, 1967).

The combustion of the starch components did not necessarily increase the ash content of the briquette which could reduce the initial temperature of degradation leading to a reduction in the heating capacity of the briquettes (Mansaray & Ghaly, 1998). El may et al. (2012) explains that during starch (corn, cassava, potato and rice) combustion, more than 80% of weight is lost before the temperature reaches 500 ºC. For the selected briquettes, the rice starch based briquettes had the least residual ash content. In view of the high ash content of both rice husk and briquettes compared to the current wood species, it is important to consider the incorporation of an ash removal system in rice husk stoves.



(a) TGA Curves



(b) DTGA curves

Figure 3.1: TGA and DTGA curves of rice husk and briquettes at the heating rate of 20 ºC/min. RCaB = Briquettes made with rice cassava binder; CoB = Briquettes made with corn starch binder; CaB = Briquettes made with cassava binder.

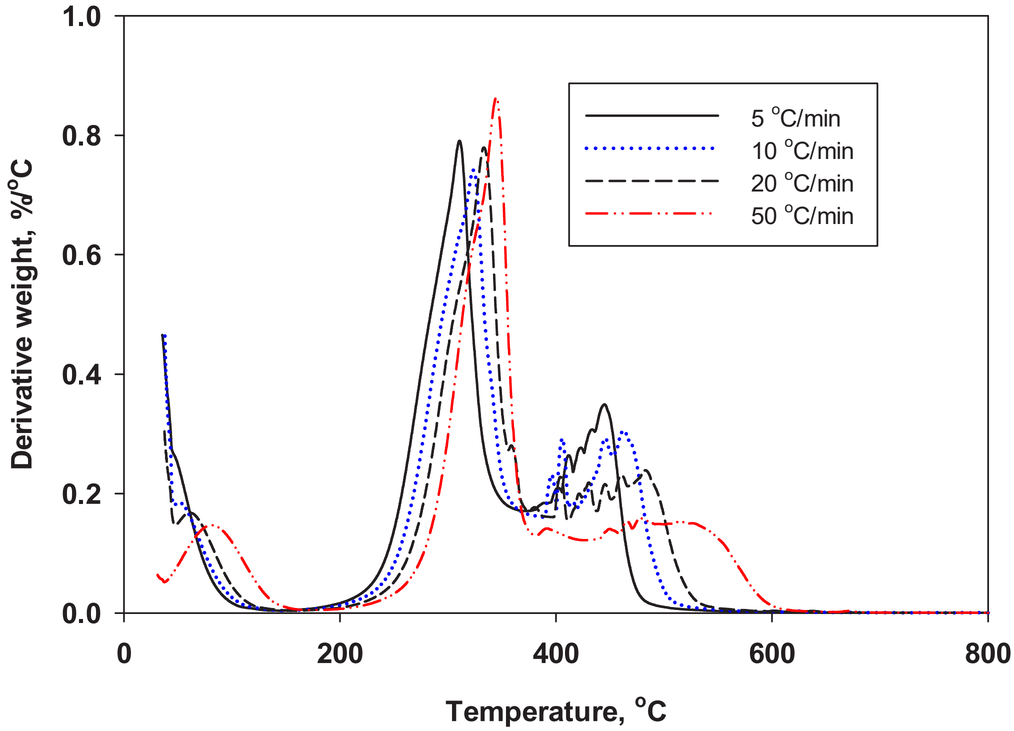


Figure 3.2: DTGA variation with heating rate of briquette with cassava-rice starch binder

3.3.2 Reactivity and Kinetics

The thermal kinetic plot for both volatile matter and fixed carbon decomposition for rice husk is shown in Fig. 3.3. The overall kinetic parameters of briquettes during devolatilization together with their corresponding linear regression coefficient are presented in Table 3.5. Activation energy (E) and frequency factor of briquette samples estimated from the Coats-Redfern plots were found to be in the range of 53.39 and 65.38 $kJmol^{-1}$ and 2.1 x 10^5 – 20.6 x 10^5 min^{-1}, respectively. Rice husk generally has higher activation energy than its briquettes irrespective of the binder used probably due to the lower reactivity of starch. This is an indication that the addition of binders reduces the activation energy. The reactivity index, estimated by plotting reactivity as a function of temperature was sensitive only at lower heating rate (5ºC/min). At higher heating rate (10ºC/min and above) reactivity within the volatile matter decomposition region was not influenced as indicated in Fig 3.3. Reactivity in fixed carbon decomposition region on the other hand, was sensitive to heating rate, decreasing with increasing heating rate. Although, the effect of heating rate on the thermal decomposition has still not been resolved (White et al., 2011), Wang et al. (2012b) suggest it could possibly be due to the addition of heat hence the lower heating time.

Several authors have also suggested that the heating rate has minimal impact on the frequency factor which depends on the material structure (White et al., 2011; Yorulmaz & Atimtay, 2009). This lower reactivity is also reflected in corresponding higher kinetic parameters, activation energy and frequency factor as depicted in Table 3.5.

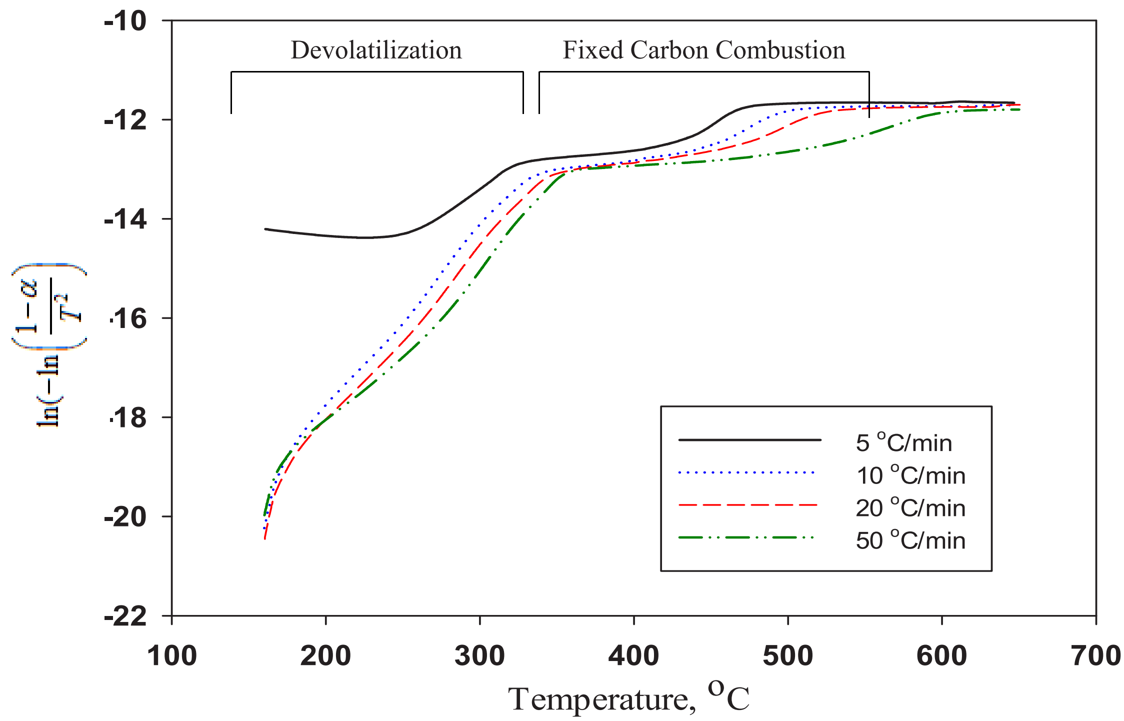


Figure 3.3: Effect of heating rate on rice husk reactivity

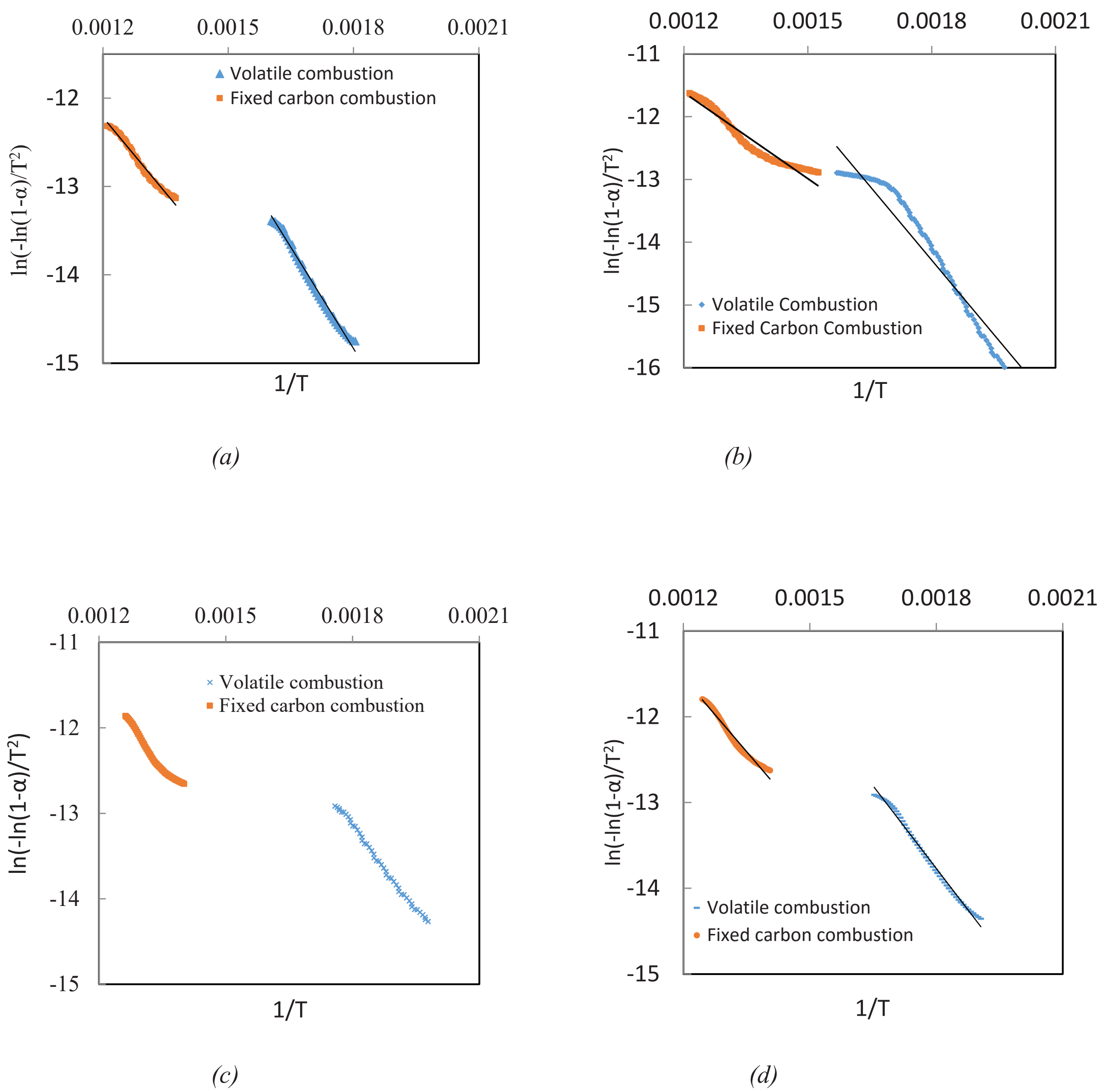


Figure 3.4: Thermal kinetics plot for briquette samples (a) Rice Husk (RH) (b) Briquette made with rice-cassava binder (RCaB) (c) Briquette made with corn starch binder (CoB) (d) Briquettes made with cassava binder (CaB).

Table 3.5: Kinetic parameters for rice husk and briquette devolatilization

Briquette Sample	**Ea (kJmol^{-1})**	**A (min^{-1})**	**R^2**
RH	65.4±2.1	20.6 x 10^5	0.9833
RCaB	63.6±1.4	12.6 x 10^5	0.9924
CoB	54.1±1.8	4.67 x 10^5	0.9958
CaB	53.4±2.3	2.1 x 10^5	0.9936

RCaB = Briquettes made with rice cassava binder; CoB = Briquettes made with corn starch binder; CaB = Briquettes made with cassava binder.

A comparison of reactivity among the samples reveals similar performance for all samples with a relative worst reactivity in briquette produced with the rice-cassava starch binder. The lower reactivity in rice binder briquette was also observed by Aggarwal and Dollimore (1996) when evaluating the reactivity of similar starches. Descending order of the activation energy was RH>RCaB>CoB>CaB. The relatively high activation energy of the briquette made from rice-cassava starch binder may be due to the presence of rice starch. Guinesi et al. (2006) while investigating the kinetics of thermal degradation applied to starches indicated that rice starch had higher activation energy compared to corn and cassava. The authors further attributed the high activation energy of rice starch over corn and cassava to morphological aspects and associated it to the intermolecular interaction between individual granules that are aggregated in the starch.

3.3.3 Ignition performance

The ignition temperature defined as the lowest temperature required for rice husk or briquette combustion was determined using the TGA-DTGA combination method (Chao et al., 2013; Li et al., 2006) as shown in Fig 3.4. A vertical line is made through the peak of the DTGA to meet the TGA at point A, a tangential line is then drawn on the TGA curve through A. Another tangential line is drawn on the TGA curve at point C (where the sample begin to loose weight). A vertical line is then made from B (the meeting point of the two tangents known as the ignition point) to meet the temperature axis at point D. The corresponding temperature was recorded as the ignition temperature. The ignition index D_i is determined by the Eq 3.15 (Li et al., 2006) as follows:

$$D_i = \frac{\left(\frac{\Delta w}{\Delta t}\right)_{max}}{t_p t_e} \quad 3.15$$

Where $\left(\frac{\Delta w}{\Delta t}\right)_{max}$ is the maximum combustion rate, t_p is the corresponding time of the maximum combustion rate and t_e is the ignition time.

The summary of the ignition performance is shown in Table 3.6. It shows that briquettes generally have higher combustion rate $\left(\frac{dw}{dt}\right)_{max}$ and lower ignition temperatures than rice husk.

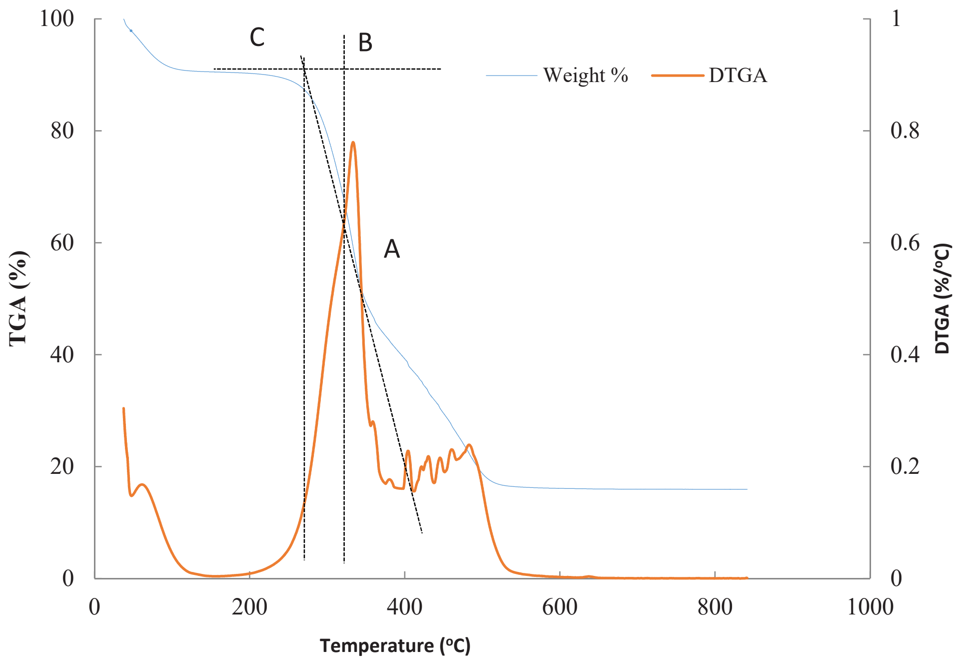


Figure 3.5: Ignition temperature determination sketch

The results show that the addition of binders to rice husk slightly reduces the ignition temperature and improve the ignition index. Briquettes made with rice-cassava starch binders (RCaB) had the highest combustion rate and ignition time but not ignition index while briquettes made with cassava starch binders (CaB) had the lowest combustion rate and ignition time but the highest ignition index. This is an indication that cassava starch binder would give the best ignition performance of rice husk briquettes.

Briquettes made with cassava starch binders (CaB) had relatively lower ignition temperatures of 286 °C, about 4 - 6 °C lower than other briquettes and higher ignition index indicating their ease of ignition during combustion processes. However, these were not significantly different ($p < 0.05$).

The difference in activation energy, frequency factor and ignition performance were not significantly different suggesting that any of the proposed binders available in rice producing communities could be used without influencing the combustion behaviour of the briquette.

Table 3.6: Summary of ignition performance of rice husk briquettes

Fuel Type	$(\Delta w/\Delta t)_{max}$	T_e (°C)	t_p (s)	t_e (s)	D_i(x10^{-3})
RH	0.755	296	15.53	13.53	3.29
CaB	0.780	286	15.46	13.17	3.83
CoB	0.806	286	15.75	13.44	3.81
RCaB	0.862	295	18.41	13.62	3.44

3.3.4 Energy replacement potential

The energy potential of rice husk is influenced by the pretreatment method, the energy conversion and the efficiency of the stove or combustor. Pretreatment in thermal conversions systems include size reduction, drying and densification. In the use of rice husk, direct combustion and gasification may not require major pretreatment before conversion. However, to ensure that the husk burns properly, high moisture husk may be dried prior to its use since high moisture may reduce the heat budget during combustion (Jenkins et al., 1998; Shen et al., 2012; Zhao et al., 2009).

The densification process generally increases the biomass bulk density from 40-200 kgm^{-3} to a final bulk density of 600 – 800 kg/m^3 (Holley, 1983; Obernberger & Thek, 2004). This higher bulk density comes with a corresponding higher energy density implying higher heating value (Moral & Rahman, 1999) hence more available energy. Miah et al. (1999) reported that when husk is densified its gross energy increases such that a kilogram of rice husk briquette could replace 1.67 kg of wood. This can increase the average heating value of rice husk briquette to about 16.3 MJ/kg (Bhattacharya et al., 1985). The pretreatment method though increases the energy density, it must be noted that additional energy input (electrical energy) may be required for milling of husk and densification. The average energy consumption for rice husk briquette production has been estimated at the laboratory scale to be 116 kWh/tonne and for commercial processes to be 179 – 250 kWh/tonne (Hardman, 2001). The consumption could be reduced to 150kWh/tonne when feed material is heated up in a pre-heater which results in a 10 % energy savings (Bhattacharya et al., 2002c).

Table 3.7: Wood replacement scenarios

Fuel	Modified LHV [MJ/kg]	Energy replacement factor [kg/kg]	Annual fuel requirement [tonne]	Annual percent wood use reduction [%]
Wood	2.03	1.00	733.8	-
Rice Husk	3.30	1.63	450.2	43.5
Briquette	3.75	1.84	398.8	49.1
Gasifier Gas	2.68	1.32	555.9	67.5

Product gas was converted to MJ/kg using a gas density of 0.95kg/m^3 (Basu, 2013)

A summary of the energy replacement potential of the different rice husk utilization is shown in Table 3.7. The results show that combustion of rice husk and briquette offers higher energy replacement potential of 1.63 and 1.84, respectively. This means that using the fabricated continuous rice husk combustor, a kilogram of rice husk could supply 38% more energy if burnt directly or 45.6% if densified into briquette than burning a kilogram of wood in a TSF. The difference in net energy of the fuels is also due to the conversion technology and combustion systems efficiency. Direct combustion systems and briquette systems undergo high temperature oxidation reaction to convert solid fuels into gaseous non-combustible product and ash while releasing heat. In this study, the efficiency of fabricated rice husk combustor was 76.9% higher than the TSF stove. This can be attributed to the fact that the combustor is an enclosed system, it had both primary and secondary air input and also due to the inner fire brick which reduced the heat loss through the stove walls. However, this efficiency was much lower than biomass gas stove which have been reported to be 38-65% (Jain, 2006) due to the gaseous nature of the fuel.

The result implies that the current practice of parboiling would require an annual wood use of 735 tonnes per village based on the annual rice processing capacity of 800 tonnes (Mainoo & Kwofie, 2014). This energy could be supplied by burning 450.2 tonnes of rice husk directly in the fabricated rice husk combustor or 398.8 tonnes of husk if the husk is densified. For the gasifier stove, 560 tonnes of producer gas will be required. Using a gas density of 0.95 kg/m^3 gives an equivalent rice husk requirement of 281 tonnes. However, the rice husk and bran generation measured during the study was 27.2%, equivalent to an annual generation rate of 218 tonnes (Mainoo & Kwofie, 2014). Assuming 90% of the husk is available for parboiling at the current average processing capacity of 50 kg/batch, about 43.5, 49.7 and 67.5% of wood could be saved using direct combustion, briquetting and gasification of rice husk, respectively.

3.3.4.1 Greenhouse gas reduction potential

Annual GHG emissions for the current process and the different rice husk utilization scenarios are shown in Fig 3.5. The current wood use for parboiling produces a total of 14.68 tCO_2e/yr with 80% emanating from wood combustion and less than 20% from uncontrolled rice husk burning. The emission from wood transport (not shown on Fig. 3.5) was 0.2%. Switching entirely the energy supply to rice husk would have reduced the emission by 43.32% and 74.66% for direct combustion and gasification. This is in agreement with a report by Jetter and Kariher (2009) who found that gasifier-blower stoves could reduce emissions by up to 90% relative to three stone fire (TSF) stoves. Adding the emissions from production of briquette, increases the emissions by 49.9 % in comparison to current wood use. On the other hand, using the manual briquetting press would reduce the total GHG emission by 54.5%. Unfortunately, the current annual production and the processing capacity does not yield enough rice husk for a complete switch. Assuming 90% of the current rice husk is available for use, direct combustion, briquetting and gasification will still reduce overall emissions by 23.6% 36.9 and 62.9%. Adding the emissions from a commercial electric powered briquetting machine will increase the total emissions by 14.37% compared to wood.

The implication of these results is that on the basis of GHG emission reduction potential, gasification would be considered the best option and briquetting using electrical powered machine would offer the worst. Nevertheless, using the manual briquetting machine would make briquetting a competitive option, but will require extra human energy in producing the briquette. The manual briquetting machine requires double pressing for each 40 g briquette it produces, therefore for each batch of paddy (50 kg) processed, the energy requirement will be equivalent to about 660 briquettes.

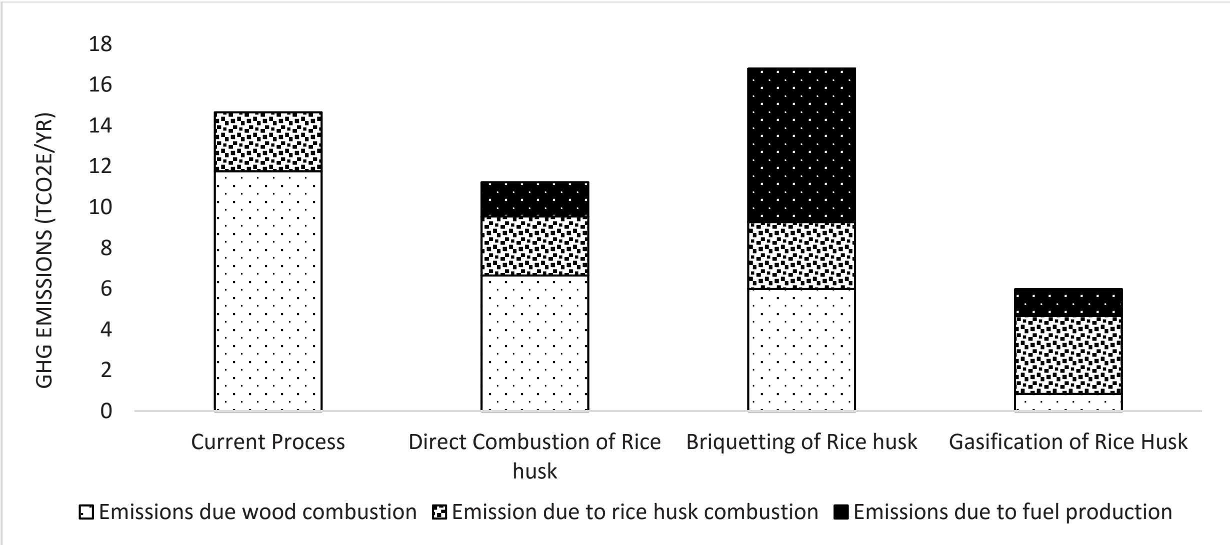


Figure 3.6: Annual Greenhouse Gas Emission

3.3.4.2 Economic evaluation

The current local parboiling system was used as a baseline for the economic evaluation. A "seat" of wood which cost GHS 60.00 (1US$ = 3.0GHS - 28/6/2014) is used for parboiling four and half sacks of paddy in nine batches of 36 – 40 kg. This yields a total of 2.5 - 3 sacks (75 – 80 kg) of polished rice depending on the variety. In the economic analysis, the efficiencies and heating values used were those used for the energy analysis in Table 3.1. The current annual fuel expenditure using the TSF stove is estimated to be GHS 114,793. Although, rice husk currently cost nothing, millers and parboilers may sell it when is used as fuel. Therefore, a minimum cost estimate of 0.05 GHS/kg has been applied when rice husk is used for either combustion or gasification whereas the cost of 0.1 GHS is applied when it is used in the form of briquette. The result shows that at the assumed minimum cost of rice husk, annual fuel expenditure could be reduced by 78.90, 62.83 and 73.00% using direct combustion, briquette combustion and gasification of rice husk, respectively. Again, it was assumed that parboilers either transport the husk to their processing centers themselves at no cost or parboiling takes place within the milling vicinity hence transporting the husk was not required. Considering a 90% availability of the current rice husk, a considerable reduction of the annual fuel expenditure up to 35.3, 31.09 or 49.13% with direct combustion, briquetting and briquetting, respectively. Using Eq. 3.14, a sensitivity analysis of the annual energy expenditure for the different scenarios was estimated with fuel cost as the variable parameter and shown in Fig 3.6-3.8.

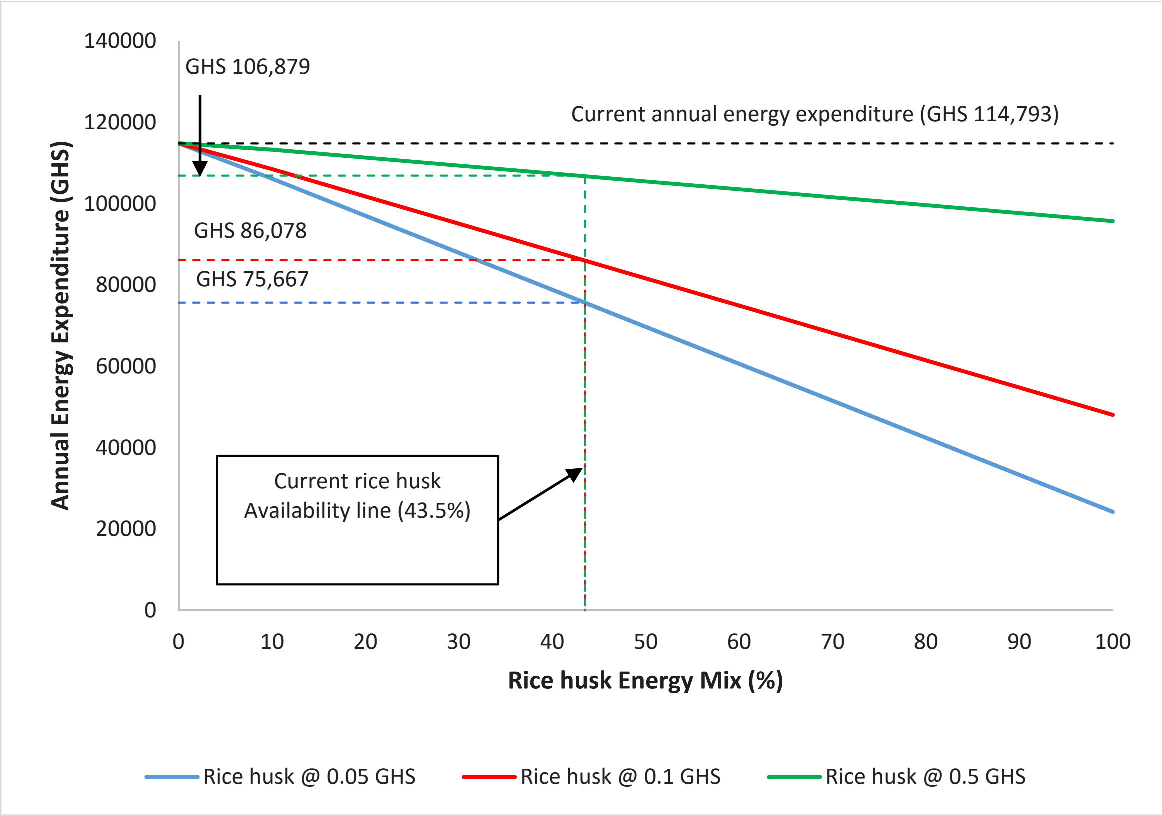


Figure 3.7 Annual Energy expenditure for rice parboiling using direct combustion of rice husk

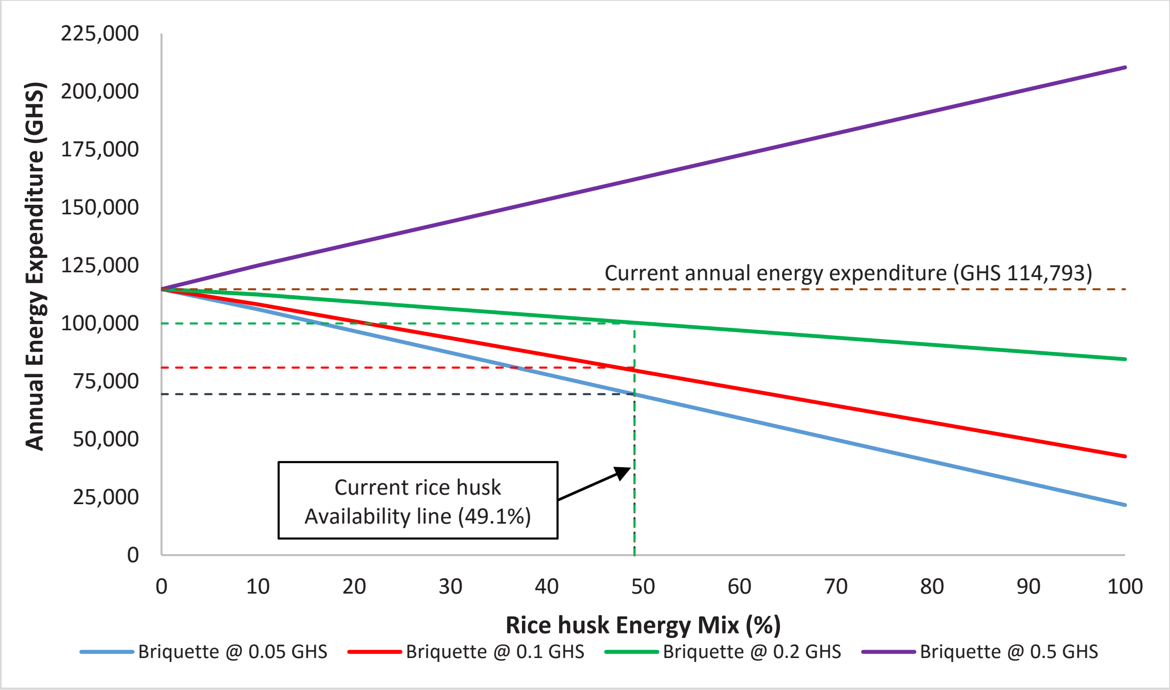


Figure 3.8: Annual Energy expenditure for rice parboiling using rice husk briquettes

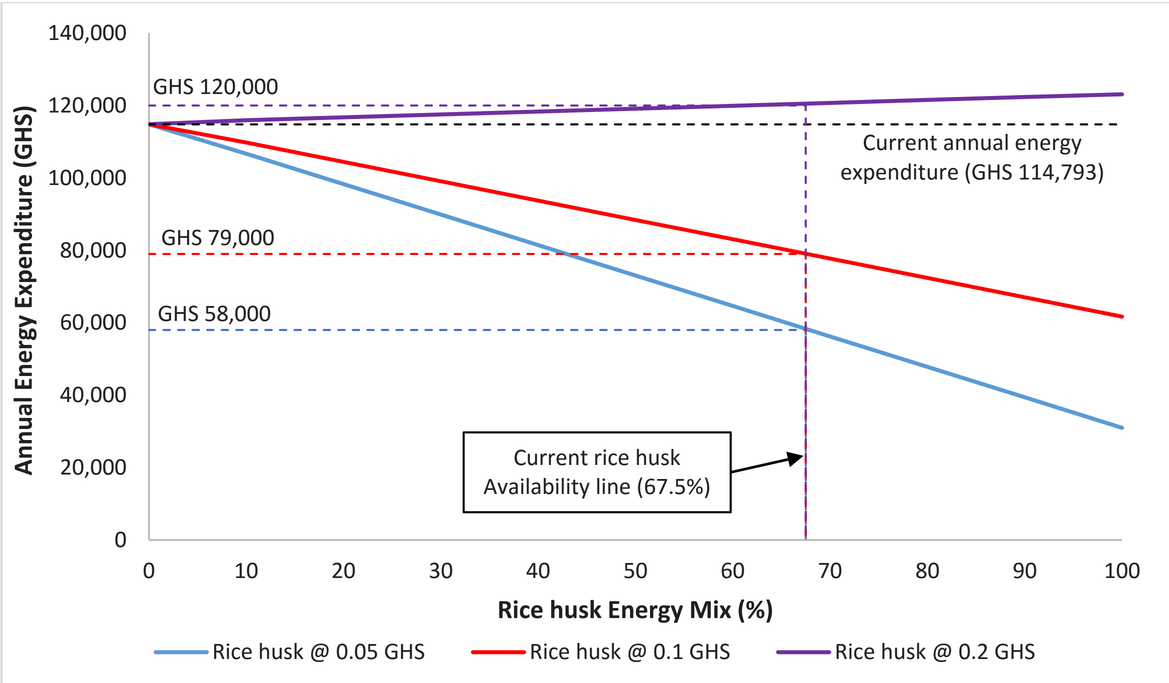


Figure 3.9: Annual Energy expenditure for rice parboiling using gasification

Doubling the cost of rice husk can still achieve a 41.9% equivalent to GHS 66740. A further increase of rice husk cost by ten folds will still make direct combustion a better choice achieving a 16.6% reduction in annual energy expenditure. On the other hand, briquetting will be an economically feasible option as long as the cost of briquettes does not exceed GHS 0.2 (see Fig 3.7). Comparing the rice husk utilization options, gasification shows the lowest cost effectiveness beyond a GHS 0.1 rice husk cost (see Fig 3.8). At GHS 0.2/kg of rice husk, annual energy expenditure using gasification increases by 7%.

3.4 Conclusion

In this study, the thermogravimetric evaluation of rice husk and its briquettes together with their potential of being utilized as alternative fuel for local rice parboiling have been presented. In the thermal behaviour assessment, three distinct combustion stages representing moisture removal, volatile combustion and fixed carbon decomposition were identified. The results indicate that rice husk briquettes generally have similar combustion behaviour irrespective of the binder used. Reactivity among the samples reveals similar performance for all samples with relative worst reactivity in briquettes produced with a rice-cassava starch binder. However, it increases with increasing heating rate. The lower activation and higher ignition index of CaB suggests a better combustion behaviour hence cassava starch would be most suitable binder for briquette production in local rice processing communities. Briquettes made with corn and cassava starch binders (CoB and CaB) had relatively lower ignition temperatures and higher ignition index, indicating their ease of ignition during combustion processes.

In the evaluation of rice husk potential, three rice husk utilization scenarios – direct combustion, briquetting and gasification, were considered based on analysis of their modified energy, wood savings, greenhouse gas mitigation potential and fuel cost. Direct combustion of available rice husk presented the cheapest way of making use of the rice husk achieving about 34% reduction in energy expenditure, reducing emissions by 43.32% and achieving a 38% more energy in the fabricated rice husk combustor. Briquetting showed a much higher energy replacement potential of 1.84 and emission reduction (54.5) using a manual press. However, the overall GHG emission may increase by 49.9% using a commercial briquetting machine. Gasification offered the best opportunity in terms of emission reduction achieving up to 75%. Usage of the current available rice husk has the potential of reducing parboiling energy burden substantially while reducing overall emissions by 24% 37 and 63% using direct combustion, briquetting and gasification, respectively. As issues of energy and environment become more critical in society, rural energy stakeholders should be considering replacement of the existing low-efficiency “wood for energy practices” with more efficient and sustainable systems using rice husk as an energy source. This will in addition to reducing deforestation, also reduce parboiling energy expenditure, improve combustion efficiency and reduce total greenhouse gas emission. Again, these rice husk energy technologies produce less smoke, therefore have the potential of reducing respiratory diseases as a result of the smoke inhalation, although this has not been quantified in this paper.

Connecting Text

In chapter three, a thermogravimetric evaluation of rice husk and its briquettes was performed. It was established that the thermal behavior of the rice husk and its briquette were similar. The assessment of rice husk energy for local community utilization revealed that, direct combustion is the best option in terms of cost and simplicity while gasification offers the best opportunities in terms of emission reduction.

Based on the results from this chapter, direct combustion and gasification of rice husk were chosen for the next stage of the work. In the next chapter (four), the first thermochemical conversion system – throatless bottom lit downdraft gasifier operated in a continuous mode, is investigated. The chapter includes system development, performance evaluation, and thermochemical equilibrium modeling and validation.

Chapter four has been submitted for publication as:

Kwofie, E. M and Ngadi, M. (2016). Development and Thermochemical Equilibrium Analysis of a rice husk gasifier stove for rural rice processing. *Energy Conversion and Management*, (under revision)

CHAPTER 4 Development and thermochemical equilibrium analysis of a rice husk gasifier stove for rural rice processing

Abstract

In the present study, a simplified throatless downdraft rice husk gasifier stove has been developed and its performance evaluated. The performance of the open core gasifier, intended for rural rice parboiling, was evaluated at varying air inputs. The results show that for equivalence ratio of 0.27-0.55, producer gas production varied from 4.15±0.15 to 12±0.4 Nm^3/h with exit temperature ranging from 427±3 to 545±4°C. The highest gasification efficiency of 58.85% was achieved at an equivalence ratio of 0.42. Based on the results, regression models were developed to predict the gas production rate, lower heating value and efficiency of the gasifier stove. A thermochemical equilibrium model was also developed, validated with the experimental results and used to evaluate the effect of gasification temperature and rice husk moisture content. The model shows that for optimal energy conversion of the rice husk, equivalence ratio, moisture content and gasification temperature should be 0.4 – 0.45, 10 – 15% and 750 – 800°C.

4.1 Introduction

Rice has become an important food for many people in developing countries. The increase in its production comes along with a corresponding increase in the processing energy demand. For rural rice processing, issues of energy supply are more challenging considering the inefficiencies of the systems used and the daunting task of wood collection. In rice producing communities, availability of rice husk presents an opportunity to meet the thermal energy requirement sustainably with the agro waste. Rice husk energy can be harnessed using biological (Abbas & Ansumali, 2010; Okeh et al., 2014a) or thermochemical pathways (Boateng et al., 1992; Ganesh et al., 1992; Lin et al., 1998; Yoon et al., 2012). For rural thermal application, thermochemical conversion systems are the most appropriate due to their simplicity and lower cost. Direct combustion of rice husk have been the primary method employed in rice processing using specially design systems (Araullo et al., 1985; Singh et al., 1980; Tumambing, 1984). Gasification is another thermochemical option for harnessing rice husk energy with great attraction for agricultural applications. Many scholars have reported its application for electricity production (Ahiduzzaman & Islam, 2012;

Bhattacharyya, 2014; Kapur et al., 1997; Yoon et al., 2012) and domestic thermal application (Belonio, 2005).

Rice husk gasification has the potential of meeting rural rice processing energy with added benefits of lower emissions as compared to direct combustion or wood combustion (Mai Thao et al., 2011). The energy requirement for rice processing based on the direct combustion of rice husk (with efficiency less than 45%) has been reported to be 1680 MJ/tonne (120 kg of rice husk) for parboiling and 1,540 MJ/tonne (110 kg of rice husk) for mechanical drying (moisture reduction from 32% to14% under hot air temperature range of 65 -130ºC) (Ahiduzzaman & Sadrul Islam, 2009). These thermal requirements can be met by small size gasifiers with efficiency of 60 - 65%. For example, a 34.3cm diameter downdraft gasifier operated at 18 kg/h feedrate and equivalence ratio of 0.41 can generate 39.7 m^3 of gas corresponding to 158.9 MJ of thermal energy (Jain, 2006). Therefore, a total of more than 1750 MJ can be harnessed from the 200 kg of rice husk generated in processing paddy to meet a large percentage of its thermal energy requirement. The advantage of burning gasification producer gas over the direct combustion of rice husk as practiced in most rice processing units is the ability to control heating, higher flame temperature and the production of seemingly smokeless blue flame and more importantly increased thermal efficiency.

To fully explore the effects of operating parameters on gasifier performance, gasification models have been developed and widely used. Several kinetic models on biomass gasification (Dupont et al., 2011; Giltrap et al., 2003; Hameed et al., 2014; Jang et al., 2013; Kajitani et al., 2013; Loha et al., 2014; Tremel & Spliethoff, 2013) have been developed to provide essential information on kinetic mechanisms. These models have the advantage of being accurate, detailed and physically more realistic (Buragohain et al., 2010; Di Blasi & Branca, 2013) which is crucial for designing, evaluating and improving gasifiers (Puig-Arnavat et al., 2010). However, they are often computationally more intensive and system specific. Their broad applicability is limited due to their inability to cover all possible gasification process reactions (Ahmed et al., 2012; Chen & Gunkel, 1987; Sharma, 2008a). Again in kinetic models, drying, pyrolysis and oxidative processes are lumped together assuming occurrence in a single zone (Sharma, 2008a). Equilibrium models, on the other hand, are not only generic and easy to implement but also predict thermodynamic limits of gasifier performance under different conditions which could serve as a basis for qualitative guidelines for design, optimization and improvement of the process. Also, input data for their development and evaluation is easily available in the literature (Buragohain et al., 2010).

With all the efficiency and emission benefits of rice husk gasification, there have been no reports of its use for rice processing in Sub-Saharan Africa. In this study, a simplified downdraft gasifier stove intended for rural rice processing has been examined. The objective of this study is to (a) develop and evaluate the performance of a throatless rice husk downdraft gasifier stove, and (b) to develop and validate a thermochemical equilibrium model used to evaluate the effect of other operating parameters including gasification temperature, moisture content and equivalence ratio on gasification output parameters.

4.2 Materials and Methods

4.2.1 Gasifier selection and design consideration

In selecting the best gasifier type for rural rice parboiling, four basic factors were considered. These include (1) cost of manufacturing, (2) ease of operation and maintenance (design simplicity and ease of handling), (3) feedstock sensitivity (moisture content elasticity) and (4) system's performance (LHV and cold gas efficiency). The four factors were given relative weight (out of 5) as 5, 3, 3 and 5, respectively. The factors were scored and their weighted score was summed and compared according to the method proposed by Guangul et al. (2012). Based on the total weighted score, downdraft gasifier was chosen.

Other researchers (Basu, 2013; Lin et al., 1998) have also proposed downdraft gasifiers for light weight biomass such as rice husk. At the commercial level, downdraft gasifiers are the most suitable and widely used gasifiers both for electricity generation and thermal applications. This is supported by a survey conducted in the USA, Europe and Canada on 50 commercial gasifier manufacturers where 75% were found to be downdraft type, 20% were fluidized bed systems, 2.5% were updraft and 2.5% representing other designs (Knoef, 2000).

A downdraft gasifier is a co-current reactor where both the product gas and fuel flow downwards. They may be designed either with a throat or throatless. Rice husk may not be appropriate as feedstock in a throated (Imbert) type gasifiers due to problems with the material flow (Jain, 2006). Downdraft gasifiers are known for their low production of tar, therefore, suitable for engine applications. This is due to the fact that the acid and tar product in product gas leaves through a bed of hot ash which provides a favourable condition for tar cracking. This makes the downdraft gasifier the lowest tar producting gasifiers among all types of gasifiers. The open-core type of throatless design where air is added from the top and not from the middle as in other types of downdraft gasifiers was chosen. Air is drawn into the gasifier from the top by the suction created downstream of the gasifier which aids in drying feedstock as they flow downwards..

Having established the throatless downdraft gasifier as the most suitable for a small scale gasifier using rice husk, three design namely diameter, height and air flow were considered. The reactor diameter is the most critical design parameter in designing throatless downdraft gasifiers (Jain, 2006) It determines not only the size of the gasifier but also the superficial air velocity (speed of air flow in fuel bed) and the duration of operation. It may be estimated by kinetic modeling or by literature values of specific gasification rate (Jain, 2006). The diameter determines the specific gasification rate which is used in estimating the height of the gasifier. Typical gasification rate of rice husk is 110-210 kg/m^2-h (Belonio, 2005) with an optimum value of 200 kg/m^2-h (Jain, 2006).

4.2.2 Gasifier Sizing and Construction

The gasifier size was based on the heat requirement for parboiling 40kg of paddy. The diameter, height and output power of continuous rice husk gasifier (CRHG) was estimated using expression proposed by Belonio.

The gasifier reactor diameter expressed in meters (m) is estimated according to Eq 4.1

$$D = \sqrt{\frac{1.27 \times FCR}{SGR}} \quad 4.1$$

Where, FCR and SGR are fuel consumption rate (kg/h) and specific gasification rate (kg/h m^2), respectively. The optimum SGR of 200 kg/h m^2 suggested for rice husk gasification in a throatless open core gasifier reactor was used (Jain, 2006). The reactor height was estimated as:

$$H = \frac{SGR \times t}{\rho_{RH}} \quad 4.2$$

Where, t is the net operating time and ρ_{RH} is the bulk density of rice husk determined to be 102.3kg/m^3. The gasifier consists of a 23 cm cylindrical reactor made from a gauge 16 galvanised steel sheet with a lid, a 40 x 40 x 35cm ash box made from 3/16 inch steel plate (Acier Lachine

Inc., Lachine, QC, Canada) which also serves as a support for the reactor. Other accessories include a variable speed fan, a 21.5 cm diameter grate and a grate-shaking rod inserted in the ash box. Fig 4.1 shows the fabricated rice husk gasifier stove. Design details of the gasifier is shown in Appendix A.

Figure 4.1: The continuous rice husk gasifier stove

4.2.3 Thermochemical equilibrium model development

The thermochemical equilibrium model has been developed on the following assumption (Altafini et al., 2003; Sharma, 2008a; Zainal et al., 2001): (1) a single zone represents the drying, pyrolysis and gasification processes, (2) residence time for reactants is high enough to establish chemical equilibrium, (3) there is a zero tar production, (4) ash is inert and does not react with other compounds. Based on these assumptions, the drying, pyrolysis and oxidation are considered as open system and can be described by a single reaction as using a rice husk formula of $CH_xO_yN_z$ (Sharma, 2008b):

$$\begin{pmatrix} CH_xO_yN_z + w(H_2O) + m(O_2 + 3.76N_2) \rightarrow n_{H_2}H_2 + n_{CO}CO \\ +n_{CO_2}CO_2 + n_{CH_4}CH_4 + n_{H_2O}H_2O + n_CC + \left(\frac{z}{2} + 3.76m\right)N_2 \end{pmatrix} \qquad 4.3$$

Where, x, y and z are the number of atoms of hydrogen, oxygen and nitrogen per unit carbon in rice husk, and m and w represent the amount of oxygen and moisture per kmol rice husk, respectively and n_x represent the stoichiometric coefficient of products.

4.2.3.1 Species balance

From the global equation, six unknown species including unconverted char are found requiring six expressions to solve them. Conducting a species balance interms of mole flow on the product of the global equation gives Eq 4.4 - 4.6

Carbon balance: $$n_{CO} + n_{CO_2} + n_{CH_4} + n_C - 1 = 0 \qquad 4.4$$

Hydrogen balance: $$2n_{H_2} + 2n_{H_2O} + 4n_{CH_4} - x = 0 \qquad 4.5$$

Oxygen balance: $$n_{CO}CO + 2n_{CO_2}CO_2 + n_{H_2O}H_2O - y - 2m = 0 \qquad 4.6$$

4.2.3.2 Equilibrium constants derivation

The other three expressions are derived from the knowledge of equilibrium constants of elementary reactions. The three primary elementary reaction essential for the description of the gasification process are used.

R1: Bouduard reaction: $C + CO_2 \rightarrow 2CO$

R2: Water-gas shift reaction $CO + H_2O \leftrightarrow CO_2 + H_2$

R3: Methanation reaction $C + 2H_2 \leftrightarrow CH_4$

From these gasification reactions, the equilibrium constants can be derived as:

Bouduard reaction: $$K_1 = \frac{n_{CO}^2}{n_{CO_2}} \qquad 4.7$$

Water-gas shift reaction: $$K_2 = \frac{\left(n_{CO_2}\right)\left(n_{H_2}\right)}{\left(n_{CO}\right)\left(n_{H_2O}\right)} \quad 4.8$$

Methanation reaction: $$K_3 = \frac{\left(n_{CH_4}\right)\left(n_{total}\right)}{\left(n_{H_2}\right)^2} \quad 4.9$$

Where, n_{total} is the total moles of gaseous product in the global reaction of air gasification expressed as:

$$n_{total} = n_{H_2} + n_{CO} + n_{CH_4} + n_{CO_2} + n_{H_2O} + \left(\tfrac{z}{2} + 3.76m\right) \quad 4.10$$

Where $\left(\tfrac{z}{2} + 3.76m\right)$ represents the N_2 fraction.

The equilibrium constants are given at constant temperature and pressure using the standard state Gibbs function of change given by (Jarungthammachote & Dutta, 2007):

$$\ln K = -\frac{\Delta G_T^o}{RT} \quad 4.11$$

$$\Delta G_T^o = \sum_i v_i \Delta g_{f,T,i}^o \quad 4.12$$

Where, ΔG_T^o is the standard Gibbs energy of change, T and R are the temperature in K and universal gas constant, respectively. The standard Gibbs function of formation at a given temperature T of gas species i expressed as $\Delta g_{f,T,i}^o$ can be evaluated using Eq 4.13.

$$\Delta g_{f,T,i}^o = h_f^o - a'T\ln(T) - b'T^2 - \left(\frac{c'}{2}\right)T^3 - \left(\frac{d'}{3}\right)T^4 + \left(\frac{e'}{2T}\right) + f' + g'T \quad 4.13$$

The values of the coefficients for Eq 4.13 are shown in Table 4.1.

4.2.3.3 Energy Balance

To estimate the equilibrium constants, the gasification temperature must be known. This can be determined using an energy balance. Assuming an adiabatic gasification process (Zainal et al., 2001) and an inlet state of 298 K, the energy balance can be expressed as:

$$\sum_{i=react} h^o_{f,\mathrm{i}} = \sum_{j=prod} n_i \left(h^o_{f,\mathrm{j}} + \Delta h^o_{T,\mathrm{i}} \right) \qquad 4.14$$

Where, h^o_f is the enthalpy of formation (kJmol^{-1}) which is zero for all species at a reference state (298 K, 1atm) while Δh_T is the enthalpy difference between a given state and the reference state given by Eq 4.15.

$$\Delta h_T = \int_{298}^{T} C_p(T) dT \qquad 4.15$$

Applying the energy equation to the global equation expressed in Eq 4.3 gives:

$$\begin{aligned}
&\Delta h^o_{f,RH} + m\Delta h^o_{f,\mathrm{O}_2} + 3.76m\Delta h^o_{f,\mathrm{N}_2} = n_{H_2}\left(\Delta h^o_{f,H_2} + C_{p,H_2}\Delta T\right) + n_{CO}\left(\Delta h^o_{f,\mathrm{CO}} + C_{p,\mathrm{CO}}\Delta T\right) \\
&+ n_{CO_2}\left(\Delta h^o_{f,\mathrm{CO}_2} + C_{p,\mathrm{CO}_2}\Delta T\right) + n_{CH_4}\left(\Delta h^o_{f,\mathrm{C}H_4} + C_{p,\mathrm{C}H_4}\Delta T\right) + n_{H_2O}\left(\Delta h^o_{f,H_2O} + C_{p,H_2O}\Delta T\right) \\
&+ n_C\left(\Delta h^o_{f,\mathrm{C}} + C_{p,\mathrm{C}}\Delta T\right) + \left(\tfrac{z}{2} + 3.76m\right)\left(\Delta h^o_{f,\mathrm{N}_2} + C_{p,\mathrm{N}_2}\Delta T\right) N_2
\end{aligned} \qquad 4.16$$

The specific heat capacity, C_p of the gaseous species can be determined from Eq 4.17. The coefficients are shown in Table 4.2

$$C_{p,}(T) = a + bT + cT^2 + dT^3 \qquad 4.17$$

The specific heat capacity of carbon was estimated in kJ/kmol K from a polynomial function taken from NIST-JANAF table,

$$C_{p,C} = -6.755 + \left(6.6253 \times 10^{2} T\right) - \left(5.8148 \times 10^{-5} T^2\right) + \left(2.4113 \times 10^{-8} T^3\right) - \left(3.812 \times 10^{-12} T^4\right) \qquad 4.18$$

The enthalpy of formation for rice husk was determined using an expression suggested by De Souza-Santos (De Souza-Santos, 2010)

$$\Delta h^o_{f,RH} = LHV_{RH} + \sum_{j=prod} \left[n_j \left(h^o_f \right)_j \right] \qquad 4.19$$

Where, $\left(h_f^o\right)_j$ is the enthalpy of formation of product j when rice husk is completely combusted and the LHV is lower heating value of rice husk in kJ/kmol

Table 4.1: Enthalpy of formation [kJ/mol] and coefficients for $\Delta G_{f,T,i}$ [kJ/mol]

Compound	h_f^o	**a' × 10^{-3}**	**b' × 10^{-5}**	**c' × 10^{-9}**	**d' × 10^{-12}**	**e' × 10^{2}**	**f'**	**g' × 10^{-2}**
CO	-110.5	5.619	-1.190	6.393	-1.846	-4.891	0.868	-6.131
CO_2	-393.5	-19.49	3.122	-24.48	6.946	-4.891	5.270	-12.07
H_2O	-241.8	-8.950	-0.367	5.209	-1.478	0.000	2.868	-1.722
CH_4	-74.8	-46.20	1.319	13.19	-6.647	-4.891	14.11	-22.34

Table 4.2: Coefficient of specific heat capacity for Eq. 4.17

Gas Species	a	b	c	D	Temperature range (K)
H_2	29.11	-0.1916 x 10^{-2}	0.4003 x 10^{-5}	-0.8704 x 10^{-9}	273-1800
CO	28.16	0.1675 x 10^{-2}	0.5372 x 10^{-5}	-2.222 x 10^{-9}	273-1800
CO_2	22.26	5.981 x 10^{-2}	-3.501 x 10^{-5}	-7.469 x 10^{-9}	273-1800
H_2O	32.24	0.1923 x 10^{-2}	1.055 x 10^{-5}	-3.595 x 10^{-9}	273-1800
CH_4	19.89	5.204 x 10^{-2}	1.269 x 10^{-5}	-11.01 x 10^{-9}	273-1500
N_2	28.90	-0.1571 x 10^{-2}	0.8081 x 10^{-5}	-2.873 x 10^{-9}	273-1500

4.2.3.4 Valuation procedure

An initial temperature was assumed to estimate the equilibrium constants from Eq 4.7 – 4.9 then together with Eq 4.4 – 4.6, the product compositions are calculated. The results are used in Eq. 4.16 to find the actual gasification temperature. The estimated T is used to recalculate the species composition. The process is repeated until the variation between two estimated T's is less than 0.1K (Jarungthammachote & Dutta, 2007).

4.2.4 Gasification experiment

4.2.4.1 Fuel preparation

The rice husk used for all experiments was purchased from California, US. The moisture content of fuel was determined based on the ASABE Standard S3582.2 (ASABE, 2006) by drying for 24 hours at 104 °C in an oven (Fisher Scientific 750F, US). The proximate analysis of the fuel was determined according to the ASTM E1131 (ASTM, 2010), standard test method for compositional analysis by thermogravimetry. The ultimate analysis was determined using VARIO MACRO cube CHNS (Elemetar Americas Inc., Mt Laurel, NJ, USA). The higher heating value (HHV) was determined using 6400 Automatic Isoperibol Calorimeter (Parr Instruments, Moline, Illinois, USA). Characteristics of the rice husk used for the experiments is shown in Table 4.3.

The lower heating value LHV_{RH} , was estimated from the HHV_{RH} according to Eq 4.19 (Mansaray & Ghaly, 1998)

$$LHV_{RH} = \left(1 - MC\right)\left[HHV_{RH} - Y\left(\frac{MC}{1 - MC}\right) + \frac{18H}{200}\right] \tag{4.20}$$

Where MC is the moisture content of rice husk (decimal), H is hydrogen fraction of fuel on wet basis (decimal) and Y is the latent heat of vaporization for water (MJ/kg)

Table 4.3: Proximate and ultimate analysis of rice husk

Fuel	Proximate Analysis (wt%)				Ultimate Analysis (wt%)				HHV (MJ/kg)	LHV (MJ/kg)
	MC	VM	FC	Ash	C	H	O	N		
Rice Husk	8.0	61.24	18.04	20.72	39.30	5.69	35.33	0.401	14.99	14.41

4.2.4.2 Experimental setup

The gasification experiments were conducted to evaluate the performance of the gasifier. A completely randomised design with air flow rate as the independent variable was used to evaluate the performance of the gasifier. Five runs on the gasifier were conducted in triplicates at different air flow rate (AFR) corresponding to a specific equivalent ratio. The AFR was selected so as to achieve an equivalent ratio in the range of 0.25 - 0.5. The range was selected considering the fact that gasification in downdraft gasifier generally occurs in ER range of 0.19 – 0.43 (Zainal et al., 2002) and rice husk gasification occurs at a narrow range of 0.3-0.43 with an optimum ER of 0.4 (Belonio, 2005; Jain, 2006) AFR was estimated in Nm^3/h according to Eq 4.21.

$$AFR = \frac{ER \times FCR \times SA}{\rho_a} \quad 4.21$$

Where, FCR is the fuel consumption rate (kg/h), SA is the stoichiometric air requirement taken as 4.7 kg of air per kg of rice husk (Belonio, 2005) and ρ_a is the density of air taken as 1.25 kg/m^3(Cengel & Boles, 2006). The amount of air used was measured using digital airflow meter (model HHF92A, Omega, Laval, QC, Canada).

During the runs, rice husk consumption, the duration and temperature in the combustion, reduction and gas outlet zones were monitored. The temperature was measured at three points (T1, T2 and T3) as shown in Fig 4.2 with the aid of K-type thermocouple wires (Omega, Laval, QC, Canada) and readings were recorded every three seconds using a data logger (visual Hotmux V.3.1.0, DCC Corporation, US). Producer gas was sampled using a 10 ml string with a needle from a sampling port created along the producer gas exit pipe. The string was immediately capped to prevent gas contamination and dilution. The producer gas was allowed to cool after which its composition was analyzed using a Gas Chromatography (HP 5890A model, Wilmington Germany).

At the beginning of each test, the reactor was filled with a measured quantity of rice husk (Setra, EL-2000S, Acton, MA, USA). Pieces of papers were inserted into the starting fire port and lighted with a match. The fan was then switched on. The gasification was assumed to have commenced when the rice husk began burning after which the opening port was closed. The run was considered to have ended when all rice husk was gasified. The difference in the starting and ending time was taken as the net operating time. The experimental setup is shown in Fig 4.2

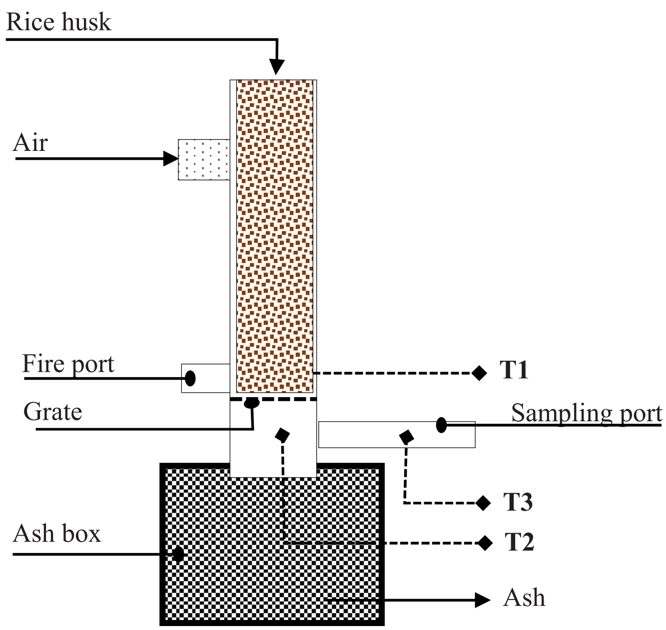


Figure 4.2: Experimental Setup

4.2.4.3 Efficiency measurement

The gasification efficiency was determined from the heating value and flow rate of the producer gas and rice husk. The producer gas lower heating value was estimated from the chemical composition of the gas and the individual components according to Eq 4.22.

$$LHV_g = \sum \left(X_i \times LHV_i \right) \tag{4.22}$$

Where, X_i and LHV_i are the volume fraction and lower heating value of producer gas component, respectively. The heating value of the producer gas constituents at standard temperature and pressure (20°C and 1 atm) used is shown in Table 4.4

Table 4.4: LHV of producer gas components at STP (Jain, 2006)

Gas Component	LHV (MJ/Nm^3)
CO	11.57
H_2	9.88
CH_4	32.92

The gasification efficiency was determined from Eq 4.23

$$\eta_g = \frac{LHV_g \times GFR}{LHV_{RH} \times FCR} \times 100\% \quad 4.23$$

Where, *FCR* is the fuel consumption rate in kg/h and *GFR* is the producer gas flow rate in Nm^3/h and the f. The producer gas flow rate was determined from a nitrogen balance,

$$N_a + N_{RH} = N_g \quad 4.24$$

Where N_{RH} and N_a are the rates of nitrogen in the rice husk and air, respectively entering the gasifier. N_g, *on the other hand,* is the nitrogen in the producer gas leaving the gasifier. Assuming a negligible N_{RH} compared to N_a, then Eq. 4.24 becomes

$$N_a = N_g \quad 4.25$$

Assuming volumetric fraction of nitrogen in the air supplied to be 0.79, then nitrogen input can be estimated as:

$$N_a = 0.79 \times AFR \quad 4.26$$

Similarly, the nitrogen output can be expressed in terms of the nitrogen fraction (N_{gv}) and the total gas flow rate as:

$$N_g = N_{gv} \times GFR \quad 4.27$$

Combining Eq 4.26 and 4.27, the producer gas flow rate can be estimated as:

$$GFR = \frac{0.79 \times AFR}{N_{gv}} \quad 4.28$$

4.3 Results and Discussion

4.3.1 Gasifier stove performance

4.3.1.1 Producer gas flow rate and temperature

The variation of gas flow rate and exit temperature with equivalence ratio are displayed in Fig. 4.3. Gas flow rate ranged from 4.15±0.15 to 12.01±0.36 Nm^3/h. As can be seen from the plot, for every 12.5% increase in equivalence ratio there is a corresponding 2.03±0.057 Nm^3/h increase in gas production. Although, Eq 4.28 shows an inverse relation between GFR and nitrogen fraction (N_{gv}) in the producer gas, the variation in the measured N_{gv} results at different ER was less than

5% hence almost a perfect linear relation is observed between the equivalence ratio and the gas production rate. The results are in agreement with those obtained by (Jain, 2006) when he gasified rice husk in a throatless gasifier with a similar diameter. A gas flow rate of 5.66 -17.40 m^3/h was reported over an equivalence ratio of 0.27 to 0.44. The producer gas exit temperature varied between 427±3 – 545±4ºC. These values fall in the lower region of the exit temperature of commercial fixed bed gasifiers which range between 450 and 650ºC (Basu, 2013).

4.3.1.2 Gas composition

Variation of producer gas composition with equivalence ratio is shown in Fig 4.4. The result reveals that all combustible gases show a decline with an increase in equivalence ratio. CO and H_2 showed a 28.8 and 17.6% reduction, respectively while CO_2 on the contrary, increased from 10.5±0.69 to 14.4±0.53%. Higher equivalence ratio represents more active oxidative reactions which end up yielding more CO_2 and H_2O and less CO and H_2. The results also reveal that the peak of H_2 (15.03±0.23) occurs at the 0.42 equivalence ratio.

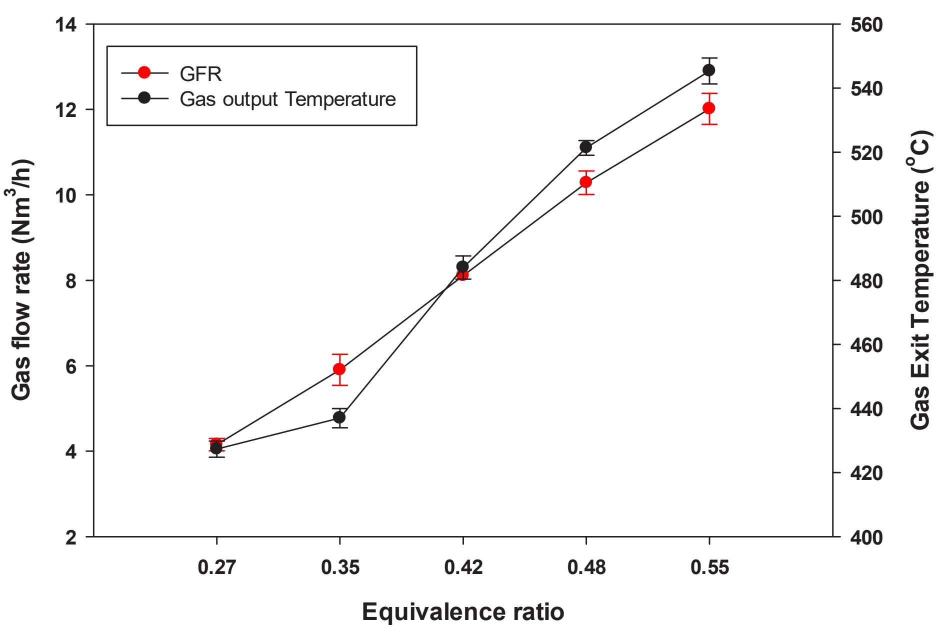


Figure 4.3: Variation of Gas flow rate and gas exit temperature with equivalence ratio

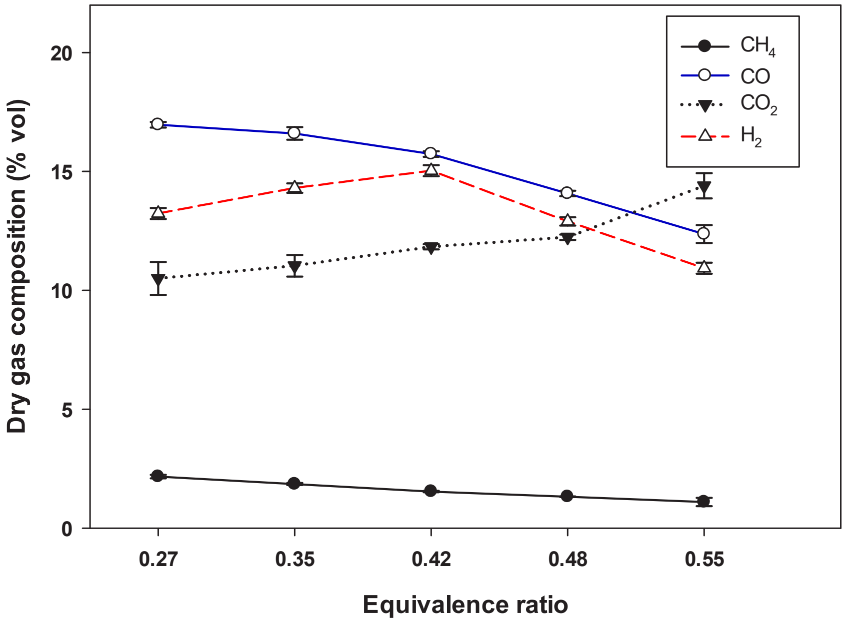


Figure 4.4: Variation of gas composition with equivalence ratio of gasifier stove

4.3.1.3 Heating value and efficiency

Fig 4.5 shows the variation of heating value and gasification efficiency with equivalence ratio. Between 0.25 and 0.42 equivalence ratio LHV varied slightly (<5%). A further increase in equivalence ratio results in a substantial decline in the LHV. As shown in Fig 4.5, variation with efficiency displays a dome bell shape with a peak efficiency of 58.85% occurring at an equivalence ratio of 0.42. This equivalent ratio corresponded to gas composition of 14.9, 15.8, 11.9 and 1.52% for H_2, CO, CO_2 and CH_4, respectively.

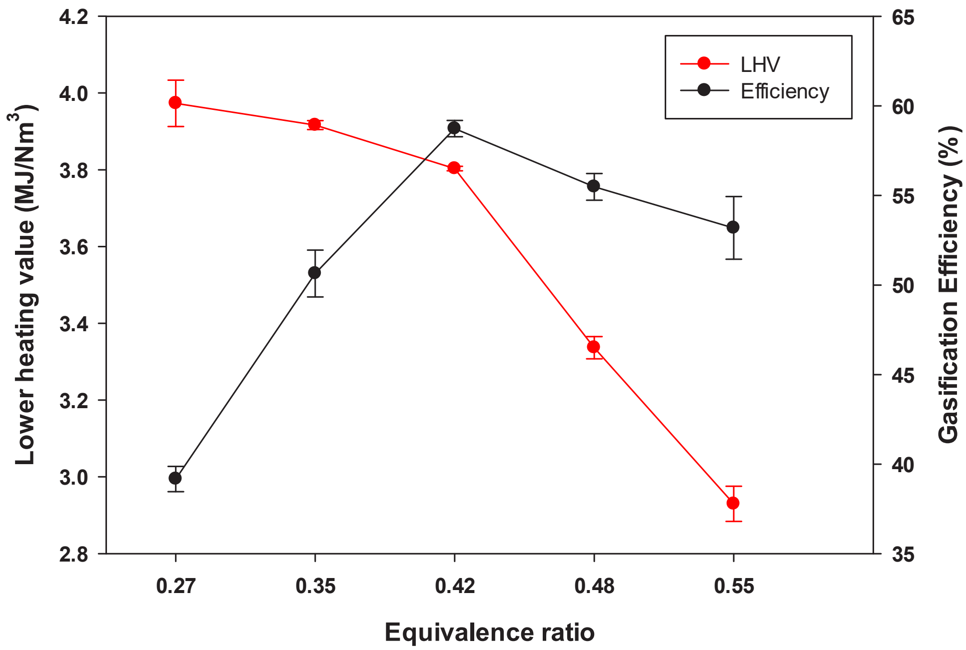


Figure 4.5: Variation of producer gas LHV and efficiency with equivalence ratio of gasifier stove

4.3.2 Gasifier output parameter prediction

Based on the output parameter result obtained from the experiment, five regression models based on the equivalence ratio were developed to predict the performance of the gasifier. Table 4.5 shows the different regression models obtained. The result shows that quadratic models can explain more than 95% of the observed variability in the efficiency and heating value data. Unlike the gasification efficiency which shows poor linearity with equivalence ratio, the gas production rate of the gasifier stove can almost perfectly be predicted by the linear expression developed.

Table 4.5: Regression models for efficiency and heating values of gasifier stove

Parameter	Model form	Model	R-Squared
Gas production rate	Linear	$GFR = 29.38ER - 4.096$	0.997
Gasification efficiency	Linear	$\eta_g = 31.24 + 46.83ER$	0.443
Gasification efficiency	Quadratic	$\eta_g = 39.15 + 41.32ER - 590(ER - 0.414)^2$	0.956
Heating value	Linear	$LHV_g = 5.13 - 3.69ER$	0.875
Heating value	Quadratic	$LHV_g = 5.32 - 3.83ER - 14.59(ER - 0.414)^2$	0.975

4.3.3 Model Validation

Validation of the model developed was achieved by comparing the calculated results with the experimental data. In comparing the dry gas composition, the equivalence ratio was set to the best experimental result (0.42) and its corresponding average gasification temperature measured (788ºC). Results from the comparison of the model and experimental data are shown in Fig 4.6. The results show that the model slightly over predicted the CO concentration and under predict CO_2 and H_2. The slight difference may be attributed to the assumptions made in the development of the model. (Sharma, 2008b) explains that all equilibrium models will show under prediction of methane due to the equilibrium constant of the methanation reaction. He further explains that the methanation reaction tends to be zero and that of the steam reforming reaction whose equilibrium constant becomes infinity at the elevated temperatures occurring in the reduction zone. The slight higher LHV of the predicted model stems from the over prediction of the CO. The root mean square was used to quantify the error in the comparison according to Eq 4.29. A root mean square error of 2.756 was achieved.

$$RMS = \sqrt{\frac{\sum_{i}^{N}\left(\text{Experiment}_i\text{-Model}_i\right)^2}{\text{Number of data}}} \qquad 4.29$$

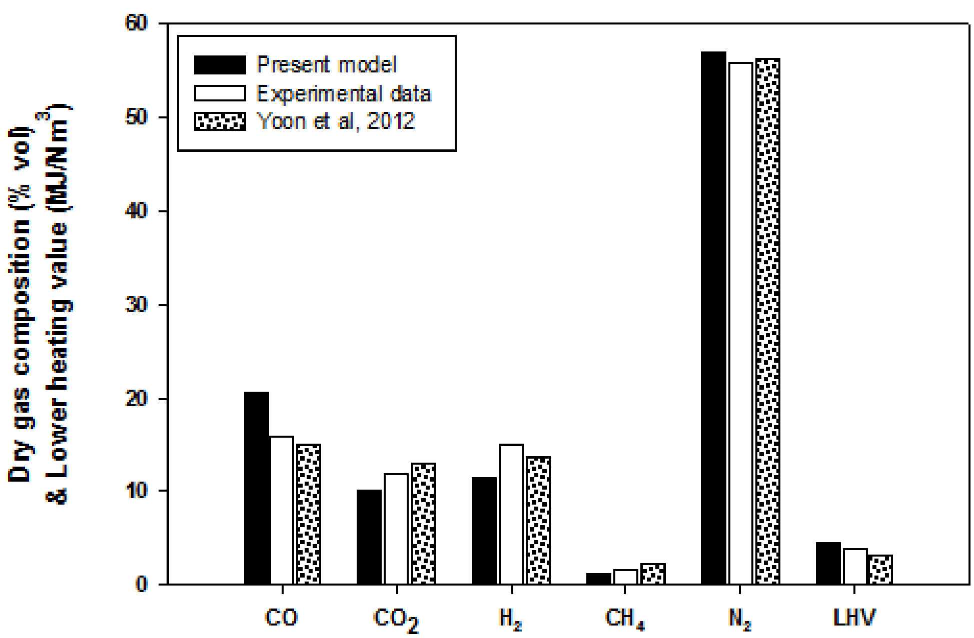


Figure 4.6: Gas composition and lower heating value comparison of predicted, present experimental and literature experimental data.

4.3.4 Parametric studies

4.3.4.1 Effect of gasification temperature

Effect of gasification temperature was examined by varying temperature from 430 - 930 ºC. The selected range was based on the measured temperature values from the reduction zone (shown in Fig 4.2 as T2) and the best equivalence ratio obtained from the experimental results (0.42). The resulting effect of gasification temperature on producer gas composition and heating value are shown in Fig 4.7 and 4.8, respectively. According to the plot, CO and H_2 concentration increase from 7.2% and 9.8 % to 26.2 and 16.8%, respectively as gasification temperature rises from 430 – 930 ºC. Considering the fact that Bouduard and the water gas reaction are endothermic, they would be promoted at higher gasification temperature hence the observed increase in CO. On the other hand, CO_2 decrease sharply as gasification temperature increases but level off after 800ºC. The result is a reflection that optimal performance may be achieved when gasification temperature is kept between 750 and 800ºC.

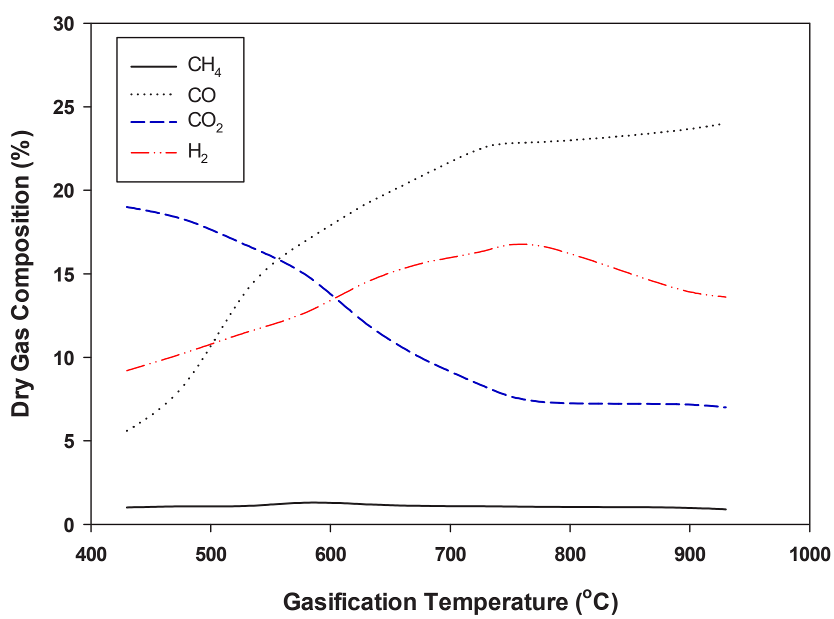


Figure 4.7: Modelling the effect of gasification temperature on dry gas composition

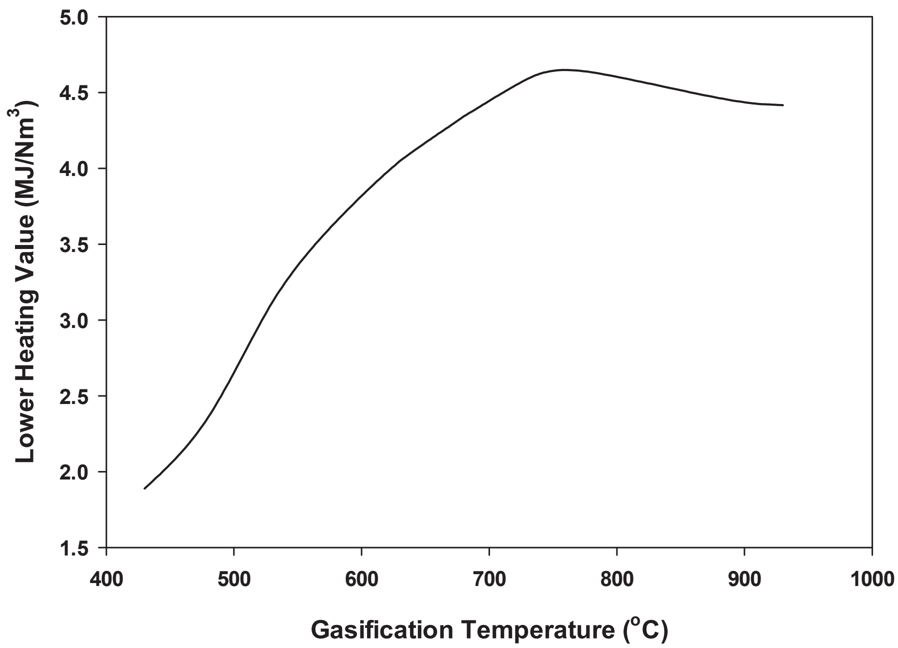


Figure 4.8: Effect of gasification temperature on lower heating value

4.3.4.2 Effect of moisture content

To study the effect of moisture content on the gas composition and efficiency, the equivalence ratio was fixed at the optimal value obtained from the experimental results (0.42). Fig 4.9 shows the effect of moisture content on gas composition. As can be seen from the plot, a deterioration in CO production from 21.0 to 16.6% occurs with an increase in moisture content. Below 15% moisture content, a marginal decrease of less than 0.4% in CO is seen indicating a comparable CO production for lower moisture content. At higher moisture content (≥20%), more than 1.0% reduction in CO can be expected. Other researchers (Jarungthammachote & Dutta, 2007; John & Willson, 2012) observed similar CO trend with moisture content. The CO trend revealed in the plot can be attributed to the reduction of gasification temperature. Increasing moisture content reduces reaction temperature and negatively affects the two endothermic carbon reactions (Bouduard and water gas reactions) responsible for CO production.

In contrast, hydrogen gas production increased from 15.3 to 19.9% as moisture content varied from 5 to 40%. A relatively stable increment of 1% is seen till the moisture content reaches 20% after which the increment subsides. The observed increase in hydrogen gas can be accounted for by the water gas shift reaction ($CO + H_2O \leftrightarrow CO_2 + H_2$) and the steam reforming reaction

($CH_4 + H_2O \leftrightarrow CO + 3H_2$). An increase in moisture content would imply a higher concentration H_2O, thus, shifting the equilibrium of these reactions towards the right which result in increased production of hydrogen gas and carbon dioxide. Zainal et al. (2001) observed a similar rising trend when evaluating variation of hydrogen concentration with moisture content during rice husk gasification. Methane production was the least affected by moisture content recording only 0.42% change for the entire range of moisture content considered for the parametric studies.

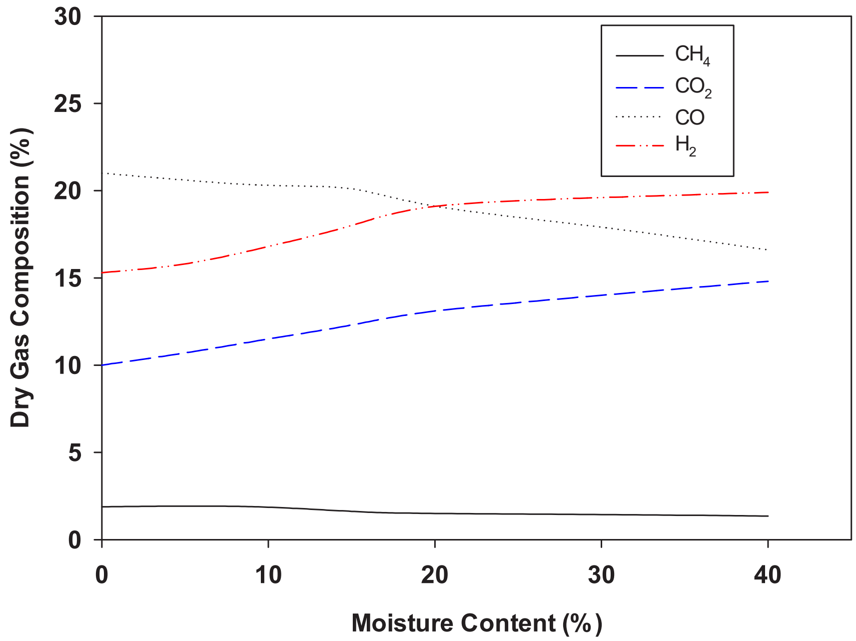


Figure 4.9: Effect of moisture content on dry gas composition

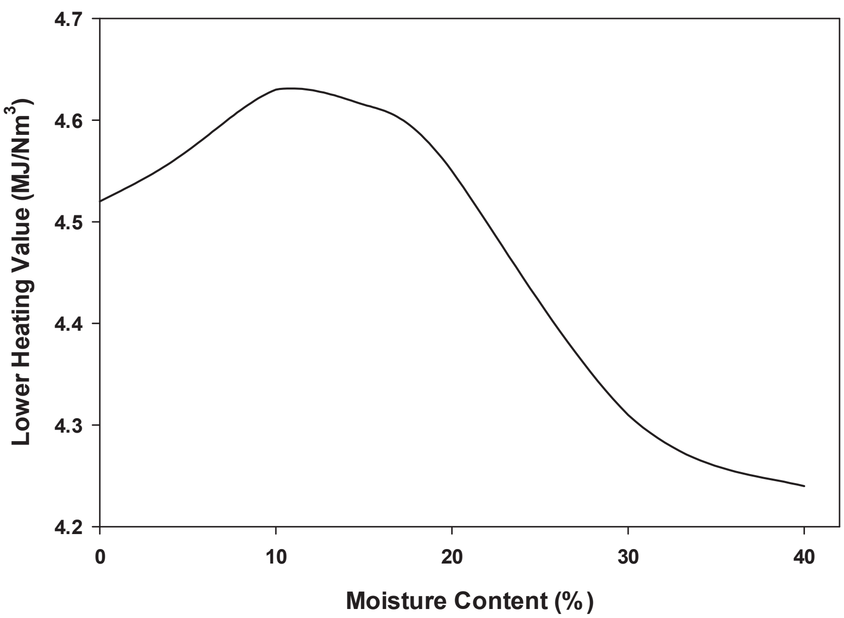


Figure 4.10: Effect of moisture content on gasification efficiency and heating value

The effect of moisture content on heating value is displayed in Fig 4.10. A sharp increase is observed from zero moisture content until a peak is reached at 10%, corresponding to a maximum heating value of 4.63. Afterwards there is a decline with further increase in moisture content. Higher moisture biomass requires more heat to dry feedstock, thus reducing the overall heat budget for gasification and affects the production of the CO, H_2 and CH_4 which determines the LHV and efficiency. As was seen in Fig 4.10, at 15% moisture, CO production declines much more while the production of H_2 stabilizes hence the observed peak in LHV. Again, higher moisture content also implies higher water vapour fraction in the product gas which dilutes and reduces the quality of the product gas since water is non-combustible. Additionally, higher water content will surely give rise to the conversion of combustible CO to non-combustible CO_2 according to the water gas shift reaction. From these preliminary results, the best moisture content for rice husk gasification would be 10-15%.

4.4 Conclusion

In the present studies, a simplified continuous rice husk gasifier stove was developed. Performance of the bottom lit downdraft gasifier intended for rural rice parboiling was evaluated by determining the variation of gas production, gas exit temperature, gas composition, lower heating variation and efficiency, with equivalence ratio. The results showed that both gas production rate and gas exit temperature increases with rising air input and that for the selected equivalence ratio range (0.27-0.55), gas flow rate varied from 4.15±0.15 to 12.01±0.36 Nm^3/h with exit temperature ranging between 427 and 545°C. The results indicated that for every 12.5% increase in equivalence ratio there is a corresponding 2.03±0.057 Nm^3/h increase in gas production for the gasifier stove. The heating value and efficiency of the gasifier stove also varied from 2.98 to 3.96 MJ/Nm^3 and 38.47-58.85%, respectively. In the experimental evaluation, the best gasifier performance was achieved at an equivalence ratio of 0.42. A thermodynamic model was developed and used to evaluate the effect of gasification temperature and moisture content. The results revealed that for best gasifier performance the gasification temperature and moisture content should be in the range of 10 – 15% and 750 – 800°C.

Connecting Text

In chapter 4, the one thermochemical pathway for harnessing rice husk energy was developed and evaluated. The continuous rice husk downdraft gasifier has shown to be more than five times more efficient than the existing combustion systems. The thermochemical equilibrium model developed also indicated that the gasifier can handle up to 20% moisture content of rice husk beyond which the gasifier performance reduces.

In chapter 5, a second thermochemical conversion system is considered. A direct combustion system presents the cheapest utilization option making a suitable option for rural energy development. A 4.5 kg capacity rice husk combustion system with a continuous fuel feeding and ash removal unit was developed. Details of the system and performance evaluation are presented together with emission and safety evaluation.

Chapter 5 has been submitted for publication as:

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CHAPTER 5 Energy efficiency and emission assessment of a continuous rice husk stove for rice parboiling

Abstract

The study presents a performance evaluation of an integrated rice parboiling stove (IRPS) fuelled with either rice husk or wood in comparison with the three stone fire (TSF) stove currently being used. The stoves were initially tested using the water boiling test. The efficiency, fire power and specific energy consumption of IRPS were found to be 28.67±2.7%, 15.9±3.2kW and 0.141±0.01kg/kg rice husk, respectively. To enhance continuous steam production, a heat exchanger extension was made to the IRPS and the efficiency was revaluated using the indirect boiler efficiency estimation approach, together with pollutants emission factors and safety. The stove efficiency after the extension increased to 46.35%. The emission factors for CO, CO_2 and C_xH_y were in ranges from 10.6-12.0, 785-793, 0.4-2.2 g/kg of rice husk. Comparison between rice husk and wood combustion in IRPS shows that emission factors for rice husk were significantly lower than wood but decreased with stove fire power. Though IRPS has some safety features, the lack of insulation around the heat exchanger and chimney gave a 'fair' (83.0) overall rating corresponding to International Workshop Agreement (IWA) stove safety Tier 2.

5.1 Introduction

Rice has become an important crop and the most rapidly growing food for population in Sub Saharan Africa (Solh, 2005). This is evident in the rise in per capita consumption which has increased by more than 50% in the last two decades (Mohanty, 2013). In 2012, more than 62%[1] (FAOSTAT, 2015) of rice within the region was locally produced. To enhance physical and nutritional quality of local rice, a pre-milling technology known as parboiling is adopted (Araullo et al., 1985; Oli et al., 2014; Tolaba et al., 2006). This three-stage starch gelatinization process rectifies the problem of cracks and incomplete grain filling and leads to many favourable changes including easy shelling, higher head rice yield, fewer broken rice, increase resistance to insect and nutrient retention (Igathinathane et al., 2005), reduced disintegration and solubilisation of kernels on cooking (Priestley, 1976), hence, improving consumer preference for local parboiled rice. The

[1] Estimated using production and import data from FAOSTAT

process as practiced in the sub-region is arduous and energy intensive with thermal energy provided through combustion of wood in an inefficient three stone fire (TSF) stove.

Wood is primarily collected and transported over long distances by women and children or purchased from local bulk wood suppliers. Wood collection activity consumes a significant amount of time and limits the other income generating activities and keeps children away from school (WHO, 2014). Although, the TSF is known to be inefficient with an efficiency of 10% - 15% (Alakali et al., 2011; Bhattacharya et al., 2002a; Bhattacharya & Abdul Salam, 2002), it is the most widely used stove due to it simplicity and lower cost. Worldwide, more than three billion people use these stoves daily for domestic cooking and heating purposes in developing countries using wood, charcoal or agricultural residue (WHO, 2014). Wood stove's inefficiency and health impact have been implicated in deforestation and regional climate change (Bond & Sun, 2005; Manibog, 1984; Ramanathan & Carmichael, 2008). In addition, the use of wood as source of energy in traditional TSF and small hand-crafted cookstoves is considered responsible for several cases of respiratory illness and death, burns, cuts, and scalds (Desai et al., 2004; Johnson & Bryden, 2012b; Wickramasinghe, 2003). Every year, more than 4.3 million premature deaths including deaths from pneumonia (12%), stroke (34%), ischaemic heart disease (26%), chronic obstructive pulmonary disease (COPD)(22%) and lung cancer (6%), traceable to household air pollution from biomass use are recorded (WHO, 2014).

Besides the challenges relating to inefficiency and health, the issue of sustainability has always been another key limitation to wood use. Deforestation within the region has been alarming considering the fact that countries like Nigeria, Benin and Ghana have lost more than 75% of forest reserves in the past five decades (Duah-Yentumi & Klah, 2004) and are currently named among 10 countries with the highest deforestation rates in the world (McDermott, 2009). Besides afforestation, the use of alternative biomass such as agricultural residue, dung etc. could be a potential pathway of reducing environmental impact emanating from deforestation. To this end, rice producing communities have a useful resource, rice husk, which can be harnessed for domestic and commercial thermal energy applications.

Unfortunately, rice husk in these communities is heaped and disposed through open field burning and dumping in water bodies. This inefficient burning activity results in air pollution releasing carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons C_xH_y such as methane and polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOC), un-burnt carbon (with trace amount of methane) as well as NOx and trace amount of sulphur dioxide (SO_2) (Lim et al., 2012). The choice of wood over rice husk by parboilers is largely due to difficulties associated with its combustion which requires specialized systems.

As a part of an ongoing project to enhance energy supply and use in rice parboiling in West Africa, four types of improved stove using wood were constructed by our research group and evaluated against the TSF stove currently being used. Efficiency of up to 25. 6% were achieved. This study continues the stove project with a focus on developing a simplified and efficient rice husk system which could reduce wood use and its implication hence reducing emissions from the TSF that may lead to respiratory health infections and other diseases among parboilers.

The objectives of study were (1) to design, fabricate and evaluate the performance of a continuously operated rice husk stove capable of using wood as alternative fuel using the water boiling test (WBT); (2) to make a heat exchanger extension to the stove to enable continuous steam generation and evaluate performance using the indirect boiler evaluation methodology; (3) to assess and compare the emission factors of different pollutants during rice husk and wood combustion in the IRPS; and (4) to assess the safety of the stove.

5.2 Materials and Methods

5.2.1 Stove design considerations

The proposed rice husk stove was intended to meet three primary conditions which include the following: (a) ability to parboil continuously, (b) be able to use other types of fuel in the absence of rice husk, and (c) simple and efficient system that local rice parboilers can easily operate and maintain.

To meet these requirements, three critical factors were considered. These are (1) install a motor to regulate both rice hull feeding and ash removal, (2) supply primary and secondary air to sustain the combustion process, and (3) use a fire tube heat exchanger for efficient heat transfer and a continuous delivery of steam.

The system also considered other design factors including: a grate to enhance combustion quality and improve efficiency by 3-5% (Sutar et al., 2015); a chimney integrated into the fire tube unit to divert smoke from parboilers and provide draft to extract air from the stove; baffles in the fire tubes to slow down flue gas movement and ensure maximum heat transfer (Lepeleire, 1981); a combination of bricks and metal for stove construction to take advantage of the low thermal inertia and the durability in high temperature conditions; and the application of a forced draft air system to improve efficiency (Bryden et al., 2012).

5.2.2 Stove construction

The stove is a rectangular metal box (85 x 70 x 50 cm) with a feed hopper, feedstock regulator and an auger for ash removal. It was made of 5mm steel sheet (Acier Lachine Inc, Lachine, QC, Canada). It has four components – a 4.5 kg hopper capacity at one end, an ash removal unit consisting of an 80 cm long auger (3 inch OD and 3 inch pitch) in a 3 inch schedule 20 (Nominal) steel pipe and a motor with 50 Amp PWM DC Motor Speed controller (QKits Electronics Limited, Kingston, ON, Canada). The rice husk is combusted on a fixed 45 º inclined grate (angle of repose experimentally determined prior to the experiment to be 40º). The stove is insulated with firebricks (23 x 11.4 x 6.4 cm) purchased from Materiaux Refractaires Direct (St-Leonard, QC, Canada). It also has a slightly inclined grate (10º) for firewood combustion. This is to allow for wood combustion during rice husk shortages. Fig 5.1 shows the improved rice parboiling stove (IRPS). Detailed design drawing of the rice husk stove is shown in Appendix B.

Figure 5.1: The improved rice parboiling stove (IRPS)

5.2.3 Experimental setup

Evaluation of the performance of the stove was achieved using the water boiling test (WBT) version 4.2.2 (Aprovecho Research Center, 2013). In this study, a single stove with multiple fuel use was being evaluated; therefore, the WBT protocol was modified to allow for the monitoring of operation parameters. A two-phase test - high power cold and high power hot start - was considered instead of the usual three-phase method. Before the test was carried out, the stove was seasoned with four water boiling tests (two each with rice husk and wood) to familiarize with the characteristics and operation of the stove under different fuel combustion and to remove any moisture in the brick lining.

A complete randomised design with two independent variables was used for the experiments. These variables were the fuel type (rice husk and wood) and the WBT phase (cold start and hot start). In each run, 15L of water at room temperature was heated to boiling point. A previously heated stove was re-run for the hot start experiments to simulate a repeated use of the stove in a day. For each of the hot start test using rice husk as fuel, the feed rate was varied at three levels to investigate the effect of fuel rate on efficiency. Each test was performed in triplicate. The tests commenced when the fuel was loaded, the fire started with either pieces of paper (for rice husk combustion) or a stack piece of wood soaked in kerosene for 5 s (for wood combustion) and the fan activated (for rice husk).

The rice husk used in the experiments was purchased from California, USA. Air-dried maple planks (JTM Sawmill, Vaudreuil, QC, Canada) cut into pieces (65 x 2.5 x 2.5) were used for the wood combustion experiments. The moisture content of the fuels were determined according to the ASABE Standard S358.2 by drying at 104 ºC for 24 hours in an oven (Fisher Scientific 750, USA). The proximate analysis of the fuels were determined using the standard test method for compositional analysis by thermogravimetry (ASTM E1131)(ASTM, 2010). The ultimate analysis was then evaluated based on linear correlations (Eq 5.1-5.3) by Shen et al. (2010)

$$C = 0.635FC + 0.460VM - 0.095ASH \qquad 5.1$$

$$\mathrm{H} = 0.059FC + 0.06VM + 0.010ASH \qquad 5.2$$

$$O = 0.340FC + 0.469VM - 0.023ASH \qquad 5.3$$

Where FC, VM and ASH represent the fixed carbon, volatile matter and ash fractions of the proximate analysis. The heating value of the fuel in MJ/kg was estimated using Eq 5.4 based on the non-linear correlation proposed by Nhuchhen and Abdul Salam (2012):

$$HHV = \begin{pmatrix} 20.7999 - 0.3214\dfrac{VM}{FC} + 0.0051\left(\dfrac{VM}{FC}\right)^2 - 11.2277\dfrac{ASH}{VM} \\ +4.4953\left(\dfrac{ASH}{VM}\right)^2 - 0.7223\left(\dfrac{ASH}{VM}\right)^3 + 0.0383\left(\dfrac{ASH}{VM}\right)^4 + 0.0076\dfrac{FC}{ASH} \end{pmatrix} \qquad 5.4$$

The lower heating value LHV_f in MJ/kg, was estimated from the HHV_f according to Eq 5.5 (Mansaray & Ghaly, 1998)

$$LHV_f = (1 - MC)\left[HHV_f - Y\left(\frac{MC}{1 - MC}\right) + \frac{18H}{200}\right] \qquad 5.5$$

Where *MC* is the moisture content of fuel (decimal), *H* is hydrogen fraction of fuel on wet basis (decimal) and *Y* is the latent heat of vaporization for water (MJ/kg)

K-type thermocouple wires (Omega, Laval, QC, Canada) were used for temperature measurement. The measured temperature was logged every 3 seconds with a *Visual Hotmux data logger* (V.3.1.0

DCC Corporation, US). A digital air flow meter (model HHF92A, Omega, Laval, QC, Canada) was used to measure the air input to the combustor.

5.2.4 Stove Performance Evaluation

The performance of the stove was evaluated by computing the thermal efficiency, firepower, specific energy consumption and heat flux using the data collected during the WBT experiments. The thermal efficiency which expresses the ratio of energy reaching the pot and used in evaporating water to the total energy supplied from fuel (Jetter & Kariher, 2009; Jetter et al., 2012b) was estimated according to Eq 5.6:

$$\eta_T = \frac{(4.186 \times m_w \times \Delta T_w) + (2260 \times w_{cv})}{f_{cd} \times LHV_f}, \% \qquad 5.6$$

$$f_{cd} = \frac{f_{cm}\left[LHV_f(1-MC) - MC\left(4.186(T_b - T_a) + 2257\right)\right] - (m_{char} \times LHV_{char})}{LHV_f}, \text{kg} \qquad 5.7$$

Where, η_T is the thermal efficiency of the stove (%); m_w is the mass of water used for the test (kg); ΔT_w is difference between the water temperature at the start and end of the test (ºC); w_{cv} is the mass of water evaporated; f_{cd} is the equivalent dry fuel consumed (takes into account the energy needed to remove moisture in the fuel and the remaining unburned char); f_{cm} is the moist fuel consumed (kg); T_b and T_a are the temperature of the boiling water and ambient air, respectively (ºC); m_{char} (kg) and LHV_{char} (MJ/kg) are the mass and lower heating value of the char generated

Considering the fact that different environmental conditions may affect the stove's fuel consumption, the temperature corrected specific fuel consumption SFC which takes into account the surrounding temperature was used and estimated as follows:

$$SFC = \frac{f_{cd}}{m_{wr}} \times \frac{75}{T1_{cf} - T1_{ci}}, \text{kg/kg water} \qquad 5.8$$

Where, m_{wr} is the mass of water remaining after the test, $T1_{cf}$ and $T1_{ci}$ are the water temperature at the start and end of the test, respectively.

The average power output in kW (Aprovecho Research Center, 2013) and the corresponding power flux in W/cm^2(Lepeleire, 1981) were also estimated according to Eq 5.9 and 5.10:

$$FP = \frac{f_{cd} \times LHV_f}{60 \times \Delta t_c}\text{, kW} \qquad 5.9$$

$$P_f = \frac{FP}{A_g} \qquad 5.10$$

where, FP is the fire power; Δt_c is the time to boil; P_f is the power flux A_g and A_g is the grate surface area in cm^2.

5.2.5 Stove extension and re-evaluation

The proposed stove was intended for steam production for rice parboiling. Therefore, an extension to ensure the continuous delivery of steam was considered. A fire tube heat exchanger 0.58 m high, made of 13 standard nominal black iron pipes (ID = 0.0381) fitted to a galvanized sheet steel with diameter 0.43 m (Acier Lachine, Lachine, QC, Canada) was added to the combustor. The performance of the new system was evaluated by estimating the initial energy supplied and the thermal efficiency using the indirect method for boiler evaluation.

Although, the direct method of evaluating a boiler required few parameters for computation, the indirect method was chosen for two reasons. Firstly, the direct method is unable to estimate the various losses which account for the efficiency level and secondly, due to significant changes in efficiency for small measurement error (BEE, 2006). For example, assuming a 90% efficiency, a 1% error in the direct method will result in a significant change in efficiency (90±0.9%) whereas a similar error using the indirect method will result in a 90±0.1%.

Another complete randomised design with the rice husk rate as the independent variable was used to evaluate the efficiency. In estimating energy efficiency, the heat capacity of the hot products from combustion and the flue gas were calculated based on the ultimate analysis of the fuel using a new approach proposed by Coskun et al. (2009). The mass flow rate of flue gas was assumed to be the sum of mass flow rate of the actual air supplied by fan and the mass flow rate of fuel (BEE, 2006). The efficiency of the system was estimated assuming that the overall heat lost within the system is due to heat lost from the dry flue gas (L_{fg}), heat loss due to H_2 in fuel (L_H), heat loss due to radiation and convection (L_{RC}) and heat loss due to unburnt carbon in ash (L_{ash}). Heat lost due to flue gas (L_{fg}) was calculated from Eq. 5.11

$$L_{fg} = \frac{m_{fg} \times C_{P,fg} \times (T_{fg1} - T_a)}{HHV_f} \quad \text{, MJ/kg} \qquad 5.11$$

Where m_{fg} is the mass of flue gas in kg/kg of fuel, C_{Pfg} and T_{fg} are specific heat capacity and temperature of flue gas, respectively, T_a is the ambient temperature, and HHV_f is the higher heating value of fuel.

The heat loss due to the H_2 in the fuel was calculated according to Eq 5.12:

$$L_H = \frac{9 \times H_2 \times \Delta H}{HHV_f} \times 100 \qquad 5.12$$

$$\Delta H = 2443 + 1.88\left(T_{fg} - T_a\right) + 4.2\left(25 - T_a\right), \quad \text{kJ/kg} \qquad 5.13$$

Where, H_2 is the percent hydrogen in the fuel.

Heat loss due to radiation and conduction (L_{RC}) was calculated according to Eq. 5.14

$$L_{RC} = 0.548 \times \left[\left(\frac{T_s}{55.55}\right)^4 - \left(\frac{T_a}{55.55}\right)^4\right] + 1.957 \times \left(T_s - T_a\right)^{1.25} \times \sqrt{\frac{169.85V_m + 68.9}{68.9}} \qquad 5.14$$

Where T_s, T_a, and $V_m$are the surface temperature (K), ambient temperature (K) and wind velocity in m/s. L_{RC} is expressed in per kg fuel by dividing the obtained value from Eq 5.14 with the total fuel input. The outcome is expressed as a percentage by multiplying it by the total combustor surface area and 100%.

The heat loss due to unburnt fuel in ash was estimated according to Eq 5.15

$$L_{ash} = \frac{m_{ash} \times LHV_{ash}}{m_f \times LHV_f} \times 100 \qquad 5.15$$

Boiler's thermal efficiency was estimated by subtracting the total heat losses from 100% as expressed in Eq 5.16

$$\eta_c = 100 - \left(L_{fg} + L_H + L_{RC} + L_{ash}\right) \qquad 5.16$$

5.2.6 Emission Test

The mass of a pollutant emitted per unit fuel consumed in g/kg of fuel known as emission factor has been the standard measure of emissions from combustion systems and is usually determined by the hood or the chamber method (Bhattacharya et al., 2002b). In this study, emission tests were performed by monitoring the concentration of flue gas throughout the experiment using a hood. Measurements were made every 15 seconds using a flue gas analyser (M700, Enerac TM, Holbrook, NY USA). Within the analyser, carbon dioxide (CO_2) and carbon monoxide (CO) were monitored using a non-dispersive infrared sensor while hydrocarbons (C_xH_y) and oxygen (O_2) were observed using a flame ionization detector and an electro-chemical sensor. Measurements were made during the extended stove evaluation, where the system had a chimney through which all combustion product passed. The analyser probe was inserted 10 cm below the end of the chimney. Though, the opening on the chimney may allow the escape of some minor fugitive emissions during measurement, Zhang et al. (2000) reported that no difference in emission ratio would be observed in such situation where emission samples have been directly taken from a vented stove flue. Particulate matter was not measured considering the fact that CO measurements could be used as a proxy for their emissions since both are formed from incomplete combustion (McCracken & Smith, 1998; Roden et al., 2009).

The combustion efficiency defined as ratio of the energy generated from fuel combustion to the total available energy in fuel (Johnson et al., 2010) was approximated by expressing it as the ratio of the carbon emitted as CO_2 to the overall carbon related emissions measured according to Eq 5.17.

$$\eta_{combustion} = \frac{CO_2}{CO_2 + CO + C_xH_y} \qquad 5.17$$

The emission factors were normalised to determine the emission per unit fuel by dividing the calculated total emissions by the equivalent dry fuel consumed using expressions reported by (Bhattacharya et al., 2002b), (Cooper & Alley, 2007) and (Zhang et al., 2000) shown in Eq 5.18 - 5.21

$$EF_f = \frac{M_T}{f_c} \qquad 5.18$$

$$M_T = \sum\left(\frac{C_{\text{pollutant}} \times 15}{10^6} \times \rho_{air} \times \dot{V}_{dry} \times \frac{MW_{\text{pollutant}}}{MW_{air}}\right) \qquad 5.19$$

$$\dot{V}_{dry} = \dot{V} \times \left(\frac{273.15}{273.15 + T_s} \right) \times \left(1 - H_2O_{vap}\right) \quad 5.20$$

Where, EF_f is the emission factor in terms of the equivalent dry fuel burnt in (g/kg); M_T is the total mass of one pollutant emitted in g; f_c is the equivalent dry fuel in kg; $C_{\text{pollutant}}$ is the concentration of pollutant; ρ_{air} is the density of air at standard condition taken as 1.294 g/m^3; $\dot{V}_{dry}$ is the dry volumetric flow rate adjusted for standard temperature (m^3/s); MW is the molecular weight in g/mol ($MW_{C_xH_y}$ was taken as 28.98g/mol because the analyser was calibrated for propane); $\dot{V}$ is the volumetric flow rate (m^3/15s); T_s is the stack temperature during the measurement; and H_2O_{vap} is the percentage of water vapour in flue gas (%) taken as 12% (Zhang et al., 2000).

5.2.7 Safety Evaluation

The biomass stove safety protocol version BSSP 1.1 (Global Alliance for Clean Cookstoves, 2012; Johnson, 2005) was used to evaluate the safety of the stove. The protocol originally developed by Nathan Johnson to provide safety guidelines for examining the hazards associated with cookstove and for evaluating the injury risk has been mapped to the tiers of performance by the International Standards Organization (ISO) International Workshop Agreement (IWA). It consists of 10 sets of test to be performed on the stove. After each test the stove is rated 1 (poor) to 4 (best). The total weight per test is then calculated from the stove rating and an already defined weight assigned to each test. The overall ratio (Safety Rate, SR) estimated as the sum of total weight per test is then used to determine the safety.

5.3 Results and Discussion

5.3.1 Energy consumption and thermal efficiency

The proximate and ultimate analysis of the fuel used in the study are shown in Table 5.1.

Table 5.1: Proximate and Ultimate Analysis of fuels

Fuel	Proximate Analysis (wt%)				Ultimate Analysis (wt%)			HHV (MJ/kg)	LHV (MJ/kg)
	MC	VM	FC	Ash	C	H	O		
Rice Husk	7.52	61.24	18.04	20.72	37.66	4.95	35.33	15.76	14.67
Maple Wood	9.67	71.05	28.02	0.98	50.17	5.86	42.34	19.22	17.43

A typical temperature profile of the stove during operation with rice husk is shown in Fig 5.2. A summary statistics on the temperature profile shows a flame temperature of 753.6±60.4ºC which was 142 ºC higher than wood in the IRPS. The water temperature profile reveals that it takes 11±2.6 min to reach boiling point which means that during parboiling, steam production will begin after about 12 minutes of operation. Again, the low mean stove temperature recorded (35.66±9.4 ºC) primarily due to the thermal insulation with fire brick lining, is an indication that burns and other safety concerns associated with TSF can be reduced with the use of the stove.

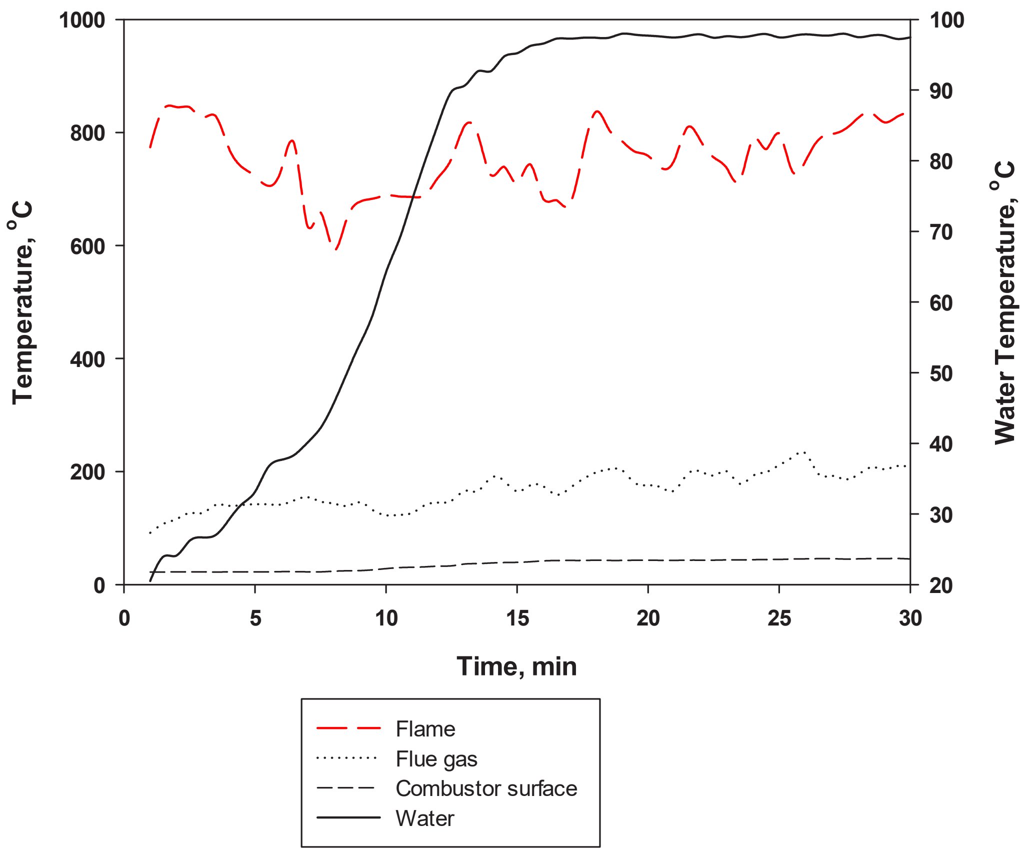

Figure 5.2: Typical temperature profile of RPS during operation

Results showing time to boil and specific fuel consumption (SFC) are presented in Fig 5.3. SFC were in the range of 0.118 – 0.154 and 0.095 - 0.123 kg/kg fuel for rice husk and wood, respectively using the IRPS. These were lower than SFC for TSF reported in other studies (Ayoub & Brunet, 1996; Berrueta et al., 2008) which were in the range 0.17 – 0.28 kg/kg fuel. Table 5.2 show results from the stove compared with other studies. Comparing means using the student t test (at $\alpha = 0.05$) reveals SFC of rice husk at different feed rate varies significantly from each other with a strong positive correlation between feed rate and SPC. However, no significant difference (p-value = 0.460) was observed between SFC at lower feed rate (2 g/s) and wood as can be seen from the connecting letters shown in Fig 5.3. This appears to imply that rice husk at the lowest feed rate would perform similarly to wood, which may be misleading because, only 14.7% of the water was evaporated compared to the 23.4% for wood. The high evaporation rate can be attributed to the 3.46MJ/kg difference in heating value between rice husk and wood. It is worthwhile to note that, in the WBT, SFC is inversely proportional to the amount of water left after the test, hence, a high evaporating rate would imply a high SFC. Therefore, care must be taken when comparing different fuels with different heating rate which can be deceptive as shown in this study. Comparing feed rate in terms of energy consumption, taking into account the heating value, shows that wood use was significantly different (p-value = 0.0221) from the 2.0 g/s rice husk feed rate but not 2.8 g/s (p-value = 0.2512). Although, IRPS is meant to use rice husk which saves 217 g of wood for every kilogram of water boiled, boiling 15 L of water using wood as alternative fuel will save 1.65 kg of wood (49%) when compared with the TSF stove result from our previous study. Comparable wood savings (44-65%) were recorded by MacCarty et al. (2010a) when they tested a fire-clay stove.

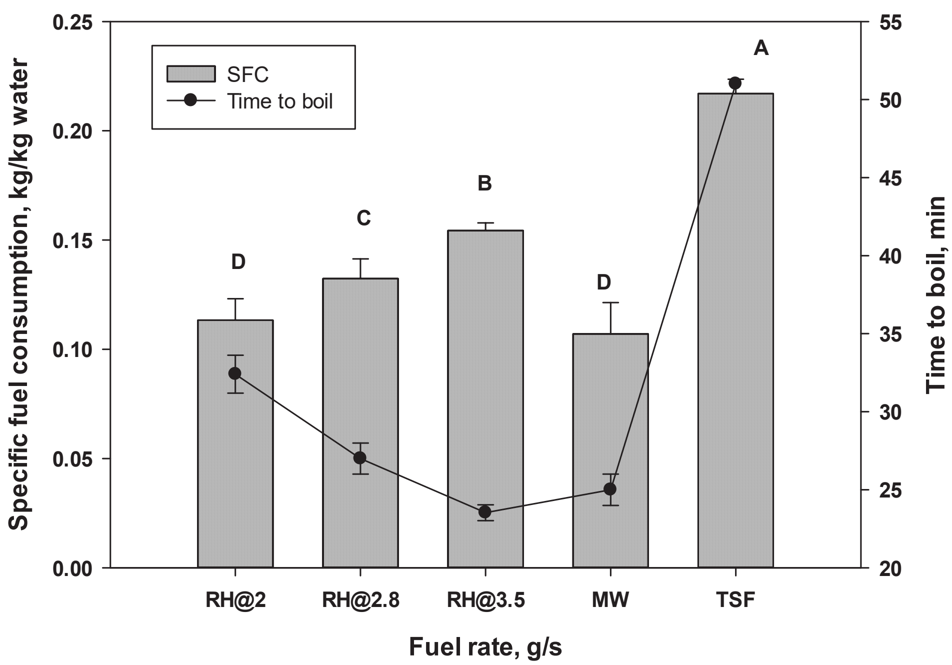

Figure 5.3: Temperature corrected specific fuel consumption (SFC) and Time to boil of RPS at different fuel rate. [RH and MW represent rice husk and maple wood, respectively and TSF represent three stone fire stove].

As expected, the time to boil decreased as the feed rate increased due to the additional energy supplied. Using rice husk as fuel, the longest recorded time to boil at 2 g/s was 33 minutes which was 5.3 and 9 minutes more than the 2.8 and 3.5 g/s feed rate, respectively. At a rice husk feed rate of 3.5 g/s, the stove's performance in terms of time to boil was similar to that of wood recording 25 min in both cases. The results were found to be relatively higher than what Ayoub and Brunet (1996) reported (35 min) when they tested a large metal community stove with similar fire power. This could be due to the larger amount of water used (30 L) and the lower specific fuel consumption (0.057 kg/kg water). The TSF stove on the other hand used more than twice the time (51 min) to boil the same amount of water. Although, time to boil may not be an important assessment criteria for stove designers, stove users consider it relevant in accepting and adopting a stove (McCracken & Smith, 1998).

Thermal efficiency and fire power of the IRPS are presented in Table 5.2. At cold start (CS) thermal efficiency of IRPS varied between, 25.5 – 30.7, 22.12 – 28.92 for with rice husk and wood, respectively which were significant different (p-value < 0.0001 in both cases) from TSF thermal efficiency. At hot start (HS) 11.1 and 14.4% increase in efficiency is observed for rice husk and wood use, respectively which implies the fire brick lining creates a high thermal inertia with substantial heat absorption during the cold start. Since the IRPS is intended to be used in a continuous fashion, effect of thermal inertia will be minimal. The higher efficiency of rice husk compared to wood seen in Table 5.2 perhaps, may be due to the large surface area of the grate, the ability to regulate the fuel flow rate, the ash removal system and the use of the forced air during rice husk combustion. With the use of a fan, air variability can be reduced, thus enhancing control over the air input. Although, fuel bed could be a hindrance to air flow (Sutar et al., 2015), the 4 cm fuel bed used in this study seems to pose no such challenge as was observed during initial air supply measurement across different position above the grate before the commencement of the test. The forced draft in the IRPS in addition to allowing the right amount of air, also ensures better mixing leading to more complete combustion hence higher efficiency with a possibility of reducing emissions (Sutar et al., 2015). Using rice husk in the IRPS will improve parboiling energy use by improving thermal efficiency.

The observed power flux in this study was 4.2 -7.3 W/cm^2 which is significantly lower than the tentative values of 50 and 10-15 W/cm^2 for stove with and without chimney, respectively (Lepeleire, 1981). For any fixed grate the power flux will increase as the feed rate increase hence the trend observed in the Fig. 5.4 is not surprising. The low rate of heat per unit area may in part be explained by the large grate used in the stove. This result therefore seems to suggest that a reduction in the grate size could enhance heat transfer and improve overall efficiency of the stove.

Table 5.2: Stove performance comparison

Stove Type	Fuel	SFC kg/kg water	Efficiency (%	Fire-power (kW)	Sources
High power Cold start					
TSF	Maple Wood	0.217±0.05	18.00±0.5	22.6±2.3	Previous study
IRPS	Rice husk	0.132±0.01	28.10±2.6	15.9±3.2	This study
IRPS	Maple Wood	0.107±0.02	25.52±3.4	21.2±2.9	This study
TSF	Maple Wood	0.24±0.04	9.74±1.3	31.8±4.3	(Ayoub & Brunet, 1996)
ICWC	Maple Wood	0.058±0.008	33.02±4.4	17.28±3	(Ayoub & Brunet, 1996)
TSF	Oak Wood	0.19±0.02	13.00±3.7	9.2±0.6	(Berrueta et al., 2008)
Patsari	Oak Wood	0.49±0.08	7.00±0.6	9.1±1.2	(Berrueta et al., 2008)
MLC	Rice husk	0.33±0.013	18.00(na)	4.1±0.6	(Parmigiani et al., 2014)
High power Hot start					
TSF	Maple Wood	0.217±0.05	19.1±0.5	20.6±2.3	Previous study
IRPS	Rice husk	0.11±0.71	31.22±2.7	13.92±3.8	This study
IRPS	Maple Wood	0.19±0.92	29.20±1.4	19.2±2.1	This study
TSF	Oak Wood	0.13±0.3	19.00±4.2	7.1±1.5	(Berrueta et al., 2008)
Patsari	Oak Wood	0.18±0.4	17.00±3.9	4.4±0.5	(Berrueta et al., 2008)

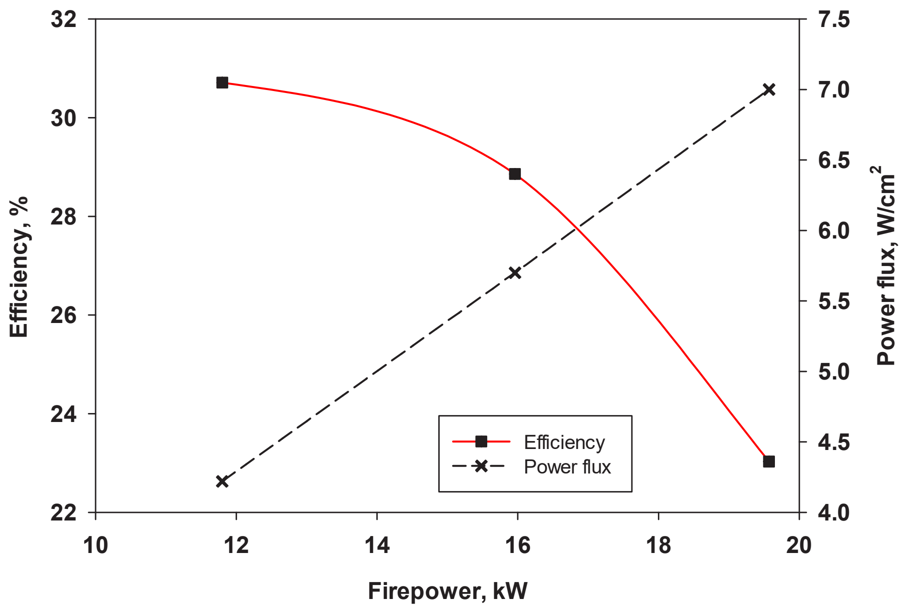

Figure 5.4: Efficiency and Power flux variation with firepower of RPS.

5.3.2 Extended stove efficiency evaluation

Four heat losses were used to evaluate the performance of the extended stove. A Sankey diagram depicting energy flow is shown in Fig 5.5. Heat loss due to dry flue gas, hydrogen in fuel, unburnt carbon in ash, and surface radiation and convection heat losses were estimated to be 16.80, 7.79, 21.08 and 7.76%, respectively giving a total heat loss of 53.65% of the total import energy. In boiler systems dry flue gas loss is usually the highest heat loss contributing more than 50% of total heat loss (BEE, 2006), however, in this study heat loss due to bottom ash was found to be the highest contributor accounting for 39.29% followed by dry flue gas heat loss (31.31%). This can be credited to the high ash generation (19 ± 3.85%) and higher heating value (6.2 MJ/kg more than rice husk). Loss through the walls of the combustor and the heat exchanger were relatively high as they are usually taken as 1.5-2.5% of total heat loss (BEE, 2006). This high heat loss is as a result of the lack of insulation around the heat exchanger which contributed 10% of the total heat loss compared to 4.38% from the combustor. The high heat exchanger surface temperature (82±15ºC) in addition to increasing the heat losses, will also possess high risk of burns to the parboilers. A cheaper option in reducing both heat loss and danger would be to construct a secondary layer around the heat exchanger and filling it with rice husk ash as insulation. A summary of the heat losses is presented below:

Heat loss due to dry flue gas, L_{fg}

$$L_{fg} = \frac{m_{fg} \times C_{P,fg} \times (T_{fg1} - T_a)}{HHV_f}$$

$$L_{fg} = \frac{7.8519 \times 1.7651 \times (485 - 294)}{15,760} \times 100$$

$$L_{fg} = 16.80\%$$

Heat loss due to hydrogen in fuel

$$L_H = \frac{9 \times H_2 \times \Delta H}{HHV_f} \times 100$$

$$L_H = \frac{9 \times 0.0495 \times 2818.9}{15,760} \times 100$$

$$L_H = 7.97\%$$

Heat loss due to unburnt carbon in ash

$$L_{ash} = \frac{m_{ash}\left(kg / kg.fuel\right) \times LHV_{ash}}{LHV_f} \times 100$$

$$L_{ash} = \frac{0.175 \times 17500}{14,320} \times 100$$

$$L_{ash} = 21.08\%$$

Heat loss through combustor and heat exchanger surface

$$L_{RC(C)} = 0.548 \times \left[\left(\frac{T_s}{55.55}\right)^4 - \left(\frac{T_a}{55.55}\right)^4\right] + 1.957 \times \left(T_s - T_a\right)^{1.25} \times \sqrt{\frac{169.85V_m + 68.9}{68.9}}$$

$$L_{RC(C)} = 0.548 \times \left[\left(\frac{316}{55.55}\right)^4 - \left(\frac{294}{55.55}\right)^4\right] + 1.957 \times \left(316 - 294\right)^{1.25} \times \sqrt{\frac{169.85 \times 4.2 + 68.9}{68.9}}$$

$$L_{RC(C)} = 458.06W / m^2 = 458.06W / m^2 \times 2.57m^2$$

$$L_{RC(C)} = 1.176kW = 2.35\%$$

$$L_{RC(HE)} = 0.548 \times \left[\left(\frac{T_s}{55.55} \right)^4 - \left(\frac{T_a}{55.55} \right)^4 \right] + 1.957 \times (T_s - T_a)^{1.25} \times \sqrt{\frac{169.85V_m + 68.9}{68.9}}$$

$$L_{RC(HE)} = 0.548 \times \left[\left(\frac{375}{55.55} \right)^4 - \left(\frac{294}{55.55} \right)^4 \right] + 1.957 \times (375 - 294)^{1.25} \times \sqrt{\frac{169.85 \times 4.2 + 68.9}{68.9}}$$

$$L_{RC(HE)} = 2310.5W / m^2 = 2.31kW / m^2 \times 1.17m^2$$

$$L_{RC(HE)} = 2.703kW = 5.41\%$$

Overall boiler efficiency is estimated according to Eq 17 as

$$\eta_c = 100 - \left(L_{fg} + L_H + L_{ash} + L_{RC} \right)$$

$$\eta_c = 100 - \left(16.88 + 7.97 + 21.08 + (5.14 + 2.35) \right)$$

$$\eta_c = 46.35\%$$

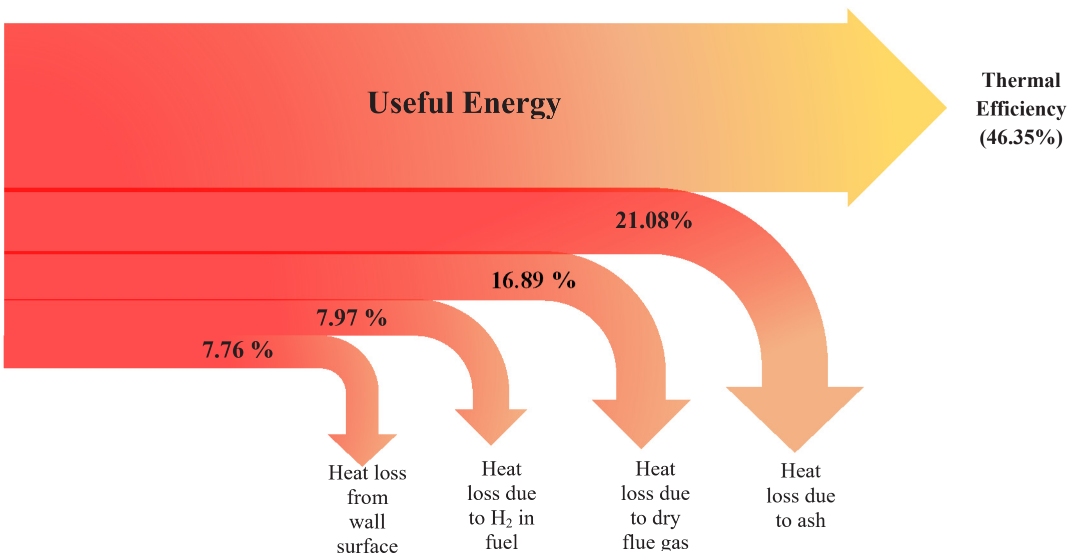

Figure 5.5: Sankey diagram for energy flow

Comparing energy efficiency of the WBT and boiler reveals that energy efficiency can be increased by 53.3% using the heat exchanger. An interesting trend can be observed from the comparison plot shown in Fig 5.6. Certainly, these trends are not virtually identical as expected. The WBT showed a declining trend as rice husk feed rate increased, whereas the boiler showed an upward trend. The seemingly ascendant trend observed for the boiler can be attributed to the parameters considered in its efficiency evaluation. Since the efficiency was estimated based on a unit fuel, the heat loss due to ash and hydrogen in the fuel will not vary. The obvious contributing parameters to any possible increase would be the unchanging air input and temperature of combustion products which will influence both heat loss due to dry flue gas and the surface radiation and convection heat losses. Increasing fuel without a corresponding increase in the air input changes the air-fuel ratio and creates a fuel-rich system leading to incomplete combustion and lower combustion temperature. Since the combustion temperature is directly proportional to flue gas temperature and boiler surface temperature, any reduction in its value will result in lower heat loss due to flue gas and across the combustor and heat exchanger surface. Again, since mass of flue gas was assumed as the sum of fuel and air, increasing only the fuel rate will reduce the mass rate of flue gas. Lower heat loss therefore implies higher system efficiency hence the observed increasing trend.

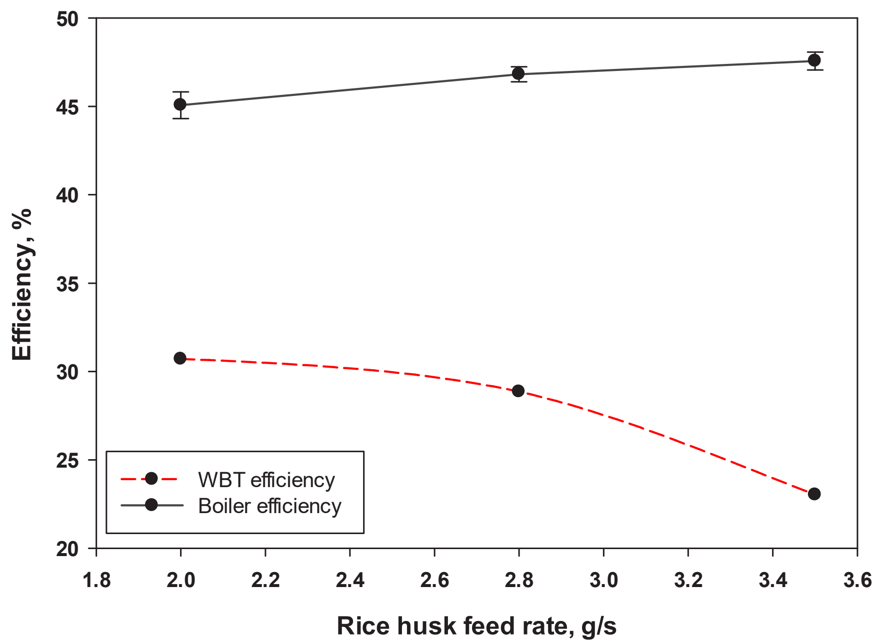

Figure 5.6: Efficiency comparison between WBT and extended boiler (extended stove) test

The results also indicates that the efficiency at rice husk feed rate of 2.8 and 3.5g/s were not significantly different (p-value = 0.167) meaning a feed rate beyond 2.8 would not significantly enhance performance. The implication of results above is that using the extended stove would further increased thermal efficiency by 61.67% (thus, from 28.67±2.7% to 46.35±0.43). In comparison with the TSF, the extended stove can improve efficiency more than fourfold (from 11.37±2.5% (Ayoub & Brunet, 1996; Berrueta et al., 2008) to 46.35±0.43). In addition, the heat exchanger will allow the continuous flow of steam hence several batches of paddy can be processed without having to stop the process.

5.3.3 Emission test

The combustion efficiency (CE) observed for this study were in the range 97.2 - 98.8% for rice husk and 96.9 – 98.1% for wood. These results were higher than those reported by Johnson et al. (2008) (87.1±4.3 and 87.6±2.6% as measured for pine oak wood in a Patsari stove) and Zhang et al. (2000) (92-.5-95%). Two reasons may account for this. Firstly, the analyser used in this study was calibrated to measure only propane hence other products of incomplete combustion (PICs) such as methane (CH_4), total non-methane hydrocarbon (TNMHC), organic carbon (OC) and elemental carbon (EC) were excluded from the CE calculation which was not the case in (Johnson et al., 2008) which also explains the lower hydrocarbon measurement shown in Table 5.3. Secondly, the use of forced air in the combustor leads to better mixing of combustible gases and oxygen hence less incomplete combustion reaction will occur. Emission factors for the stove using rice husk and wood have been presented together with emissions from other stoves in Table 5.3. CO and CO_2 emission factors for rice husk combustion were in the range of 10.6-12 and 785-793 g/kg rice husk, respectively and were much lower than fuel wood (36.3 – 42.7 and 1519-1531 g/kg wood). The lower emissions of rice husk was evident in the lower CO/CO_2 ratio (14.3±0.8 g CO per kg CO_2) compared to wood (25.9±2.0 g CO per kg CO_2) reported in this study and other studies (28.3-44.9 g CO per kg CO_2) (Johnson et al., 2008; Smith et al., 200). The CO emission factor for wood measured in this study is comparable to values reported for the Berkeley-Darfur stove (BDS) (Preble et al., 2014) and the Vietnamese improved Cookstove but were relatively lower than the TSF and the Lao improvised stove. CO_2 emission factors were also slightly lower than the literature values reported in Table 5.3. Comparing rice husk and wood, the results demonstrate CO and CO_2 emissions were decreased by 28.3 and 736 g/kg of fuel, respectively.

The implication of these results can be viewed in two ways. Firstly, the choice of rice husk over wood as a parboiling fuel in the same stove has a potential of reducing environmental and health impact on parboilers. Secondly the use of rice husk in the improved stove would have even a greater impact on parboiling. For example, using heating values reported in Table 5.1 and assuming energy consumption of 2583MJ/tonne (Roy et al., 2006), 3.458 kg of CO and 75.8 kg of CO_2 can be mitigated for every tonne of paddy processed using rice husk instead of wood in IRPS.

Again, with the superior efficiency (more than 300%) recorded for IRSP, a reduction of up to 10.4 kg of CO and 227.4 kg of CO_2 can be realized from processing a tonne of paddy when compared with TSF.

Table 5.3: Summary of emission factors

Stove type	Fuel	Emission factors (g/kg fuel)			Source
		CO	CO_2	C_xH_y	
RPS	Rice Husk	11.2±0.8	789±4	1.3±0.9	This study
RPS	Wood	39.5±3.2	1525±6	0.9±0.5	This study
TSF	Wood	56.0±3.0	1745±5	-	(Preble et al., 2014)
BDS	Wood	42.0±3.0	1767±5	-	(Preble et al., 2014)
VIC	Wood	47.1±4.5	1577±4	5.3±1.0	(Bhattacharya et al., 2002b)
LIC	Wood	51.9±2.5	1565±4	6.0±0.6	(Bhattacharya et al., 2002b)

RPS is rice parboiling stove, TSF is the three stone fire stove, BDS is Berkeley-Darfur stove, VIC is Vietnamese Improved stove and LIC is the Lao improved cookstove.

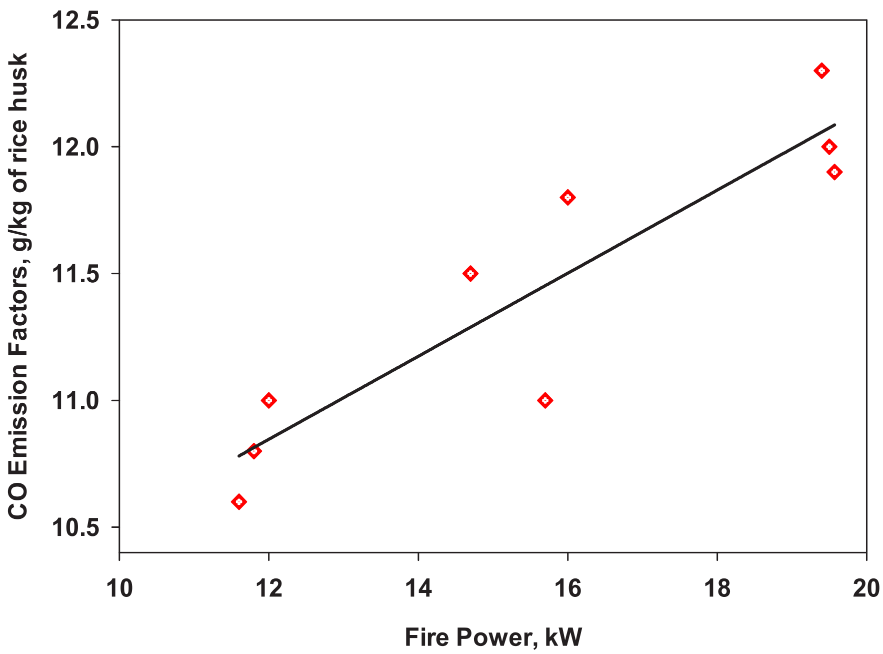

Figure 5.7: Variation of CO emissions with fire power

The variation of CO emissions with fire power is shown in Fig 5.7. Although, there is no consensus in literature about the trend of CO emissions with fire power, CO emission factor in this study favoured a positive trend showing a relatively small (1.7 g/kg of rice husk) increase over the fire power range. Similar observations were made by Kandpal et al. (1994) while evaluating the *Sugam*

II, and Claus and Sulilatu (1982), when comparing the performance of three cookstoves. Other researches (Heeden et al., 1983; Kandpal & Maheshwari, 1995) also observed a positive correlation between the fire power and both CO/CO_2 ratio and CO emissions. Even though, contrasting trend have been reported by some researches (Ahuja et al., 1987; Gupta et al., 1998), the results from this study could be attributed to the fact that increase in fire power was achieved by increasing the rice husk feed rate. However, the same amount of air was supplied by the fan for all test which implies, as fire power increased a corresponding reduction in available oxygen ratio took place resulting in further incomplete combustion reactions and hence an increase in CO emission.

5.3.4 Safety Evaluation

Safety evaluation of the extended IRPS have been presented in Table 5.4. A total safety rating (SR) score of 83.0 (='fair') was achieved which is significantly higher than TSF currently in use with SR = 44 (Johnson, 2005). IRPS had comparable score with other improved wood fuel stove such as the Ecofogon (SR = 84) or the Patsari (SR = 83) (Johnson, 2005) but lower SR when compared with other rice husk stove such as the '*mlc*' stove (SR = 87.5) (Parmigiani et al., 2014). Even though there were safety features such as enormous weight to avert stove tipping, a fuel containment to prevent flame and fuel protruding from fuel loading area, a tight fitting of heat exchanger into combustor to avoid flames being in contact with hands or cloths, the lack of insulation around the heat exchanger and chimney gave a poor score for surface temperature and chimney shielding hence the observed overall rating corresponding to a stove safety IWA Tier 2. This is a signal that a better score can be achieved with heat exchanger insulation and chimney shielding modification.

Table 5.4: Summary of safety score

	Test	Rating	Value	Weight	Score
1	Sharp edges and point	Good	3	1.5	4.5
2	Cookstove tipping	Best	4	3	12
3	Containment of fuel	Best	4	2.5	10
4	Obstruction near cooking surface	Best	4	2	8
5	Surface temperature (< 0.9/>0.9)	Good/Poor	1	2	2
6	Heat transmission to surrounding (floor)	Best	4	2.5	10
7	Temperature of operational construction	Good	3	2	6
8	Chimney shielding	Poor	1	2.5	2.5
9	Flame surrounding cookpot	Best	4	3	12
10	Flames exiting fuel chamber, canister or pipes	Best	4	4	16
	Total				**83.0**

5.4 Conclusion

In this study a continuous rice husk parboiling stove capable of using wood as alternative fuel was developed using the WBT protocol. To enhance continuous steam generation for rice processing, an extension was made to include a fire tube heat exchange and revaluated using the indirect boiler efficiency methodology alongside pollutant emission factors and stove safety. The water boiling test (WBT) revealed a thermal efficiency of 28.7±2.7%, a fire power of 15.9±3.2kW and a specific energy consumption of 0.141±0.01kg/kg rice husk implying using IRPS saves 217 g of wood for every kilogram of water boiled compared to TSF. The extension, in addition to continuous steam production, further increased thermal efficiency by 61.67% (thus, from 28.67±2.7% to 46.35±0.43). The combustion efficiency (CE) observed for stove was in the range of 97.2 - 98.8% for rice husk and 96.9 – 98.1% for wood. CO and CO_2 emission factors for rice husk combustion were also in the range of 10.6-12 and 785-793 g/kg rice husk, respectively and were much lower than fuel wood (36.3 – 42.7 and 1519-1531 g/kg wood). This implied a reduction of up to 10.4 kg of CO and 227.4 kg of CO2 can be realized from processing a tonne of paddy when compared with the TSF stove currently being used. Though IRPS has some safety features, the lack of insulation around the heat exchanger and chimney gave a ‘fair’ overall rating corresponding to a stove safety IWA Tier 2.

Connecting Text

In chapter 5, the second thermochemical conversion system was developed and tested. An extension to allow continuous steam production was made and the system was revaluated. The results indicated a fourfold improvement was obtained. Although, the energy efficiency improvement gained is high, the flue gas temperature was quite high (190±18.6ºC) implying a further improvement could be made.

While heat losses are inevitable in combustion system, identifying system leakages and sources of heat losses in addition to making use of waste heat are always recommended as options for improving combustion system. In the next chapter (6) the project focuses on achieving further improvement in energy efficiency through the use of a waste heat recovery system and thermodynamic evaluation. A second heat exchanger unit was developed to extract heat from the flue gas leaving the steam heat exchanger for hot air generation which could be used for paddy drying. To identify the sources of energy loses and exergy destruction with the system which may lead to further design improvement, an energy and exergy analysis was performed. Based on the results obtained, a simplified excel-based energy and exergy assessment framework for quick evaluation of parboiling systems was developed.

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- **Kwofie, E. M** and Ngadi, M. (2015). A Simplified Excel-Based Energy and Exergy Assessment Framework for Local Parboiling System. *Energy for sustainable development*, (under revision)

CHAPTER 6 Thermodynamic performance evaluation of an integrated paddy steaming and drying system

Abstract

This paper presents a simplified energy improvement system using agricultural waste for local rice processing. An integrated steam and hot air production unit using rice husk energy is evaluated thermodynamically. Besides the characteristics of steam and hot air, temperature effectiveness of the fluid streams, energy and exergy flow within the system components have also been studied. Effects of input operating parameters on steam production and drying air temperature together with their correlation have been shown. Overall system energy and exergy efficiencies were found to be 47.81% and 10.93%, respectively. Although, the combustor showed the highest temperature, energy and exergy efficiencies, it was the main source of exergy destruction contributing more than 60%.

6.1 Introduction

Rice parboiling is a pre-milling hydrothermal process employed in the gelatinization of starch to enhance the physicochemical and nutritional properties (Ballogou et al., 2013; Bello et al., 2006; Bhattacharya & Subba Roa, 1966). It takes place in a three-stage process known as soaking, steaming and drying of paddy (rough rice). The process as practiced in rural rice processing is laborious and energy intensive requiring about 1659 - 2758 MJ/tonne of paddy processed (Ahiduzzaman & Sadrul Islam, 2009). Soaking is the most time-consuming process lasting 12 – 48 hours (Igathinathane et al., 2005). Traditional soaking occurs in vessels or concrete masonry tank with either cold water or hot water. Steaming although shorter in time, is energy intensive since it requires the production of steam. Traditional steaming is done in sub-Saharan African by pouring paddy rice into a pot containing water and precooking for 20 -30 minutes on an inefficient (13%) three stone fire (TSF) stove (Houssou & Amonsou, 2004). This process, besides rendering some paddy fully cooked and others uncooked, resulting in poor rice quality also requires long hours of travelling for wood collection. Recently, Zossou et al. (2009) reported an improved steaming process in Benin, West Africa under a collaboration between the National Agricultural Institute of Benin Republic, AfricaRice Centre and local artisans. This improved process prevents the direct contact of paddy with water by placing a perforated steel container with soaked paddy rice over boiling water. The steam generated is used for the starch gelatinization. Although this process avoids a direct contact of paddy with water, it is both operationally and energy inefficient. This is attributed to the following reasons: (1) it requires addition of water after each batch; (2) as the water boils to steam there is no way to replenish it which can lead to system damage when water is used up; (3) the system uses fuelwood and still requires the long hours for wood collection; (4) it still uses the inefficient TSF stove.

For every steam production system, such as the one describe above, it is important to maximize the heat transfer process and minimize the heat losses. To improve the performance, it is imperative to locate and quantify the losses. Unfortunately, the first law of thermodynamics, which is conventionally used to evaluate energy systems provides information only on energy consumption and losses without any information on the internal inefficiency of the system. Thus, the quality aspect of the energy is not accounted for. Exergy (2^{nd} law) analysis overcomes this shortfall and provides information on how much of the usable work potential is supplied and consumed.

Besides, the inefficiencies with energy use, the local rice processing also suffers from poor quality output as a result of drying. Steam paddy usually has moisture content of more than 40% (Araullo et al., 1985) and requires drying to a lower moisture content for storage which is usually achieved by sun drying. In this process, paddy is spread on a flat surface usually on the floor or on tarpaulins and solar energy is absorbed to dry the grain. This process reduces the quality of rice due to the introduction of foreign material such as stones and dirt. It is also dependent on the weather conditions, applicable only during the day and also requires large drying space and time.

This study is an attempt to improve energy use and rice quality through the development of an integrated system which replaces wood use with rice husk energy, employs a heat exchanger system for enhancing energy efficiency and uses the waste heat after steam production to heat up air for drying in a simplified Louisiana State University (LSU) recirculating dryer. The objectives of this paper are to evaluate the performances of steam and hot air generators thermodynamically and examine the sensitivity of the operating conditions and their influence on efficiency.

6.2 Materials and methods

6.2.1 ISDS Description

The integrated steaming and drying system consist of a continuous rice husk combustor, double-fire tube heat exchangers, a 50 cm high conical chimney and a drying unit. The system components are described in detailed in this section. Steaming and drying as practiced in local rice processing is shown in Fig 6.1 along with the proposed improved system.

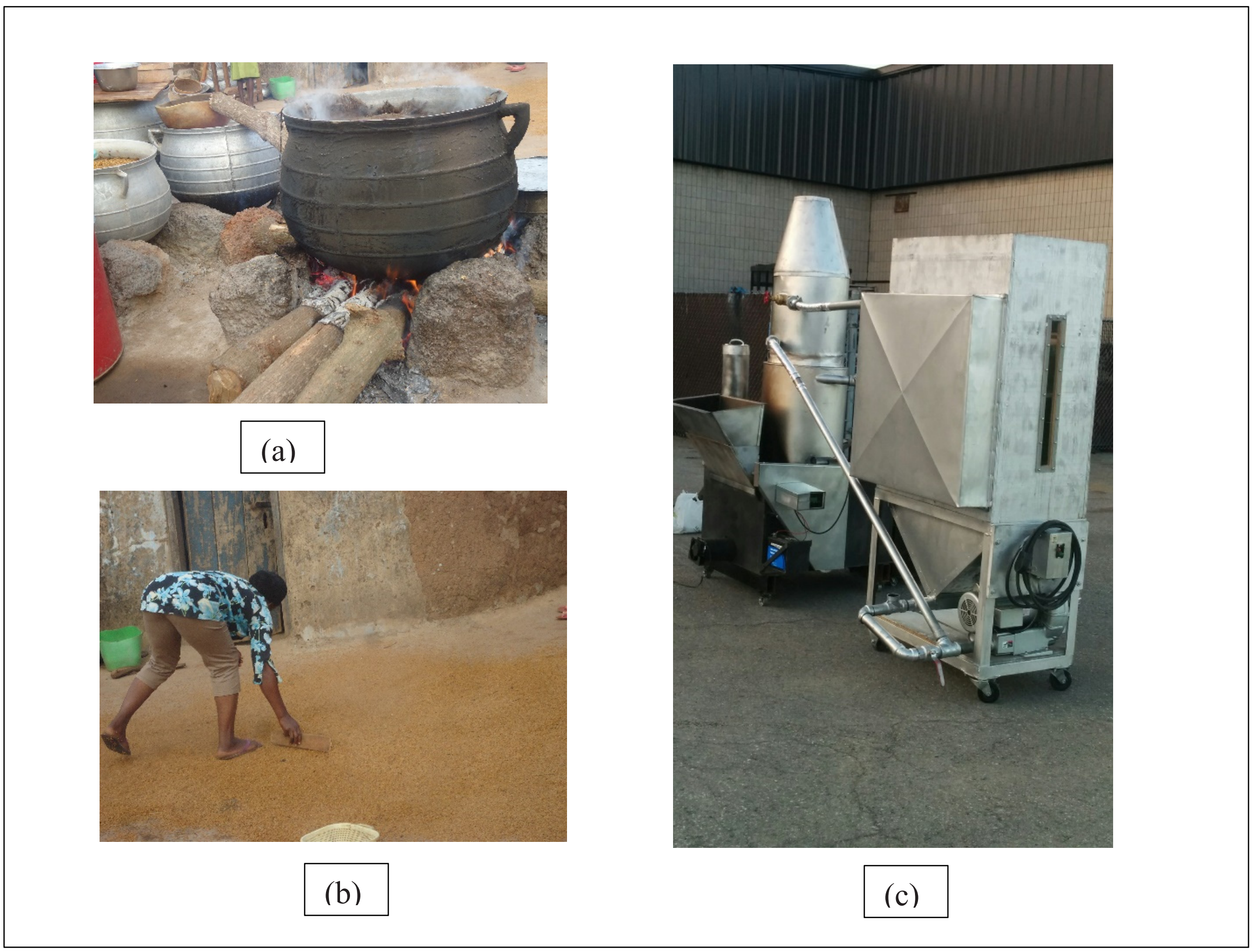


Figure 6.1: (a) Current paddy steaming method (b) current drying method and (c) proposed paddy steaming and drying system

6.2.1.1 Combustor unit

The combustor consists of a firebox (80 x 75 x 55 cm) made from 3/16 inch steel plate with a firebrick (23 x 11.4 x 6.4 cm) lining purchased from Materiaux Refractaires Direct – St-Leonard, QC Canada. The feed material is introduced into the combustor through a triangularly shaped 4.5

kg capacity feed hopper made with a gauge 24 steel sheet at the rear end. Combustion occurs on a 20 x 20 cm^2 perforated gauge 16 steel plate inclined at 45° (angle of repose experimentally found to be 40) and the ash generated is removed from the side of the combustor through a 60 cm long, 7.6 pitch, and 7.6 diameter auger. The front section of the combustor has a removable metal sheet that provides secondary air for rice husk combustion and serves as an opening for feeding with other feed material such as wood and briquette. A 25 W fan placed at the lower end of the feed hopper provides primary air. The air enters the combustor through a spout that also serve as the port for starting the fire. The upper part of the combustor is a 50 cm circular opening at the top where the heat exchanger fits. Detailed drawing of combustor is shown in appendix B.

6.2.1.2 Heat Exchanger (HE) unit

The proposed double-decker heat exchanger unit produces steam for paddy gelatinization and hot air for drying. The lower steam heat exchanger is described in detail in section . The hot air heat exchanger is also a firetube type with consists of a 9 standard 1 1/2 inch nominal tubes arranged to achieve a triangular pitch. The tubes are fitted into a 41 cm diameter shell 50cm high made of gauge 16 metal sheet. Engineering schematic of the heat exchangers have been provided in Appendix C. The heat exchangers were designed to achieve an average logarithmic mean temperature difference (LMTD) of 330.9 and 131.3 °C for the steam and hot air generator, respectively. This is based on the assumption that the overall heat transfer coefficient remains constant over the heat exchangers' flow length. The chosen design parameters ensure the steam generator delivers steam at 0.0045 kg/s to parboil 50 kg of paddy rice. The heat duty for the hot air generation was based on the energy required to dry 250 kg of paddy in a recirculating dryer, which was estimated to be 2.48 kJ/s. The two heat exchangers are removable which allows for easy cleaning and maintenance.

6.2.1.3 Drying unit

The drying unit was made of a wooden drying chamber with 21 V-shaped channels. The channels were arranged alternately to deliver inlet air at one level and outlet air in the next. Heated drying air from the hot air generator flows into a plenum with an aspect ratio of 0.76 prior to the drying chamber. The channels provide a column for downward movement of grain with an average thickness of 100 mm. Grains are collected at the bottom of the column through a hopper bolted at the lower end of the dryer. Recirculation is achieved through a pneumatic system. Cold air from the blower transport grains through a plastic pipe (38 mm ID) to the drying chamber.

6.2.2 Experimental setup

The two heat exchangers and the conical chimney were fitted together and tightly fixed on the combustor. Two initial test run were performed prior to the start of the study. Eight temperature measurement points indicating the temperature of ambient, water inlet, steam outlet, air input, air output, combustion hot products, flue gas point 1 (entrance of the air heat exchanger) and flue gas point 2 (in the chimney), were taken with K-type thermocouple wires (Omega, Laval, QC, Canada). Temperature readings were recorded every three seconds using a data logger (visual Hotmux V.3.1.0, DCC Corporation, US). The feed water flow rate was measured with a flowmeter (7520 series acrylic tube flowmeter, King instrument company, Garden Grove, CA, USA). Air input to the combustor and to the dryer were measured using digital airflow meter (model HHF92A, Omega, Laval, QC, Canada). The amount of steam generated was measured by condensing the generated steam (SEC Heat Exchangers, model PL-70, Belfast, Prince Edward Island, Canada) over a weighing scale (Setra, EL-2000S, Acton, MA, USA). The condenser had running water at 10 ºC to convert steam to liquid water. Steam pressure was recorded in inches of water using a glass U-tube manometer.

A surface response methodology using a Box-Behnken design type with three center points was used for the study. Three factors were used to study the steam and hot air characteristics, the systems' efficiency and their variation with operating parameters. Table 6.1 shows the factors considered for the experiment.

Table 6.1: Factors for experimental design

Factors	Name	Units	Low level	High Level
A	Fuel rate	g/s	2.0	3.5
B	Feed water rate	g/s	1.1	7.3
C	Air flowrate	g/s	16	82

The experiments were segregated into five blocks. The first three blocks were replicates of the experimental design. For each run, the rice husk is fed into the feed hopper, the fire started with pieces of paper, the fan switched on and the feed water flow rate set to the selected level. The process was monitored for the first drop of condensed steam to be noted and the time recorded as the minimum estimated time to produce steam. Steam production was continued for another 30 minutes (which was maximum steaming time practiced for local parboiling). In block four and five, the system was operated continuously for three and a half hours after the start of the steam production to ascertain the variation of systems performance over long operating hours. All the runs were performed by setting each run parameters for 13 minutes. The first 3 minutes were not used in the analysis because there were assumed to be the systems' normalization period. Flue gas analysis was carried out using a gas analyser (M700, Enerac, TM, Holbrook, NY, USA). The material flow in the system is shown in Fig 6.2

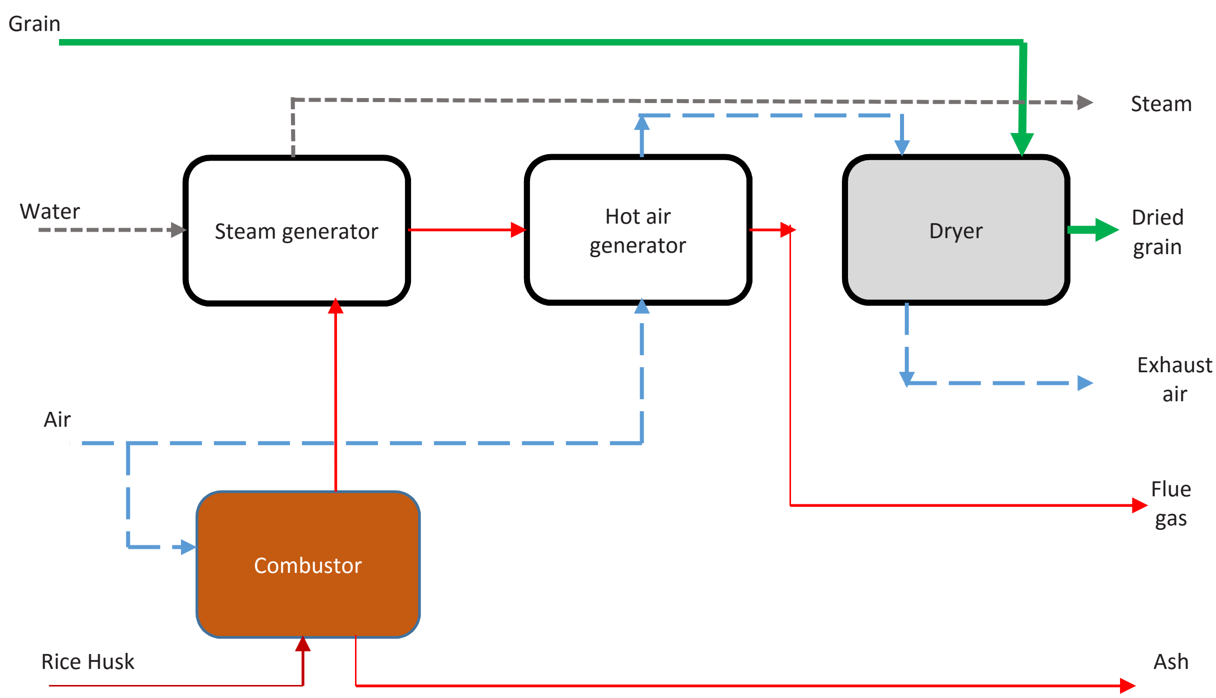


Figure 6.2: Material flow in the ISDS

6.2.3 Fuel supply

The rice husk used for all experiments was purchased from California, US. The moisture content of fuel was determined based on the ASABE Standard S3582.2 (ASABE, 2006) by drying for 24 hours at 104 °C in an oven (Fisher Scientific 750F, US). The proximate analysis of the fuel was determined according to the ASTM E1131 (ASTM, 2010), standard test method for compositional analysis by thermogravimetry. The ultimate analysis was determined using vario MACRO cube

CHNS Analyzer (Elemetar Americas Inc, Mt Laurel, NJ, USA). The higher heating value (HHV) was determined using 6400 automatic Isoperibol calorimeter (Parr Instruments, Moline, Illinois, USA).

6.2.4 Temperature assessment

One way to evaluate the performance of a heat exchanger is to determine the heat transfer effectiveness of each fluid stream. In this study, temperature assessment for both heat exchangers were evaluated by estimating the temperature efficiency and LMTD variation with time for each stream. The temperature efficiency was determined by comparing the temperature change in each fluid stream with the maximum achievable temperature difference between the two fluids of an exchanger of infinite size using the expression in Eq 6.1 and 6.2.

$$\textit{Temperature efficiency for hot fluid } \eta_h = \frac{T_{h,inlet} - T_{h,outlet}}{T_{h,inlet} - T_{c,inlet}} \times 100 \tag{6.1}$$

$$\textit{Temperature efficiency for cold fluid } \eta_c = \frac{T_{c,outlet} - T_{c,inlet}}{T_{h,inlet} - T_{c,inlet}} \times 100 \tag{6.2}$$

The temperature driving force for heat transfer was evaluated by calculating the LMTD variation with time using the co-current heat flow expression shown in Eq 6.3

$$\Delta T_{LMTD} = \frac{\Delta T_2 - \Delta T_1}{\ln \frac{\Delta T_2}{\Delta T_1}} \tag{6.3}$$

Where ΔT_1 and ΔT_2 represent the temperature difference at each end of the heat exchanger.

6.2.5 Energy Analysis

6.2.5.1 Energy assessment of combustor

The energy analysis of the combustor has been established by conducting material and energy balances on the combustor. The energy balance takes into account energy input from the fuel (rice husk), ash and the energy from the various fluid streams. Since the combustor is not well-insulated, radiation and convective heat losses to the surrounding air have also been considered. The combustor energy balance is shown in Fig 6.3 and is expressed as:

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \quad 6.4$$

$$\dot{Q} + \sum \dot{m}_{in} h_{in} = \dot{W} + \sum \dot{m}_{out} h_{out} \quad 6.5$$

Neglecting changes in kinetic and potential energies with any heat or work transfers, and considering the fact that rice husk ash constitutes more than 20%, the energy balance can be written as:

$$\dot{m}_f h_f + \dot{m}_a h_a = \dot{m}_p h_p + \dot{m}_{ash} h_{ash} + E_{RC} \quad 6.6$$

where, $\dot{m}_f$, $\dot{m}_a$, $\dot{m}_p$ and $\dot{m}_{ash}$ are the mass flow rate of fuel, air, combustion hot products and ash, respectively. h_f , h_p and h_{ash} are the corresponding specific enthalpies. h_f and h_{ash} are taken as the higher heating values of the fuel and ash, respectively. E_{RC} is the heat dissipated at the combustor surface.

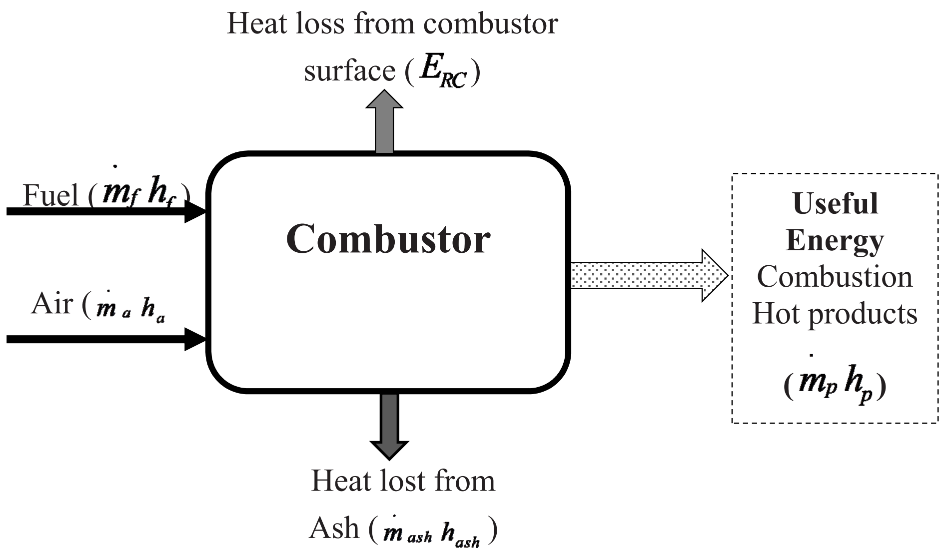


Figure 6.3: Energy balance of Combustor

$\dot{m}_f$ and $\dot{m}_{ash}$ were measured experimentally while $\dot{m}_a$ and $\dot{m}_p$ were determined using data from the ultimate and flue gas analysis. The mass of air was estimated from the theoretical air and excess air using Eq. 6.7 and 6.8.

$$m_a = \left[(2.9978 \cdot H\ w\%) - (0.3747 \cdot O\ wt\%) + C\ wt\%\right] \cdot (11.445 \cdot n) \qquad 6.7$$

$$n = 1 + \left(\frac{O_2\%}{21 - O_2\%}\right)\ \left[O_2\%\ \text{measured from flue gas analysis}\right] \qquad 6.8$$

The mass of combustion products m_p was estimated from a mass balance of the combustor according to Eq 6.9 and 6.10.

$$m_{in} = m_f + m_a = m_{out} = m_p + m_{ash} \qquad 6.9$$

$$m_{fg} = m_p = m_f + m_a - m_{ash}\ \ [kg/\text{s}] \qquad 6.10$$

The specific heat capacity was estimated based on a new approach proposed by Coskun et al. (2009).

$$C_{p,fg} = \frac{C_{p,C}}{(a_C + b_N + c_H + d_S)} . \frac{m_{a.steo}}{m_{fg}} + f_A \qquad 6.11$$

The model coefficients *a, b, c, d*, and *f* are estimated according to Coskun et al. (2009)

The heat loss from the combustion surface can be estimated from the losses through radiation and convection and expressed as:

$$E_{RC} = 0.548 \times \left[\left(\frac{T_s}{55.55}\right)^4 - \left(\frac{T_a}{55.55}\right)^4\right] + 1.957 \times (T_s - T_a)^{1.25} \times \sqrt{\frac{169.85V_m + 68.9}{68.9}} \qquad 6.12$$

The first law efficiency of the combustor was evaluated as the ratio of the useful energy from the combustor to the energy from the fuel as

$$\eta_C = \frac{\dot{m}_p h_p}{\dot{m}_f h_f} \times 100 \qquad 6.13$$

6.2.5.2 Energy and efficiency assessment of the steam generator

Heat loss from the system can be expressed in terms of the enthalpy change due to the heat transferred from the hot combustion products to the water to produce steam. An energy balance around the steam generator can be expressed as:

$$Q_{sg} = \dot{m}_{fg}\left(h_p - h_{fg1}\right) - \dot{m}_s\left(h_s - h_w\right) \quad 6.14$$

During rice parboiling, steam will not be condensed before usage, hence, no loss in steam quantity as observed during the experiment. Therefore, the steam and water flow rates are taken to be the same.

Steam generator efficiency is estimated as the ratio of heat transferred to produce steam to that given out by the combustion product and expressed as:

$$\eta_{sg} = \frac{m_s\left(h_s - h_w\right)}{\dot{m}_{fg}\left(h_p - h_{fg1}\right)} \quad 6.15$$

6.2.5.3 Energy and efficiency assessment of hot air generator

The heat transferred to the air was defined as the difference in enthalpy changes of the flue gas and air across the air heat exchanger. The heat dissipated and energy efficiency was estimated according to Eq 6.16 and 6.17

$$Q_{hag} = m_{fg}(h_{fg1} - h_{fg2}) - m_{d.a}(h_{h.a} - h_{c.a}) \quad 6.16$$

$$\eta_{hag} = \frac{m_{d.a}(h_{h.a} - h_{c.a})}{m_{fg}(h_{fg1} - h_{fg2})} \times 100 \quad 6.17$$

where, $m_{d.a}$, $h_{c.a}$, $h_{h.a}$ are the mass of drying air, specific enthalpies of the cold drying air and hot drying air, respectively.

6.2.5.4 Overall system energy efficiency

The overall energy efficiency of the unit is defined as the ratio of the energy supplied to heat water and air to the energy supplied by fuel (Eq 6.18)

$$\eta_{ISDU} = \frac{m_s\left(h_s - h_l\right) + m_{d.a}(h_{h.a} - h_{c.a})}{m_f h_f} \times 100 \qquad 6.18$$

6.2.6 Exergy Analysis

Energy balance or the first law of Thermodynamics and the concept of energy are not enough to identify and correctly quantify the inefficiencies of a system which is generally the occurrence of an irreversible process due to entropy generation. The concept of exergy is a thermodynamic standard for the assessment of the quality of energy and it is useful in identifying and quantifying the inefficiencies of a conversion process caused by reduction in the value of the energy and increase of losses.

6.2.6.1 Exergy ealculation

The general exergy balance can be written in the rate form as

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \sum \dot{E}x_{destroyed} \qquad 6.19$$

$$\sum \dot{m}_{in}\, \varepsilon_{in} - \sum \dot{m}_{out}\, \varepsilon_{out} = \sum \dot{E}x_{destroyed} \qquad 6.20$$

The determination of the exergy destroyed or irreversibility requires the estimation of specific exergies of all input and output streams which have been done using the following expressions:

- Specific exergy of fuel:

  The specific exergy of the fuel is estimated as:

  $$\varepsilon_f = LHV_f \times \varphi \qquad 6.21$$

  $$\varepsilon_f = LHV_f \times \begin{bmatrix} 1.0401 + 0.1728\frac{H}{C} + 0.0432\frac{O}{C} \\ +0.2169\frac{S}{C}\left(1 - 2.0628\frac{H}{C}\right) \end{bmatrix} \qquad 6.22$$

  Where, φ denotes the chemical exergy factor with all ratios taken from the ultimate analysis
- Specific Exergy of air, water and steam

  The exergy of air water and steam are evaluated with Eq 23-25 using enthalpy and entropy data from steam tables (Cengel & Boles, 2006)

$$\varepsilon_a = h_a - T_o s_a \quad 6.23$$

$$\varepsilon_w = h_w - T_o s_w \quad 6.24$$

$$\varepsilon_s = h_s - T_o s_s \quad 6.25$$

where, T_o is the ambient temperature.

- Specific Exergy of flue gas and hot combustion products
  The exergy of hot products and flue gas is estimated from the expression:

$$\varepsilon_p = C_{p,\mathrm{p}} \cdot \left[\left(T_p - T_o \right) - T_o \left(\ln \frac{T_p}{T_o} \right) \right] \quad 6.26$$

$$\varepsilon_{fg1} = C_{p,fg1} \cdot \left[\left(T_{fg1} - T_o \right) - T_o \left(\ln \frac{T_{fg1}}{T_o} \right) \right] \quad 6.27$$

$$\varepsilon_{fg2} = C_{p,fg2} \cdot \left[\left(T_{fg2} - T_o \right) - T_o \left(\ln \frac{T_{fg2}}{T_o} \right) \right] \quad 6.28$$

6.2.6.2 Exergy analysis of combustor

In the exergy analysis of the combustor, exergy destruction and exergy efficiency were evaluated according to Eq 6.29 and 6.30. The exergy destruction took into account the total exergy tot the combustor and the useful exergy from the hot combustion products.

- Exergy destruction in the combustor

$$I_C = \dot{m}_f \, \varepsilon_f + \dot{m}_a \, \varepsilon_a - \dot{m}_p \, \varepsilon_p \quad 6.29$$

- Exergy efficiency of the combustor

$$\psi_C = \frac{\dot{m}_p \, \varepsilon_p}{m_f \varepsilon_f} \quad 6.30$$

6.2.6.3 Exergy analysis of the steam generator

Exergy balance around the steam heat exchanger considered exergy of hot combustion products ($\dot{m}_p \varepsilon_p$), feed water ($\dot{m}_w \varepsilon_w$), steam ($\dot{m}_s \varepsilon_s$) and the flue gas leaving the steam heat exchanger ($\dot{m}_{fg1} \varepsilon_{fg1}$). The exergy destroyed was estimated as the difference between input exergies and output exergies. Here again, the mass of feed water and mass of steam was assumed to be same to simplify the estimation.

- Exergy destruction in the steam generator

$$I_{sg} = \dot{m}_p \varepsilon_p - \dot{m}_{fg1} \varepsilon_{fg1} + \dot{m}_w \varepsilon_w - \dot{m}_s \varepsilon_s \quad 6.31$$

$$I_{sg} = \dot{m}_{fg}\left(\varepsilon_p - \varepsilon_{fg1}\right) + \dot{m}_w\left(\varepsilon_w - \varepsilon_s\right) \quad 6.32$$

- Exergy efficiency in the steam generator

$$\psi_{sg} = \frac{\dot{m}_w\left(\varepsilon_w - \varepsilon_s\right)}{\dot{m}_{fg}\left(\varepsilon_p - \varepsilon_{fg1}\right)} \quad 6.33$$

6.2.6.4 Exergy analysis of the hot air generator

Similar to the steam generator, the hot air generator exergy analysis considered both input and output exergies and estimated the exergy destroyed and efficiency according to Eq 6.34 and 6.35.

- Exergy destruction in the hot air generator

$$I_{hag} = \dot{m}_{fg}\left(\varepsilon_{fg1} - \varepsilon_{fg2}\right) + \dot{m}_{d.a}\left(\varepsilon_{h.a} - \varepsilon_{c.a}\right) \quad 6.34$$

- Exergy efficiency of the hot air generator

$$\psi_{hag} = \frac{\dot{m}_{d.a}\left(\varepsilon_{h.a} - \varepsilon_{c.a}\right)}{\dot{m}_{fg}\left(\varepsilon_{fg1} - \varepsilon_{fg2}\right)} \quad 6.35$$

6.2.6.5 Overall system exergy efficiency

The overall system exergy efficiency was estimated as the ratio of the sum of the exergies used to generate steam and hot air to the exergy supplied by the fuel as shown in Eq 36.

$$\psi_{ISDU} = \frac{\dot{m}_w\left(\varepsilon_s - \varepsilon_l\right) + \dot{m}_{d.a}\left(\varepsilon_{h.a} - \varepsilon_{c.a}\right)}{\dot{m}_f\,\varepsilon_f} \times 100 \qquad 6.36$$

6.3 Results and Discussion

6.3.1 Steam and hot air characteristics

6.3.1.1 Temperature efficiency and LMTD variation with time

The temperature assessment of the integrated system is shown in Fig 6.4. The LMTD profile for the two heat exchangers is shown in Fig 6.4a. The average LMTD was estimated to be 344.6 and 128.9 ºC for the steam and hot air generators, respectively. The experimental LMTD for the steam generator was 4.14% more than the design value while that of the hot air was 1.53% below the design value, however, these differences were not statistically significant (p-value < 0.001). In Fig 6.4b, the average temperature efficiency of the hot combustion products, water, and air are reported as 72.9, 32.5 and 35.6%, respectively. This is an indication that, on the basis of temperature, the combustion products give out a substantial amount of energy before exiting the system inferring a possible high thermal efficiency. The chart (Fig 6.4b) also reveals dip points (about 5.2-9.8%) in temperature efficiency during the fuel addition period which occurred at 8, 16 and 24 minute. This is because during fuel addition fresh husk covers the flame hence the recorded temperature decreases, but the condition is restored when the fresh husk begins to burn. The addition of the air heat exchanger appears to have improved the temperature efficiency significantly, with a 40.4% rise in temperature efficiency. During the first 6 minutes of the process, temperature efficiency of water increases steadily at 8.18% per minute before reaching a steady condition of 40.1%. The maximum achievable temperature efficiency for steam production was 49.68%. Drying air followed a similar pattern of increasing 4.34% per minute for five minutes before establishing a temperature equilibrium resulting in an average of 34.4%. Although, temperature efficiency may differ from thermal efficiency, it provides an opportunity to predict the performance of the heat exchangers with a single parameter, temperature.

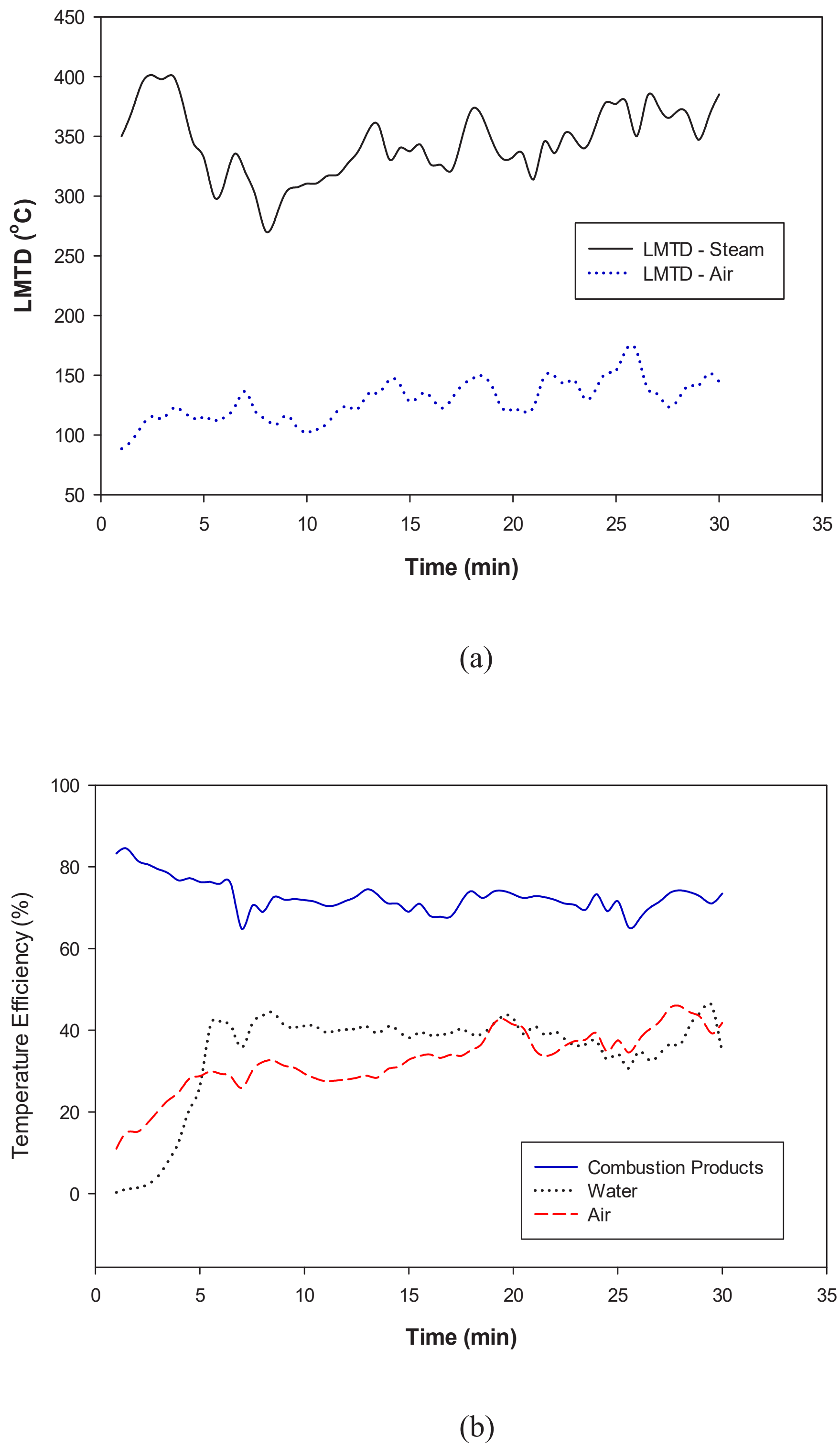


Figure 6.4: Temperature assessment of heat exchangers (a) LMTD variation with time (b) Temperature efficiency of fluid streams

6.3.1.2 Effect of feed water and fuel flow rate on steam production

Undoubtedly, steam production will be influenced by the fuel flow rate and the feed water rate but to what extent? As expected, higher fuel and water flow rate resulted in higher steam production and higher steam temperature as shown in Fig. 6.5. The results, however, reveals that the effect of water flow rate shows more prominence than fuel flow rate. For a given water flow rate, increasing fuel increases steam production marginally. For example, a 40% increase in fuel flow rate results in a 9.6% increase in steam production, however, a similar increase in water flow rate increases steam production by 32.1%. This may be due to the stationary grate used in this design. For a given fixed grate, the amount of rice fuel (rice husk) that could be combusted is limited to its size. Considering the grate area of 400 cm^2 and a maximum feed bed of 4 cm (based on the grate side plate) used, the optimum expected feed rate of 3.6 g/s was expected. As was observed during the experiment, feed rate above 2.8 g/s resulted in more unburnt rice husk in the ash indicating overfeeding of fuel. Based on these results, the recommended fuel feed rate for steam production is 2.8 g/s. Table 6.1 shows the steam production characteristics at the recommended fuel flow rate. At a lower feed water rate, higher steam to water ratio were achieved. The ratio reduced from 0.75 to 0.47 as the flow meter operates from 15% to full capacity. A 1:1 ratio was not achieved largely due to the steam measurement system employed (not all steam was condensed). It was observed that part of the steam were not condensed. The amount of water in the shell of the steam heat exchanger determines the time steam would be produced. As expected, lower water feed rate resulted in shorter steam production time and higher steam temperature since the same amount of heat energy is supplied to a smaller amount of water. For every 28% increase in water flow rate, the steam production time increased by an average 33%; although the increase decreased gradually from 38.9 - 28.4% at full capacity. Even though steaming time may not be relevant for the continuous operation of this system, it does suggest that the system can be started at a lower feed water rate and then increased during operation. The decrease in the average steam temperature observed (Table 6.2) is due to the inverse relation between mass and temperature difference for heat transfer systems. Hence, the increased mass flow rate of water accounts for the observed decease in steam temperature. Again, from basic thermodynamics, this decrease in temperature was in sync with the observed steam pressure which also showed a downward trend due to the direct relationship between temperature and pressure.

Table 6.2: Steam generation parameters at fuel rate of 2.8 g/s

Water flow rate (g/s)	Time to produce steam (min)	Steam production rate (g/s)	Steam temperature (°C)	Steam pressure (inH_2O)
1.10	8.05	0.83	132	3.44
2.90	11.18	1.07	128	3.40
4.80	13.91	2.13	112	3.30
7.30	16.20	3.45	106	3.10

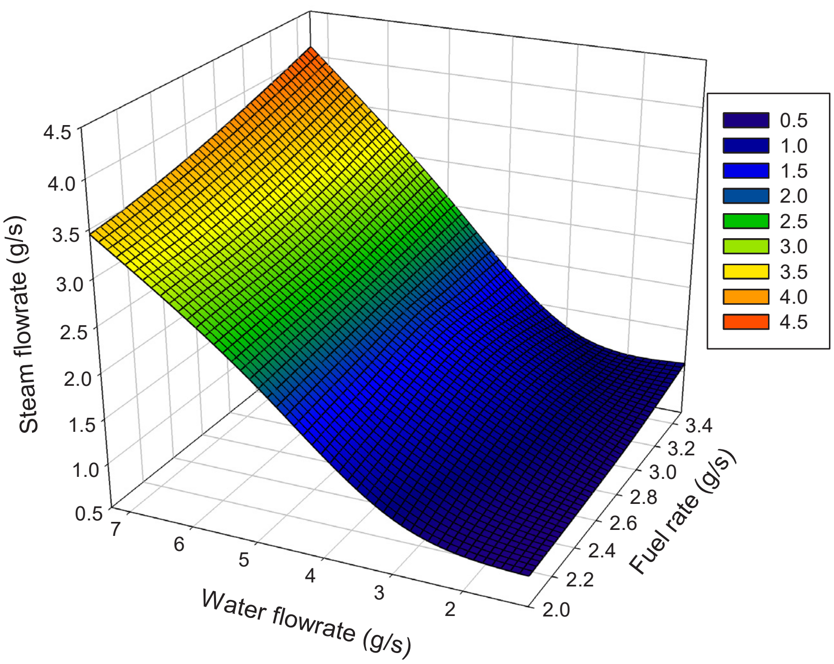


Figure 6.5: Effect of fuel and feed water flow rate on steam production

6.3.1.3 Correlation between steam and hot air production

Excess heat from flue gas was used for heating the hot air. Therefore, the extent of heat energy supplied to the air is dependent on the heat extracted for steam production. The heat transfer to drying air and its dependence on the steam production was assessed by the correlation between air temperature, steam flow rate (calibrated with water flow rate) and drying air flow rate. A multivariate correlation analysis performed indicates that there is a strong negative correlation (-

0.9156) between steam flow rate and drying air temperature. However, disregarding the influence of air flow using partial correlation significantly reduces the correlation coefficient (-0.3077). On the other hand, an initial negative correlation (-0.4385) between air flow and the temperature is increased (-0.750) when the effect of steam production is eliminated. Fig 6.6 shows a 3D plot illustrating the variation of air temperature with air and water flow rate. Higher drying air temperature was observed for lower air velocity and water flowrate; thus, for fuel rate of 2.8 g/s, water flow rate of 1.1 g/s (corresponding to a steam rate of 0.83 g/s) and an air velocity 3.1 m/s provide temperature readings above 100 °C. The plot also reveals that the effect of air flow on the temperature may not be as pronounced as water flow rate. This is seen in the marginal increase in temperature (<5°C) at higher water rate; although, up to 25°C can be achieved at water flow rate below 3 g/s. On the other hand, for higher air velocity, more than 12°C temperature difference may be achieved at a full range of the water flow rate. The difference is doubled for air velocity less than 6 m/s.

The implication of these results for rice processing would be that higher water and air flow rates would be required to achieve lower air temperature for paddy drying. It is also an indication that the air temperature could be regulated by air and water flow rate adjustments. This is so important because higher drying air temperature may intensify yellowness of milled rice and increase the hardness of cooked rice, decrease its water absorption capacity (Inprasit & Noomhorm, 2001) Operating the system to maintain lower air temperature will avoid severe cracking hence increase head rice yield since the temperature difference between the drying air and paddy will be lower than the 43°C threshold (Arora et al., 1973; Hashemi & Shimizu, 2008).

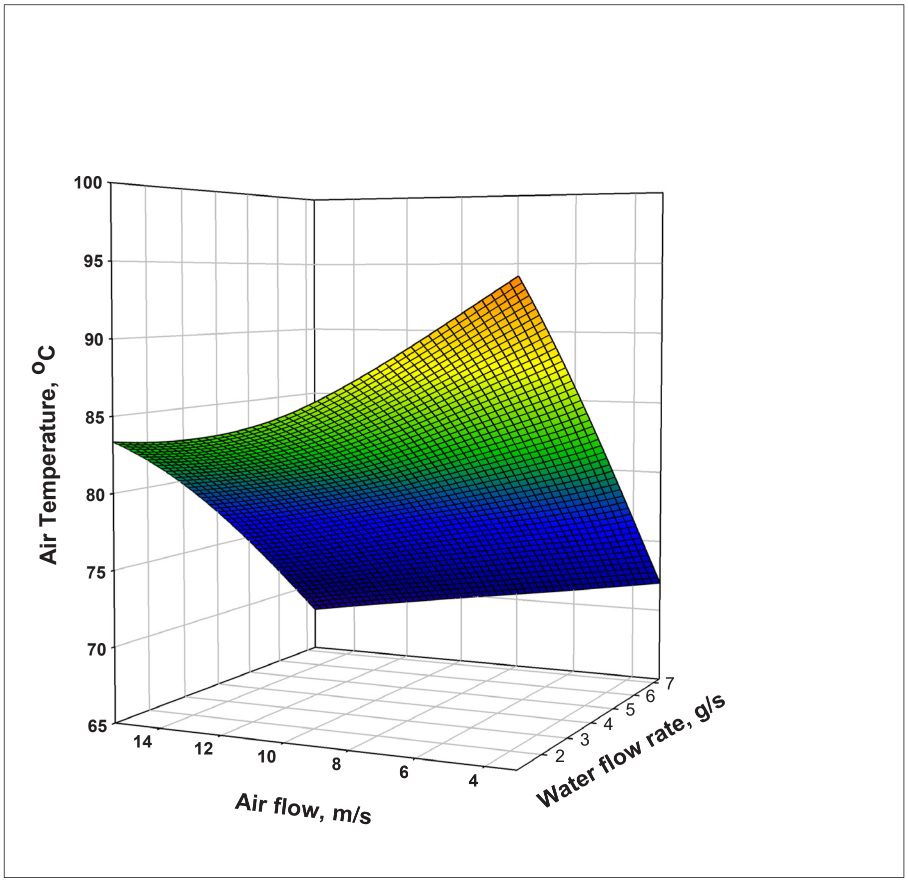


Figure 6.6: Effect of steam and air flow rate on hot air temperature

6.3.2 Energy and Exergy Analysis

6.3.2.1 Energy efficiency evaluation

The energy analysis of the combustor was done using fuel characteristics data and input parameters shown in Table 6.3 and 6.4, respectively. Rice husk feed rate of 2.8 g/s was used for the energy analysis reported in this section (3.2.1).

Table 6.3: Proximate and ultimate analysis of rice husk

Fuel	Proximate Analysis (wt%)			Ultimate Analysis (wt%)				HHV	LHV
	VM	FC	Ash	C	H	O	N	MJ/kg	MJ/kg
Rice Husk	61.24	18.04	20.72	39.30	5.69	35.33	0.401	14.99	14.41

Table 6.4: Input parameters

Substances	Mass flow rate (kg/s)	Average temperature (ºC)	Enthalpy (kJ/kg)	Entropy (kJ/kg)
Fuel	0.0028	753	15,760	-
Combustion air	0.0197	22.0	295.17	1.68515
Feed water	0.0073	20.5	85.92	0.2965
Drying air	0.0650	22.0	295.17	1.68515
steam	0.0073	118	2722.66	9.66629
Hot drying air	0.0650	68	350.49	1.85708
Combustion products	0.0218	354	-	-
Flue gas 1	0.0218	218	-	-
Flue gas 2	0.0218	167	-	-

Based on the assumption stated in section 2.5, 2.6 and the input data shown in Table 6.4, the energy analysis was estimated and displayed in a Sankey diagram (Fig 6.7). The total energy input supplied to the combustor was the sum of energy from fuel and air estimated to be 49.85 kJ/s. The heat losses through ash and the combustor walls were also evaluated. The results show that out of the 8.45 kJ of energy lost every second in the combustor, only 13.91% was as a result of the heat transferred through the combustor walls with the remaining through the ash. This is primarily because of the high percentage of ash generated in the process. About 19 ± 3.85 wt% of fuel was collected as ash for each run. Again, the insulation provided by the firebrick lining reduced significantly the heat lost to the combustor wall. For instance, whereas the flame temperature during combustion was recorded as more than 700 ºC, the combustor walls were barely more than 45 ºC. It must be noted that the data presented are the result of preheated stove, therefore, heat absorbed by the insulating firebrick lining is assumed to be negligible. A cold start experiment, however, shows a 2.87% reduction in combustion efficiency for a 30-minute run. Nonetheless, a 3-hour stove use makes this initial energy supplied to the insulating material insignificant (0.39% reduction in efficiency) compared to the total energy supplied to the stove. The steam generator accounts for 39.42 % of the overall energy loss of the system mainly due to the lack of insulation.

This result seems to suggest that the efficiency of the system can be improved by considering heat exchanger insulation which will also increase the safety of the system.

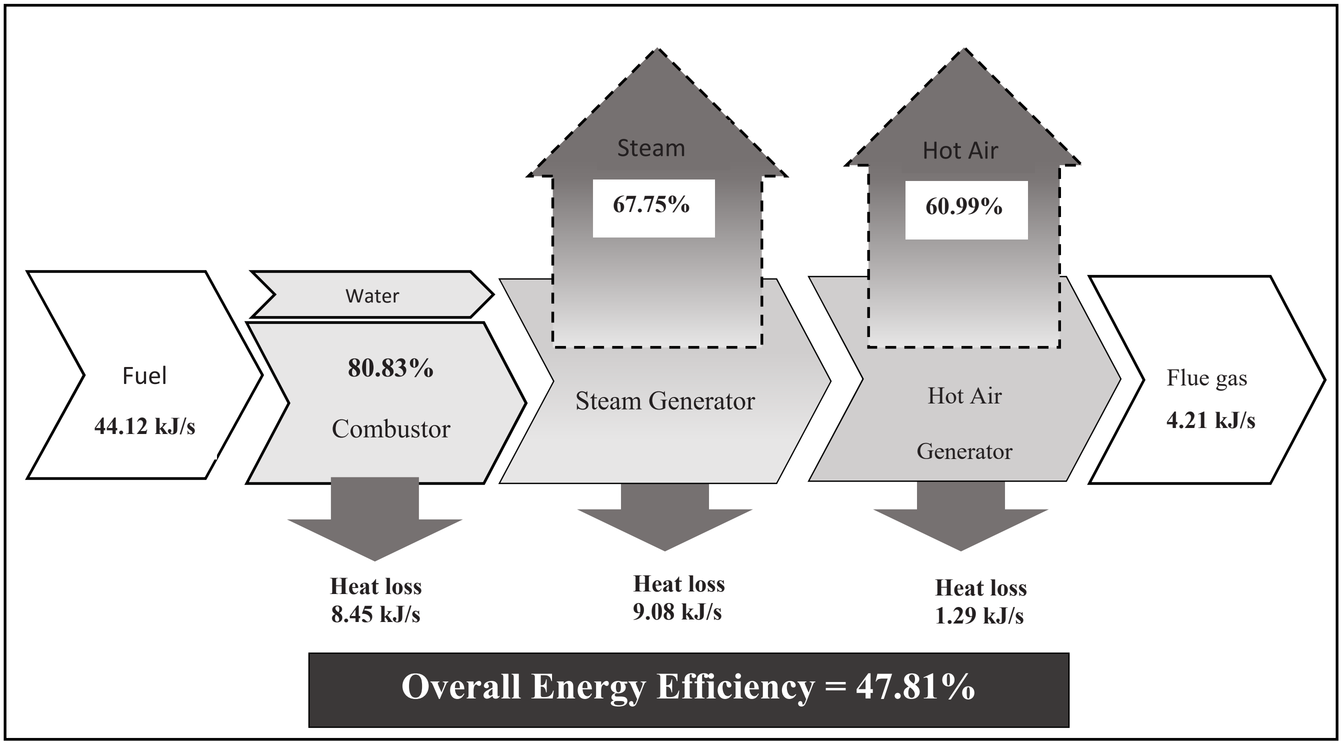


Figure 6.7: Sankey diagram for energy flow in the system

6.3.2.2 Effect of feed water flow rate on energy efficiency and heat loss

The efficiency of the steam generator and the overall energy efficiency are subject to change depending on the operating conditions of the system. High feed water flow rate means more heat is extracted from the hot combustion product. Fig 6.8 shows the variation of energy efficiency and steam generator heat loss with feed water. The maximum overall steam efficiency occurred at a feed rate of 7.3 and was found to be 47.8%. The result also reveals that steam efficiency varies from 8.45 – 67.75% for water flow rate of 1.1 to 9.2g/s, respectively. The results show that as the feed water rate increases, heat loss decreases and as expected, steam generator and overall efficiency of the system increase. However, beyond 7.3 g/s a reduction in both steam and overall efficiency was observed. For example, a 12.23% reduction in efficiency was noted for 25% of feed water increment. This can be attributed to the fact that increasing the water rate reduced both steam temperature and production rate because more energy and time is required to heat up all the water and produce steam for the same energy supplied from the combustor. Since steam generator efficiency is a function of steam enthalpy and mass, which have both been reduced, a reduction in efficiency can be anticipated.

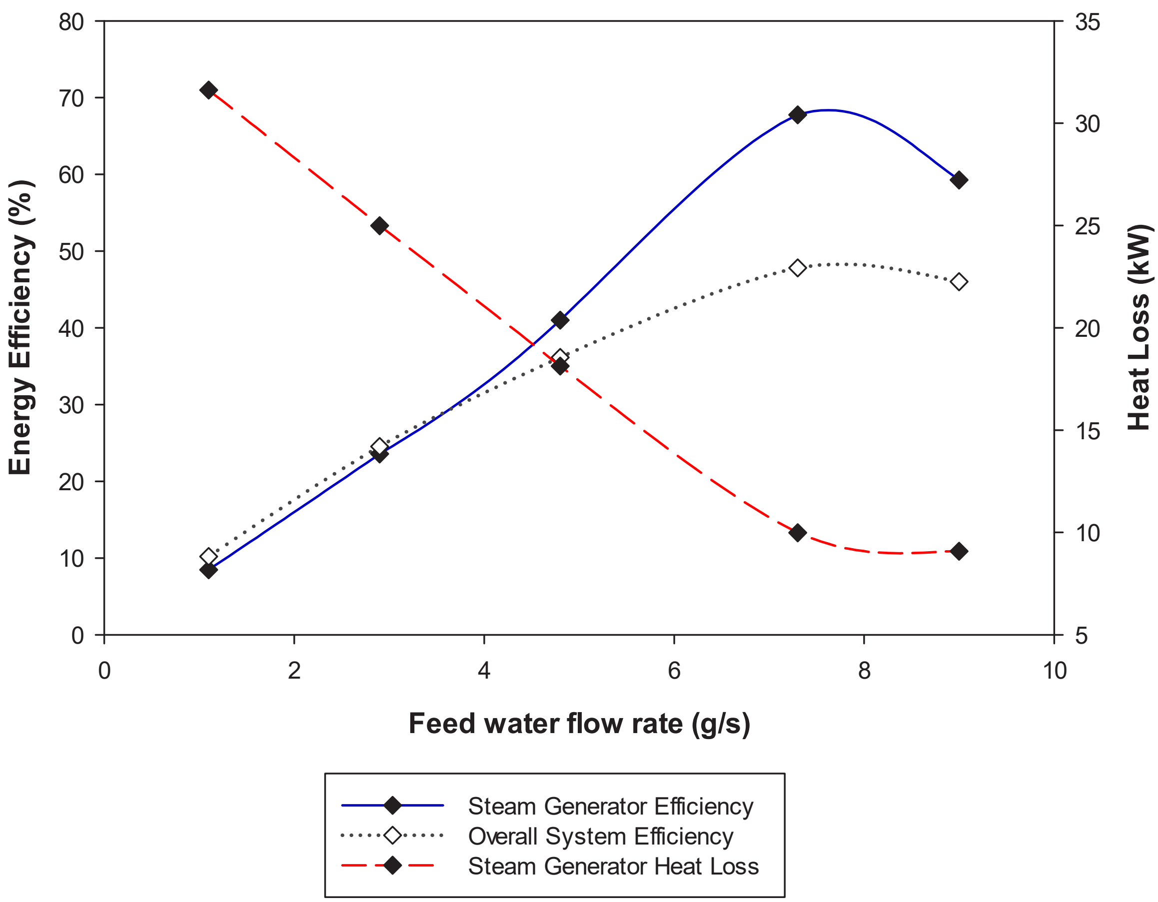


Figure 6.8: Energy efficiency and heat loss variation with feed water flow rate

6.3.2.3 Predicting steam production and energy efficiency

To predict the system's performance and predict steam production (since steam production was less than the feed water for all runs) and overall efficiency, multiple linear regression were established. The expression for steam production and energy efficiency are shown in Eq 6.37 and 6.38, respectively:

$$Steam\ production = -0.5093 + 0.4654 m_w + 0.2592 m_f \quad (6.37)$$

$$Efficiency = 4.8 + 5.90 m_w \quad 6.38$$

Where, m_w and m_f are the mass flowrate of feed water and fuel, respectively.

The steam production prediction equations explain 93% (adjusted R^2) of the variability with an RMSE of 0.3085 while the efficiency prediction has an adjusted R^2 of 97%. For the steam production prediction, a model with no interaction between the two input parameters was chosen over one that considered interaction because the latter reduced the adjusted R^2 by 0.4%, showed a higher p-value (although both were significant at 95% CI) and higher Akaike Information criterion (AIC) (46% higher).

6.3.2.4 Second law (exergy) efficiency evaluation

Exergy analysis of the system has been shown by a Grassman diagram in Fig 6.9. The overall exergy destroyed was found to be 20.48 kJ/s more than the energy loss. The combustor accounts for more than 60% of total exergy loss and 53% of the total exergy supplied by rice husk. Saidur et al. (2010) credited the high exergy destruction in combustor chambers of boilers to non-adiabatic nature of combustion systems and occurrence of incomplete combustion. Nishida et al. (2002) further explains that in combustion processes, the maximum loss of exergy occurred during the conversion of the chemical energy into heat energy due to the high production of entropy. Entropy generation during combustion is mainly due to four irreversible processes namely viscous dissipation, heat conduction, mass diffusion and chemical reaction (Hirschfelder et al., 1964). Unlike gaseous fuel, where the internal thermal energy exchange is the major contribution to the destruction of useful energy (Dunbar & Lior, 1990), the high irreversibility observed in this system may also be attributed to the high quantity of ash generated and its corresponding high chemical exergy which makes up more than 56 % and 34% of the exergy loss in the combustor and the system, respectively.

Considering the fact that reactant mixing and the temperature difference between input material (fuel and air) and flame (which was about 700ºC in this system), may be sources of exergy destruction, preheating may be an option for possible reduction. Patel and Ramana (2013) suggested that supplying air-fuel mixture at a maximum possible temperature and the use of a catalyst can reduce exergy loss in a combustion system and contribute towards improving first law efficiency. However, this may not be very applicable to the system under investigation bearing in mind the systems' simplicity and affordability would be the driving force for acceptance and usage of such local technology in a local rice producing community.

Another major source of exergy loss was the lack of insulation around the heat exchangers which collectively accounted for 26.76% of the total exergy destroyed. Additional wall around the heat exchangers filled with an insulating material such as rice husk ash could be a simple and low cost solution for insulation.

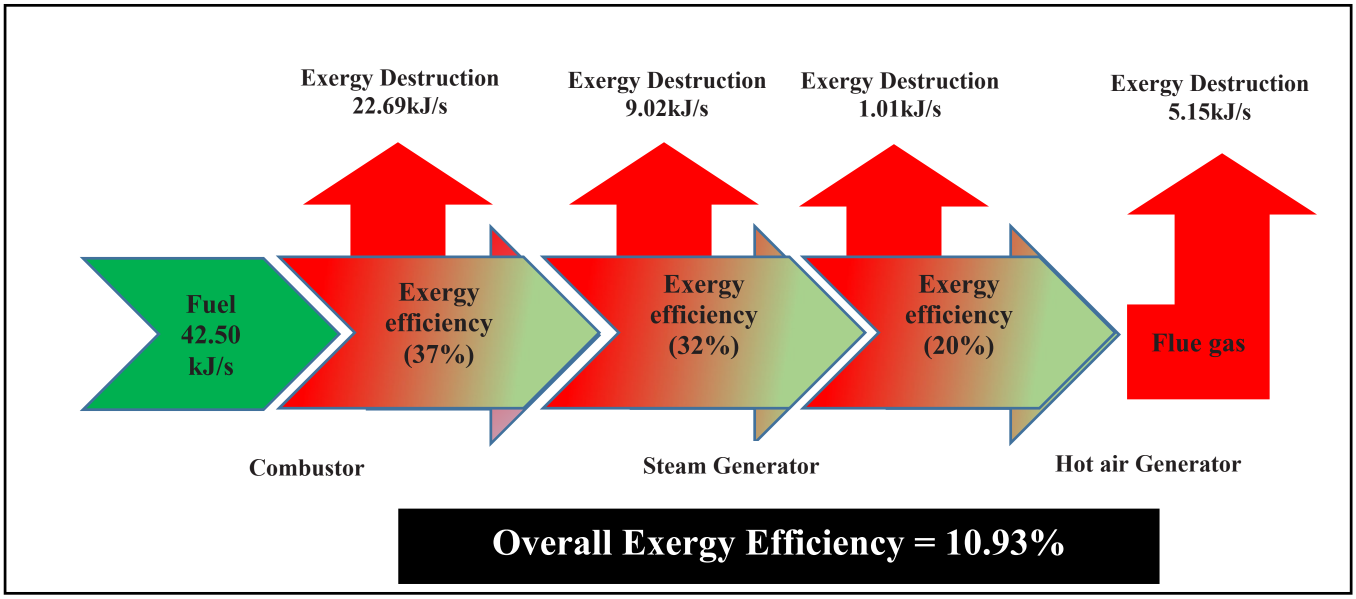


Figure 6.9: Grassman diagram for exergy flow in the system

6.3.2.5 Exergy efficiency variation with reference temperature

Exergy efficiency is a function of the reference temperature. Although, the temperature, T_o and pressure p_o of the environment are usually taken as standard state values, (298.15K and 1.013 bar, respectively), in this study, the reference temperature was taken as the average ambient temperature during the time of the experiment (295 k). The proposed system is intended to be used in West Africa, where the average ambient temperature is expected to be more than 303 K. Therefore, it was useful to investigate the variation of the exergy efficiency with reference temperature. Variation of exergy destruction and efficiency is shown in Fig 6.10. A 2.66 and 5.28 % decrease was observed in combustor and steam generator efficiency as the reference temperature increased from 293 to 310 K which resulted in an overall system efficiency reduction of 2.41% and a 0.8% increase in total exergy destruction. The results imply that the location of the system within the intended region will have no adverse effect on the overall efficiency as far as the reference temperature is concerned.

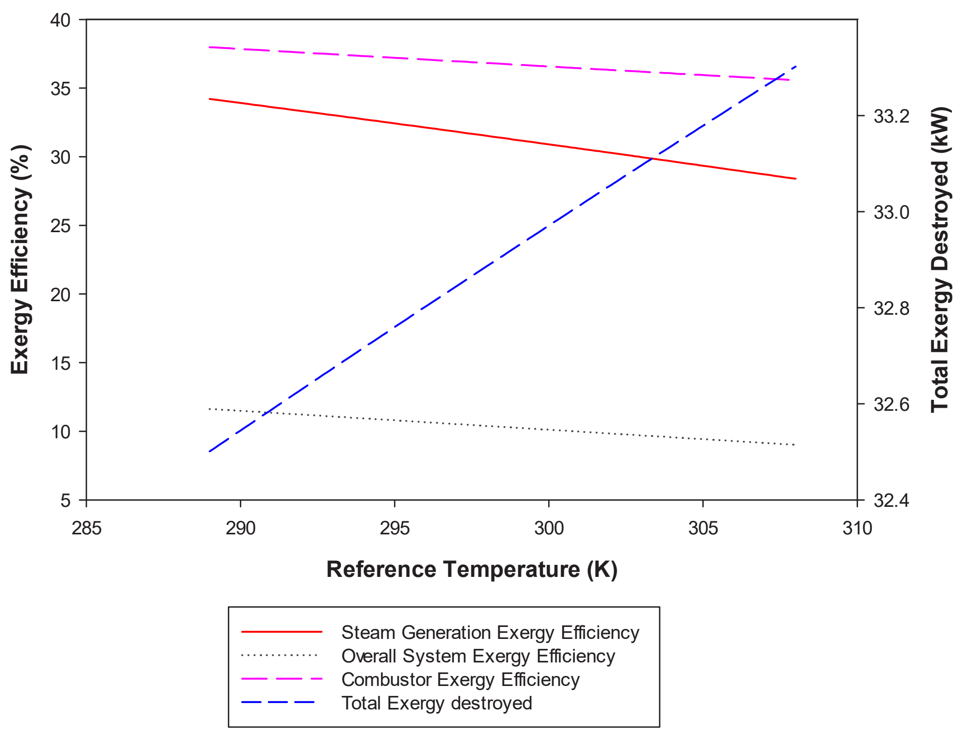


Figure 6.10: Variation of Exergy destruction and efficiency with reference temperature

6.3.3 Excel-based thermodynamic assessment framework for local parboiling systems

An excel-based thermodynamic assessment framework was developed for the evaluation of parboiling energy systems. The framework estimates energy consumption, energetic (1st law) efficiency, exergy destruction and exegetic (2nd law) efficiency of the combustor, steam production unit and the overall system. Depending on available input data, the energy efficiency and losses are estimated using either the direct method (based on steam and flue gas temperatures) or indirect method (based on proximate analysis of fuel).

The framework has three tabs namely general information, data input and results. In the general information tab, the user enters name of tester, date, text location and selects from a list of options the type of stove, fuel and parboiling systems. In the input tab, mass and temperature data are entered together with steaming duration. The user has an option of using default fuel ultimate and proximate values or enter measured fuel data. The default data is an average of at least five literature value of each selected fuel (seven fuel choicesss). The results tab provides graphical representation of the results. It presents a Sankey diagram for the energy analysis and a Grassman diagram for exergy assessment. Preview of the three tabs are shown in Fig 6.11-6.13.

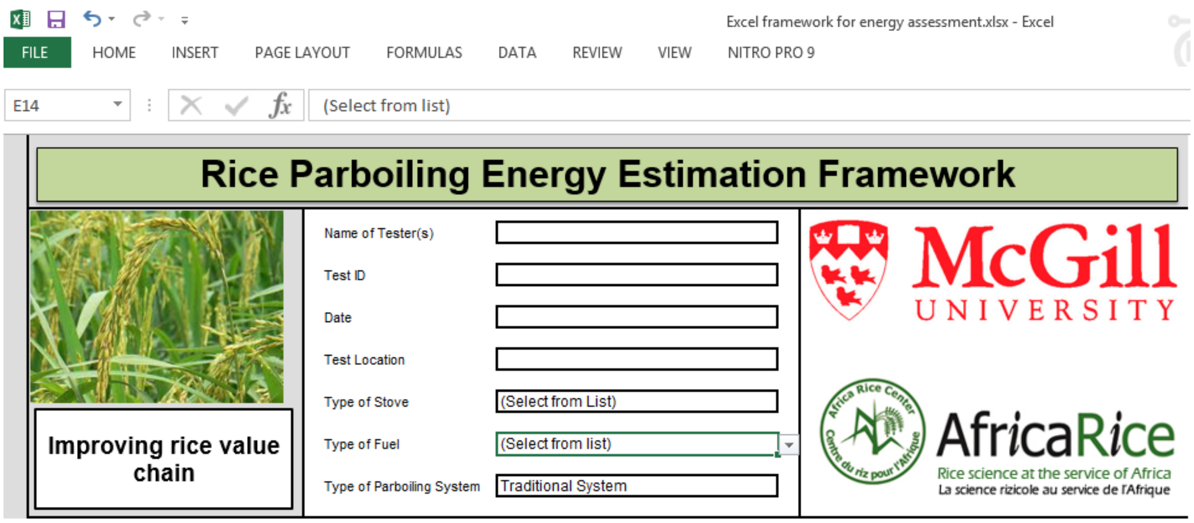


Figure 6.11: General information Tab of the rice parboiling energy estimation framework

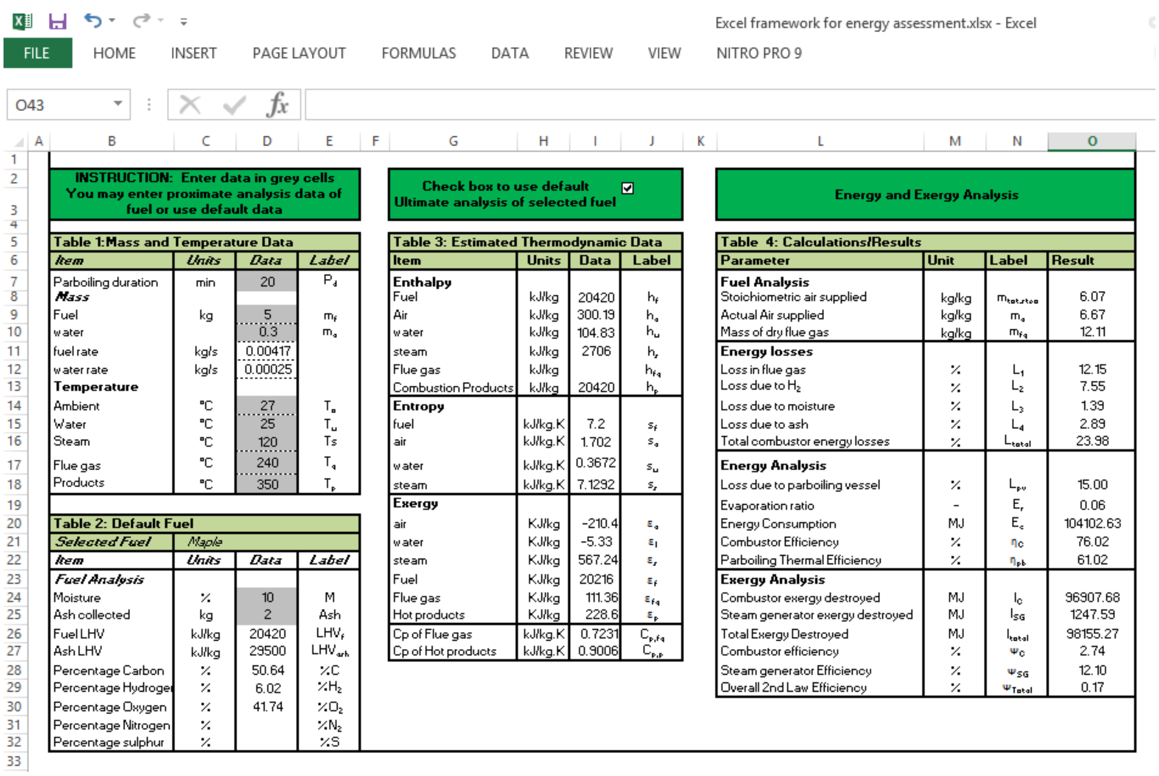


Table 1: Mass and Temperature Data			
Item	*Units*	*Data*	*Label*
Parboiling duration	min	20	P_d
Mass			
Fuel	kg	5	m_f
water		0.3	m_a
fuel rate	kg/s	0.00417	
water rate	kg/s	0.00025	
Temperature			
Ambient	°C	27	T_o
Water	°C	25	T_w
Steam	°C	120	Ts
Flue gas	°C	240	T_g
Products	°C	350	T_p

Table 2: Default Fuel			
Selected Fuel	*Maple*		
Item	*Units*	*Data*	*Label*
Fuel Analysis			
Moisture	%	10	M
Ash collected	kg	2	Ash
Fuel LHV	kJ/kg	20420	LHV_f
Ash LHV	kJ/kg	29500	LHV_{ash}
Percentage Carbon	%	50.64	%C
Percentage Hydroge	%	6.02	$\%H_2$
Percentage Oxygen	%	41.74	$\%O_2$
Percentage Nitrogen	%		$\%N_2$
Percentage sulphur	%		%S

Table 3: Estimated Thermodynamic Data			
Item	Units	Data	Label
Enthalpy			
Fuel	kJ/kg	20420	h_f
Air	kJ/kg	300.19	h_a
water	kJ/kg	104.83	h_w
steam	kJ/kg	2706	h_s
Flue gas	kJ/kg		h_{fg}
Combustion Products	kJ/kg	20420	h_p
Entropy			
fuel	kJ/kg.K	7.2	s_f
air	kJ/kg.K	1.702	s_a
water	kJ/kg.K	0.3672	s_w
steam	kJ/kg.K	7.1292	s_s
Exergy			
air	KJ/kg	-210.4	ε_a
water	KJ/kg	-5.33	ε_l
steam	KJ/kg	567.24	ε_s
Fuel	KJ/kg	20216	ε_f
Flue gas	KJ/kg	111.36	ε_{fg}
Hot products	KJ/kg	228.6	ε_p
Cp of Flue gas	kJ/kg.K	0.7231	$C_{p,fg}$
Cp of Hot products	kJ/kg.K	0.9006	$C_{p,p}$

Table 4: Calculations/Results			
Parameter	Unit	Label	Result
Fuel Analysis			
Stoichiometric air supplied	kg/kg	$m_{tot,stoa}$	6.07
Actual Air supplied	kg/kg	m_a	6.67
Mass of dry flue gas	kg/kg	m_{fg}	12.11
Energy losses			
Loss in flue gas	%	L_1	12.15
Loss due to H_2	%	L_2	7.55
Loss due to moisture	%	L_3	1.39
Loss due to ash	%	L_4	2.89
Total combustor energy losses	%	L_{total}	23.98
Energy Analysis			
Loss due to parboiling vessel	%	L_{pv}	15.00
Evaporation ratio	-	E_r	0.06
Energy Consumption	MJ	E_c	104102.63
Combustor Efficiency	%	η_c	76.02
Parboiling Thermal Efficiency	%	η_{pb}	61.02
Exergy Analysis			
Combustor exergy destroyed	MJ	I_c	96907.68
Steam generator exergy destroyed	MJ	I_{SG}	1247.59
Total Exergy Destroyed	MJ	I_{total}	98155.27
Combustor efficiency	%	ψ_c	2.74
Steam generator Efficiency	%	ψ_{SG}	12.10
Overall 2nd Law Efficiency	%	ψ_{Total}	0.17

Figure 6.12: Data Input Tab of the rice parboiling energy estimation framework

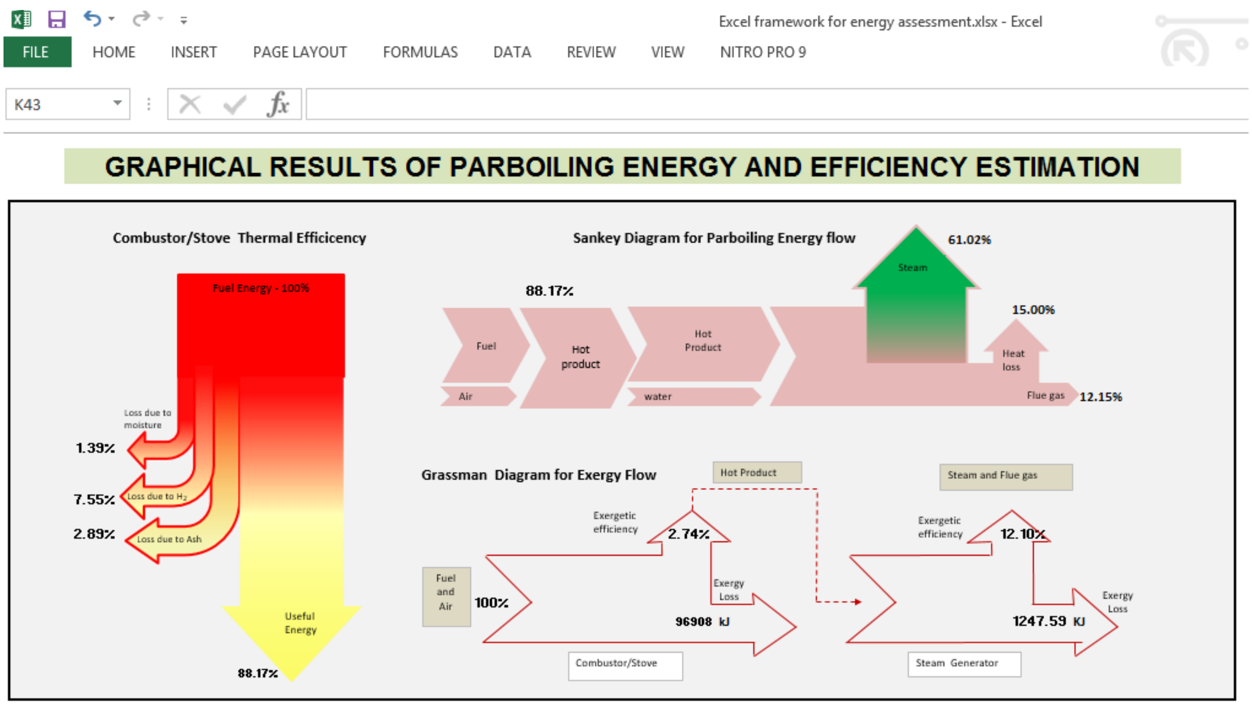


Figure 6.13: Result Tab of the rice parboiling energy estimation framework

As research improve rural energy utilization, the framework will provide the quickest route in determining the extent of improvement in energy use in rice processing. Visual Basic codes for the excel framework has been provided in appendix D. The framework is available upon request at michael.ngadi@mcgill.ca .

6.4 Conclusion

In this study, an integrated steaming and hot air generator was developed and evaluated thermodynamically. Experiments were performed to determine the steam and hot air characteristics and the energetic and exergetic efficiencies and heat losses. The results revealed that the heat exchangers were operated above the designed LMTD with temperature efficiencies of the hot combustion products, water, and air as 72.9, 32.5 and 35.6%, respectively. The experimental LMTD for the steam generator was 4.14% more than the design value while that of the hot air was 1.53% below the design value. A strong negative correlation (-0.9156) was observed between steam flow rate and drying air temperature. The maximum overall steam efficiency occurred at feed rate of 7.3 g/s and was found to be 47.8%. Maximum heat loss occurred during the steam production due to lack of insulation of the heat exchangers. On the other hand, exergy efficiency was found to 10.93%. The large amount of ash with its high chemical exergy added to the high anticipated exergy loss within the combustor which contributed to more than 60% of total exergy destroyed. The reference temperature did not significantly influence the second law efficiency of the system.

Connecting Text

Two thermochemical conversion systems were developed and evaluated in chapters 4 and 5. In Chapter 6, energy use improvement were made through waste heat recovery and energy losses and exergy destruction identification and estimation which would lead to further design improvement of the system. It has been obvious that the integrated steaming and drying system would improve overall energy efficiency of rural parboiling system tremendously, more than fourfold. The system with the use of rice husk is also expected to reduce emission substantially as indicated in chapters 3 and 5. However, to what extent will the reduction in combustion emission influence the overall environmental and human health of the parboilers?

In the next chapter, a life cycle analysis is conducted to determine the environmental and human health impact of the integrated steaming and drying system in comparison with the current practice of rural parboiling. The essence of this chapter is to quantify the environmental gain of the newly developed system and to provide stakeholders a more tangible reason to view the system a possible option for rural energy development.

Chapter 7 has been submitted for publication as:

- **Kwofie, E. M** and Ngadi, M. (2016). A comparative Lifecycle Assessment of Rural Parboiling System and an Integrated Steaming and Drying System fired with rice husk *Journal of Cleaner Production,* (revised version submited)

CHAPTER 7 A comparative life cycle assessment of rural parboiling system and an integrated steaming and drying system fired with rice husk

Abstract

The study presents a comparative life cycle assessment of the current rural rice parboiling system (RPS) used in Ghana and a newly developed integrated steaming and drying system (ISDS). With a functional unit of 1 tonne of paddy processed, the environmental impacts of the two systems have been evaluated. The environmental indicators considered were climate change, terrestrial acidification, particulate matter formation and photo-oxidant formation, which were applied through the ReCiPe version 1.08 evaluation method available in the GaBi 6 LCA software. The normalised environmental impacts were at least 68.2% higher in all impact categories. Overall, up to 80% reduction in total environmental impact can be achieved by replacing the existing process with ISDS. The sensitivity of the results have been examined using an alternative evaluation method, TRACI version 2.1, and a variation in rice husk availability.

7.1 Introduction

Rice has become a staple food for many individuals in Sub-Saharan Africa and its production at the rural level has huge implication for the livelihood of the many small-scale farmers (Kula & Dormon, 2009; Ministry of Food and Agriculture, 2009). There have been several national and international efforts to improve local production, although, they are geared towards cultivation (Kula & Dormon, 2009). Along the value chain, energy supply and use has always been a major challenge especially for the women who travel several kilometres in search for wood or purchase wood from wholesale wood vendors for the hydrothermal processing known as parboiling. The three-stage process has been found to improve the physical, chemical and nutritional value of the processed rice (da Fonseca et al., 2011; Luh & Mickus, 1991; Tolaba et al., 2006).

As the quest to provide food in a safe environment and concerns about natural resource depletion and environmental degradation increase, conscious efforts are required in developing systems which result not only in resource savings but also have the ability to minimize impact on health and wellbeing of those involved in it. In response to improving rice quality within the region, an integrated steaming and drying system powered with rice husk was developed. This system is expected to improve energy, minimize deforestation, reduce overall emissions and improve the health of the parboilers. However, to what extent will this anticipated environmental impact have been reduced?

Different assessment tools have been developed to analyse the environmental impacts of different product systems (Höjer et al., 2008). Life cycle assessment (LCA) is one of such internationally recognized tools used for controlling technical activity development and for assessing environmental performance of products and processes (Rousset et al., 2011). The standard life cycle assessment guidelines provided by the International Organization for Standardization (International Standard Organization (ISO), 2006) in the ISO 14040 and 14044 defines the LCA process as 'the compiling and evaluation of the inputs and outputs and the potential environmental impacts of a product system during a product life time'. It covers all stages in the life cycle of the product or process including raw material acquisition, manufacturing, use/reuse/maintenance as well as end of life (recycle/waste management) (Berg & Lindholm, 2005; EPA, 2006).

Life cycle analyses have been employed in evaluating the environmental impact of different aspects of the rice value change by several authors. For instance, Wang et al. (2010) reported on the environmental impact of the rice value chain from seedling to milling, but excluded parboiling from the system boundary; Roy et al. (2009) reported the Life cycle inventory (LCI) of different forms of rice consumed in households in Japan; (Roy et al., 2007) used life cycle analysis to evaluate the challenges and choices of rice production. The authors discussed resource use, energy use, environmental emissions (CO_2 emissions) and solid waste (ash) production for parboiling in Bangladesh. There is no fully evaluated life cycle impact assessment report on local parboiling processes especially in sub Saharan Africa where wood is used as the energy source.

The objective of the study is to determine the environmental impacts of a newly developed integrated steaming and drying system and to compare the results with the impact of the current paddy parboiling system used in northern Ghana using Life Cycle Assessment (LCA).

7.2 Materials and Methods

7.2.1 Goal and scope of study

Rice parboiling is practiced in the West African Sub region using traditional methods and energy from wood. The husk generated during the milling process is treated as waste and disposed by open fire burning. In finding an alternative energy supply system, and ways to improve both energy use and product quality, an improved integrated parboiling system was developed. However, the extent of environmental improvement can be judged by comparing it with the system being used currently. The goal of this LCA is therefore to determine the life cycle environmental impact of the new integrated system in comparison with the current local parboiling system over selected impact categories using a functional unit of 1 tonne of paddy processed.

In this study, a cradle-to-grave approach was considered for each scenario to provide an overview of the entire rice processing process (soaking, steaming, drying and milling). The system boundaries therefore included system fabrication, system utilization and disposal of rice product (rice and husk). For each system boundary, all the input and output flows including energy resource, raw materials and waste have been considered. However, the emissions from the cultivation of paddy, milling system fabrication and disposal, rice marketing and consumption, were excluded from the assessment because it would be the same for both systems.

7.2.2 System description and boundaries

7.2.2.1 Rural parboiling system (RPS)

For the purpose of this study, the local parboiling process as practiced in Ghana has been used. Thermal energy for this process is supplied by wood combustion in a three-stone fire (TSF) system. The process occurs in a three-stage process namely soaking, steaming and drying. During the soaking process, cleaned paddy is poured into the soaking vessel containing hot water (75-80ºC) and covered. After about 20-22 hours, the soaked paddy is transferred to another pot containing hot water (80-85ºC). The steaming vessel is then covered with jute sack and placed on the TSF for 20-30 minutes. The steamed paddy is dried in the sun for 6-7 hours. The parboiling process is completed when a moisture content of about 14-15% is achieved.

The system boundary for the RPS is shown in Fig 7.1. It includes the wood transport and combustion process, all three stages of parboiling as well as milling. For wood transport only diesel consumption have been considered without emissions from diesel production. Rice husk generation and disposal are the only processes considered during milling. To enable consistency in the two systems, the sun drying process have also been considered.

7.2.2.2 Integrated steaming and drying unit

The multi-fuel system uses rice husk as primary fuel (but could use wood in the absence of rice husk) to generate hot water and steam for parboiling. It also uses the waste heat from the flue gas to heat air through a fire tube heat exchanger which is used to dry paddy in a simplified LSU recirculating dryer. The system boundary for the ISDS evaluation included the construction of the system (taking into account raw materials and energy input), fuel combustion (rice husk and wood), drying process (electrical energy for blower) and milling (product, by-products and energy). Fig 7.2 shows the system boundary for the ISDS.

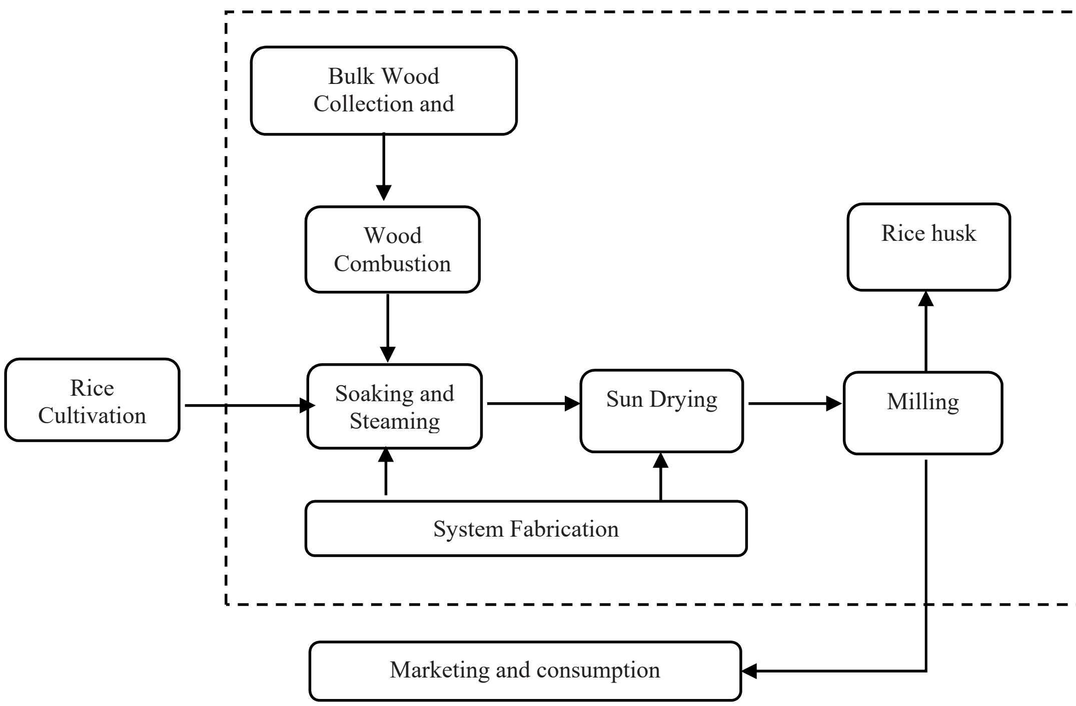


Figure 7.1: System boundary for Rural Parboiling System (RPS)

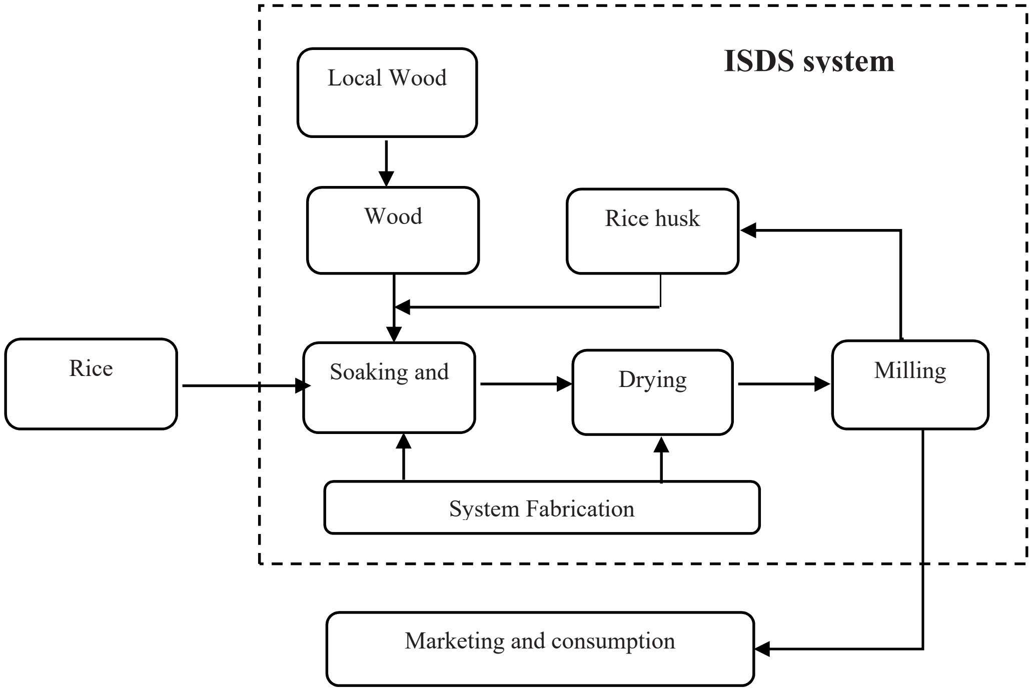


Figure 7.2: System boundary for Integrating Steaming and Drying System (ISDS)

7.2.3 Inventory data collection

7.2.3.1 RPS Data Collection

The inventory data on RPS were obtained from a study to assess local parboiling energy dynamics in Sishiagu, located in the new district of Sagnarigu in the Northern Region of Ghana (N9° 24.288' W0° 52.805') (Mainoo & Kwofie, 2014). The data covered the parboiling process, materials and equipment, energy supply and consumption, as well as rice husk availability and use.

In the RPS scenario, a tonne of paddy will be parboiled in 20 batches of 50 kg (average parboiling capacity within selected region) with 2680 MJ of thermal energy. The inventory includes data for stove construction, wood collection and transport, energy for soaking and steaming and solar energy for dying. The input materials for the RPS construction include stones, aluminium for the pot, jute sack, and concrete for the drying floor. The average water use for parboiling was estimated to 0.84 and 0.089 kg/kg of paddy for soaking and steaming, respectively. About 5±1.23% of ash is generated after wood combustion which is disposed of at backyard dumping sites.

Different types of wood are used in the RPS, hence, the five main types of wood used in the selected area, as shown in Table 7.1, have been used for the LCA. The average moisture content, density and heating value are estimated as 5.6%, 630 kg/m^3 and 18,932 kJ/kg, respectively (Brown, 1997; Dhillon et al., 2008; Günther et al., 2012; Venture Renewable Energy, 2012). The total wood consumption for parboiling a tonne of paddy with the RPS was estimated to 973 kg. Considering the fact that, local parboilers collect 35% of the wood from the surrounding forest (average round trip distance of 6.2 km) and buy the remaining from bulk wood vendors, only 633.1 kg have been associated with wood transport inventory. This amount corresponds to 15% of the total bulk wood transported per trip. The transport distance covered estimated was 116-212 km per trip (distances from processing centres to other districts). However, the trucks usually return empty hence an average round trip distance of 297 km was used. This was estimated from the average of three villages where most wood come from – 116, 118 and 212 km away from rice producing ommunities. Solar energy used for drying was taken as 556 MJ/tonne (Ahiduzzaman & Sadrul Islam, 2009). Data from the field measurement shows that an average 270 g of rice husk and bran are generated for every kilogram of paddy milled. A 5% usage of husk was assumed since some farmers use the husk as bedding for animals and another 5% was assumed lost. The total husk disposed by the open field burning was therefore taken as 243kg.

Table 7.1: Species and properties of wood used in RPS

Wood species	Other name	Wood Fraction (%)	Density Kg/m^3	HHV (MJ/kg)	Sources
Azadirachta indica	neem tree	28	690	18.09	(Brown, 1997; Dhillon et al., 2008)
Anacardium occidentale	cashew tree	24	-	18.90	(Venture Renewable Energy, 2012)
Tectona grandis	teak tree	20	500	20.30	(Brown, 1997; Günther et al., 2012)
Vitellaria paradoxa	shea tree	10	650	18.20	(Brown, 1997; Nhuchhen & Abdul Salam, 2012)
Irvingia gabonensis	Africa mango tree	18	520	19.17	(Biomass Energy Foundation, 2009; Dwarf Fortress, 2014; Nhuchhen & Abdul Salam, 2012)

Emissions from wood transport and combustion, and that from the open field burning of rice husk have been considered with the RPS. Emission from the combustion of wood were taken from other wood combustion studies in rural setting in other developing countries (Bhattacharya et al., 2002b;

Hays et al., 2002; Johnson et al., 2008; Mantananont et al., 2012; Wang et al., 2012a). Emissions from the wood transport was taken from the GaBi 6 database. Open field burning emissions used were the same as those used for the ISDS.

7.2.3.2 ISDS Data Collection

The inventory data for the integrated steaming and drying system was taken both from laboratory experimental result and literature. Carbon dioxide (CO_2) and carbon monoxide (CO) were measured using flue gas analyser (M700, Enerac TM, Holbrook, NY USA) during operation of the system. Methane (CH_4) and particulate matter (PM) emissions from rice husk combustion were taken from (Chungsangunsit et al., 2009; Wang et al., 2012a). Table 7.2 and 7.3 shows the life cycle inventory data used for the impact assessment. The thermal efficiency, lifespan and annual processing capacity of the system were taken as 47%, 10 years and 140 tonnes, respectively. The main raw materials input to the system fabrication were steel (283 kg), (black iron pipes (242 kg), plywood (87 kg), and firebricks (56kg). However, based on the chosen functional unit chosen, the raw material, energy input and emissions to the system fabrication was spread across the total processing capacity over the lifespan.

Table 7.2: LCI for parboiling using integrated steaming and drying system (per tonne of paddy)

Input/output	Unit	Value
Inputs		
Materials		
Paddy rice	kg	1.00E 03
Water	kg	9.56E 02
Energy		
Wood	kg	6.20E 01
Rice husk	kg	2.43E 02
Electricity	MJ	6.30E 01
Output		
Main pollutant		
Carbon dioxide	kg	3.36E 02
Carbon monoxide	kg	5.90E 00
Nitrogen dioxide	kg	6.39E-01
Methane	kg	1.94E 00
Dust (PM 2.5)	kg	1.94E 00
Ash particles	kg	4.92E 01

Sources: measured data, (Chungsangunsit et al., 2009; Wang et al., 2012a)

Table 7.3: LCI for parboiling using rural parboiling system (per tonne of paddy)

Input/output	Unit	Process		
		Wood transport[a]	Paddy Processing[b]	Rice husk Disposal[c]
Inputs				
Materials				
Paddy rice	kg	0.00E-00	1.00E 03	0.00E-00
Water	kg	0.00E-00	9.56E 02	0.00E-00
Energy				
Wood	kg	0.00E-00	9.73E 02	0.00E-00
Rice husk	kg	0.00E-00	0.00E-00	2.43E 02
Diesel	MJ	8.08E 00	0.00E-00	0.00E-00
Solar	MJ	0.00E-00	5.56E 02	0.00E-00
Electricity	MJ	0.00E-00	6.20E 00	0.00E-00
Outputs				
Main pollutant				
Carbon dioxide	kg	3.92E 01	1.23E 03	2.28E-02
Carbon monoxide	kg	6.21E-02	3.89E 01	2.43E-00
Nitrogen dioxide	kg	6.43E-03	9.3E 00	4.60E-02
Nitrous oxide	kg	2.63E-04	0.00E-00	0.00E-00
Sulphur dioxide	kg	2.47E-04	0.00E-00	0.00E-00
Ammonia	kg	2.05E-04	0.00E-00	0.00E-00
Group NMVOC	kg	1.07E-03	2.18E 01	0.00E-00
Benzene	kg	1.83E-05	0.00E-00	0.00E-00
Methane	kg	2.64E-04	2.63E 00	2.68E-02
Dust (PM 2.5)	kg	1.03E-03	3.79E 00	1.95E 00
Ash particles	kg	0.00E-00	4.87E 01	4.61E 01

Sources: [a] (PE International, 2015); [b](Ahiduzzaman & Sadrul Islam, 2009; Bhattacharya et al., 2002b; Johnson et al., 2008; Kwofie & Ngadi, 2016); [c] measured data, (Chungsangunsit et al., 2009; Wang et al., 2012a)

The ISDS is designed to use rice husk and where necessary augment rice husk usage with wood when there is shortage. It was assumed that all the rice husk disposed through the open field burning is available for use in the ISDS. Therefore, considering the efficiency of the system, an additional 62kg of wood will be required to meet the total parboiling energy demand (Ahiduzzaman & Sadrul Islam, 2009).

7.2.4 Quality and consistency of data

As indicated earlier, no emission measurement were made for RPS, hence, only published literature values were used. Unfortunately, the quality of these published data cannot be verified.

Additionally, the ISDS emission measurement were taken the laboratory scale which may differ in real use. Due to the unavailability of the process data from Ghana, most of the data used in this study (e.g. Diesel use in truck transport, material for fabrication etc.) were based on European unit process data which may vary widely and may not reflect the real situation in Ghana. The study did not include any data quality rating since the rating for some data were unknown.

For data consistency, process data for the different units were adapted to the same level of details to enable comparison among the two systems. For instance, it was assumed that fuel for both systems were available, therefore, cutting of wood and deforestation which could increase the impact of RPS were excluded in the inventory. Also in both systems biogenic carbon had been included in the evaluation. Again, for processes that were similar in both systems such as milling electricity consumption, their emissions were also excluded.

7.2.5 Life cycle impact assessment

The LCIA was conducted based on the inventory data collected for the two parboiling systems using the GaBi 6 software (PE International, 2015). Following the mandatory impact assessment elements provided by ISO 14044 (International Organization for Standardization, 2006) namely impact category selection, category indicators and characterization models, classification and characterization, four midpoint indicators were chosen for the assessment based on their relevance to the systems being studied. However, since the mandatory elements end at classification which gives indicator result for each category which makes comparison among impact category and interpretation difficult, an optional impact assessment elements provided ISO namely normalization (International Organization for Standardization, 2006) was chosen for further evaluation. Due to the difficulty in defining normalized factors specific to Ghana, normalised factors based on world population were used.

The potential impact to human health and environmental burden environment have been evaluated using the ReCiPe 2008 version 1.08 developed by the Netherlands (Goedkoop et al., 2012). The four midpoint impact categories selected include Climate Change, Terrestrial Acidification, Particulate Matter Formation and Photo-oxidant Formation (Goedkoop et al., 2009). The Recipe methodology provides three perspectives for environmental mechanism, therefore, Hierarchist (H) perspective whose models are based on consensus and the balance between short and long term perspective (Goedkoop et al., 2000) was chosen. It also uses a 100 year horizon for climate change which will allow comparison with other evaluating models during the sensitivity analysis.

7.3 Results and Discussion

7.3.1 Comparison of characterized results among parboiling systems

Table 7.4 presents characterized midpoint environmental impact assessment result for RPS and ISDS. As can be seen, environmental impact of RPS are generally higher in all categories, demonstrating a definite possibility of reducing the current health and environmental impact substantially with the use of ISDS. The midpoint indicators of selected impact categories are discussed below.

Table 7.4: Characterised LCIA results for parboiling systems (analysed by Recipe midpoint (H) V1.08/world Recipe H characterization)

Impact Categories	Unit	RPS	ISDS
Climate Change (CC)	kg CO2 Equiv	2029	298
Terrestial Acidification (TA)	kg SO2 eq	5.22	0.35
Particulate Matter Formation (PMF)	kg PM10 eq	6.09	1.93
Photochemical Oxidant Formation (POF)	kg NMVOC	11.92	0.88

7.3.1.1 Climate Change (CC)

The characterized result shows the Global Warming Index (GWI) (final sum of all GWP estimated) of RPS is 6.8 times more than of ISDS, indicating how severe the current process impact climate in comparison to ISDS. The wide variation in the GWI stems from the amount of biomass used in the process and the emissions. With the use of TSF stove with efficiency of 13-15% (Ayoub & Brunet, 1996; Berrueta et al., 2008) in the RPS, about 973 kg of wood would be used to parboil a tonne compared to 333 kg of biomass (87.1% rice husk and 12.9% wood) used in the ISDS. Again, according to the results from the emission test conducted on the ISDS system, for every kilogram of biomass combusted, wood releases 48.5% more CO_2 than rice husk. This is most likely due to the relatively high carbon content of carbon in wood (50.17%) compared to rice husk (37.66%). The use of rice husk in ISDS for local rice parboiling will not only eliminate the 229 kg CO_2-Equiv due to the open field burning but more importantly will reduce quantity of fuel use, therefore reducing the overall climate change impact by up to 85.3% (1731.13 kg CO_2-Equiv for every tonne of paddy processed).

7.3.1.2 Acidification Potential (AP)/Terrestrial Acidification

The characterised Terrestrial Acidification results shows a much higher environmental impact from the use of RPS - 14.9 times higher than the ISDS. From the inventory data used for the LCA shown in Table 7.2, SO_2 emissions have not been included for all combustion processes, therefore, the reported terrestrial acidification results are primarily due to NO_x emissions. In the case of RPS, NO_2 emissions accounted for 98.5% from wood combustion and the rest are as a result of NO emissions (1.42%) from wood transport. Similarly, results from the ISDS is largely due to the NO_2 emissions from the wood supplied to supplement the rice husk combustion. There a strong indication that the use of wood in the current process deposits relatively more atmospheric concentration of NO_3^- as a result of oxides of nitrogen. Although, these may not be significant due to the generally low (< 1%) fraction of nitrogen and sulphur in both wood and rice husk, their cumulative effects may lead to ecosystem changes, plant and animal death and also have corrosive effect on buildings (Bare, 2002) as leaching of H+ and nutrient cations increases in the water body acidity and reduce plant health. Considering the fact that these rural rice producing communities do not treat both drinking and parboiling water collected from dug wells and streams, changes in the alkalinity of water systems around the villages could be a source of damage to human health as they continue to burn large quantities of wood daily.

7.3.1.3 Particulate Matter Formation (PMF)

According to the results displayed in Table 7.3, current parboiling process emits more fine particulate matter (with diameter less than 10μm) than the ISDS. This result supports earlier claims from the other characterized impact categories that the health damage of parboilers can be minimized with the use of ISDS, in this case by up to 68.4%. This assertion can be explained by the assertion from some earlier studies (van Zelm et al., 2008) which indicates that the main causes of human health damage are primary fine particles less than 10μm in diameter (PM_{10}) and inorganic secondary PM_{10} aerosols produced by ammonia, NH3, nitrogen oxides (NO_x) and sulphur dioxide (SO_2). These particulate matter formation leads to several diseases leading to chronic mortality, acute mortality, acute respiratory morbidity and acute cardiovascular morbidity (van Zelm et al., 2008). Therefore with the observed reduction, PM associated diseases can be curtailed.

7.3.1.4 Photochemical Oxidant Formation POF)

POF results were no different from the other midpoint indicators. The results also shows that in the use of RPS, about 13.5 times more hydrocarbons are released into the environment compared to ISDS due to the amount of wood combusted and the open field burning of rice husk. The photo oxidants may be detrimental to both human health and the natural environment and may be responsible for respiratory problems among local parboilers and damage to food crops (Haagen-Smith & Bradley, 1953). Bare (2002) explains that the interaction between sunlight and certain primary air pollutants such as Volatile Organic Compounds (VOC) and carbon monoxides (CO) in the presence of nitrogen oxides (NOx) leads to the formation of reactive chemical compound formation such as ozone which may be responsible for plant mortality as well as human morbidity and mortality.

7.3.2 Comparison of impact category among systems using normalised results

The normalised results of environmental impact are displayed in Fig 7.3. The normalised results present all impact categories in the same unit to enable comparison and to ascertain which category impacts the most. The normalised results expressed in person equivalent is the average global per capita environmental impact. Summing all normalised results reveals that, the overall influence of RPS on the environment is five time more than that of ISDS. This implies 80% of the existing total environmental impact can be eliminated by replacing the existing process with ISDS. A closer look at the individual category shows that particulate matter formation impacts the environment most contributing 39.0% and 65.9% of total normalized environmental impact of RSP and ISDS, respectively. Acidification, on the other hand had the least overall normalized impact account for 12.3% and 4.7% of total normalized impact of RSP and ISDS, respectively.

The world health organization (WHO) has recently published that more than 4.3 million premature deaths traceable to household air pollution from biomass use occur every year (WHO, 2014). Out of this recorded deaths, 26% originates from ischaemic heart disease, 22% from chronic obstructive pulmonary disease (COPD) and 6% lung cancer. A reduction in the particulate matter formation from daily household emissions through the use of improve systems such as the ISDS is very likely to improve parboilers' health and reduce the diseases and deaths.

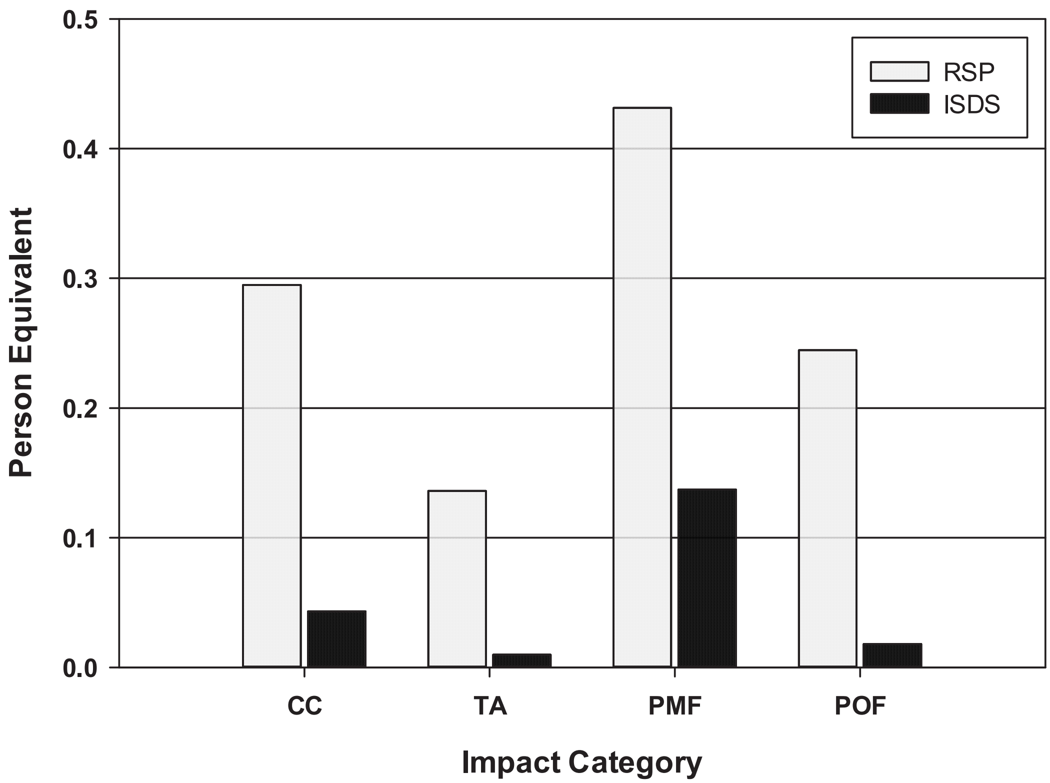


Figure 7.3: Normalized impacts of processing 1 tonne of paddy using different parboiling systems (Analysed by RECIPE Midpoint (H) V1.08/world Recipe H/normalization). CC = Climate Change; TA = Terrestrial Acidification; PMF = Particulate Matter Formation and POF = Photo-oxidant Formation

7.3.3 Process Contribution Analysis

The contribution of various processes to the environmental impact is shown in Fig 7.4 and 7.5 for RPS and ISDS, respectively. In terms of climate change, open field burning may be seen as a main environmental issue in the current process because of the heavy smoke release during the process, however, the results shows otherwise. The results indicate that open field burning contributes only 11.3% of the total climate change impact. More than 86.8% emanates from wood combustion while GHG emission released during the transport of wood contributes less than 2% to the total GWI. Even though wood use in ISDS constitutes only 12.9%, its emissions accounted for more than a third (38.0%) of the overall ISDS impact. This may be attributed to difference in CO_2 emissions. Although, there were carbon dioxide and nitrous oxide emissions from the system fabrication, they contributed less than 1% to global warming in both systems.

Wood combustion again contributes the greatest to the particulate matter formation in both systems. For photo-oxidant formation and Terrestrial acidification, wood combustion contributed more than 99% in RSP and more than 85% in ISDS.

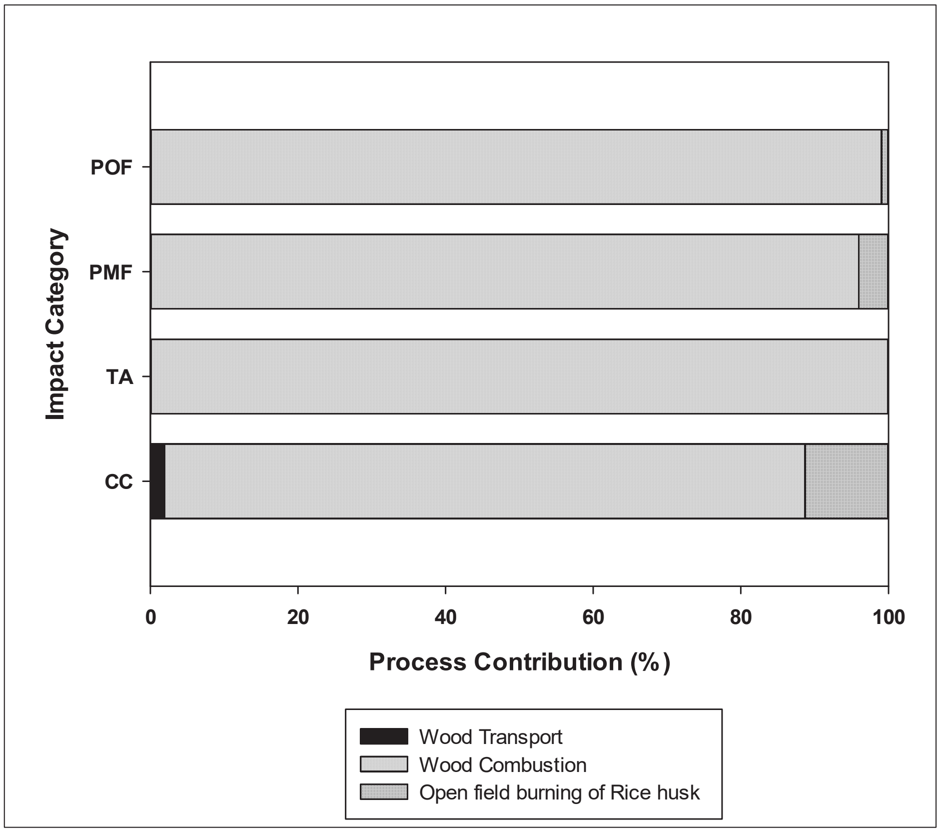


Figure 7.4: Process contribution to environmental impact in RPS
Based on RECIPE Midpoint (H) V1.08/world Recipe H/normalization results. CC = Climate Change; TA = Terrestrial Acidification; PMF = Particulate Matter Formation and POF = Photo-oxidant Formation

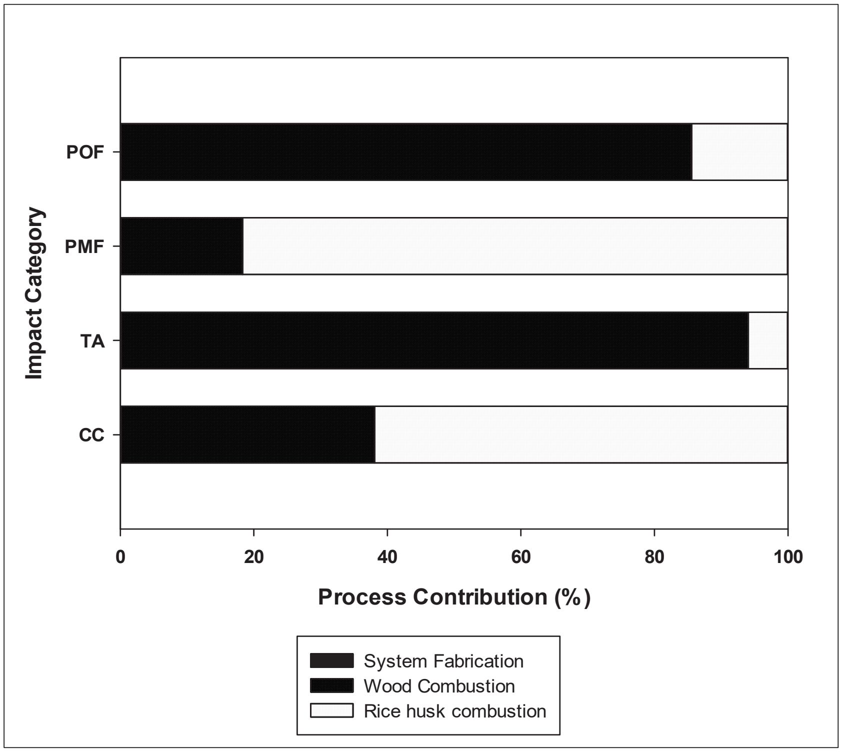


Figure 7.5: Process contribution to environmental impact in ISDS
(Analysed by RECIPE Midpoint (H) V1.08/world Recipe H/normalization results. CC = Climate Change; TA = Terrestrial Acidification; PMF = Particulate Matter Formation and POF = Photo-oxidant Formation

7.3.4 Consistency Analysis

The data used for the study were from different sources – measured experimental data, surveys, literature, and LCI databases which can result in inconsistency in the final LCA result. To ensure a consistency of processes and emission data with the assessment method, the consistency check within the GaBi 6 software was used. This function reports all raw materials and substances that have not been accounted for in the results so that where inconsistency exits they can be corrected or adapted to the data which have been accounted for.

7.3.5 Sensitivity Analysis

7.3.5.1 Impact Assessment Method

The sensitivity of the results obtained from the LCA was evaluated by analysing the LCIA with another method and comparing the characterised results with the RECIPE evaluation method used (Prasara-A, 2009). The chosen evaluation method for the sensitivity analysis was LCIA-TRACI (Bare, 2002) version 2.1 developed by the EPA in USA. TRACI is based on US data thus, providing a different environmental setting for comparison. The chosen method was consistent with the ReCiPe to allow for comparison. For example, the TRACI method uses a 100 year horizon for climate change which is consistent with the hierarchist (H) perspective used in the Recipe, which also uses similar time frame.

Table 7.5: Characterised midpoint LCIA results for different parboiling systems based on the TRACI method

Impact Category	Unit	RPS	ISDS
Global warming potential (GWP)	kg CO_2 - Equiv	2028.6	297.47
Acidification Potential (AP)	H+moles-Equiv	377.6	25.24
Human Health Criteria	kg PM 10-Equiv	6.7	2.85E-04
Smog	kg O_3-Equiv	162.4	0.12

The Characterized midpoint results shown in Table 7.5 indicates that the impact categories are comparable but are given different names. For example, the impact on climate are referred to as Climate Change CC in ReCiPe whereas in TRACI it is known as Global Warming Potential (GWP). The GWP/CC results are similar for both methods as shown in Table 7.3 and 7.4. This is because both evaluation methods use the same midpoint metric proposed by the International Panel on Climate Change (IPCC) for estimating the strength of GHGs relative to CO_2 (IPCC, 2007) using IPCC's proposed the 100-year time horizon. Hence, the same characterised environmental impact is recorded.

Besides the different impact category names, the units also differ giving rise to different results. For instance, Acidification is assessed differently in both evaluation methods with different results. However, in both cases, RPS was found to be 14.9 times higher than that of the ISDS. In the TRACI evaluation method, the acidification potential is expressed in H+ mole equivalent deposition. Thus, the acidification model in TRACI estimates the total terrestrial deposition of expected H^+ equivalents due to atmospheric emissions of NO_x and SO_2 within the North America as a function of the emissions location using results of an empirically calibrated atmospheric chemistry and transport model. In this estimation the N expressed as NO_3^- deposition is converted to moles of H+ equivalents per kilogram by a factor of 71.4 g or moles. In the ReCiPe method, a fate factor, accounting for the environmental persistence of an acidifying substance is used at the midpoint level and is based on an European scale forest ecosystem (Goedkoop et al., 2009).

The normalized results shown in Fig 7.6 however, displays a wide variation in the two methods although the same unit (person equivalent) is used. The difference in obtained results is primarily due to the different normalization factors which are based on world population in Recipe and US population in TRACI.

Another obvious difference seen is that whereas particulate matter shows the greatest impact in the ReCiPe evaluation method, Smog air appears to impacts the environment most in the TRACI method.

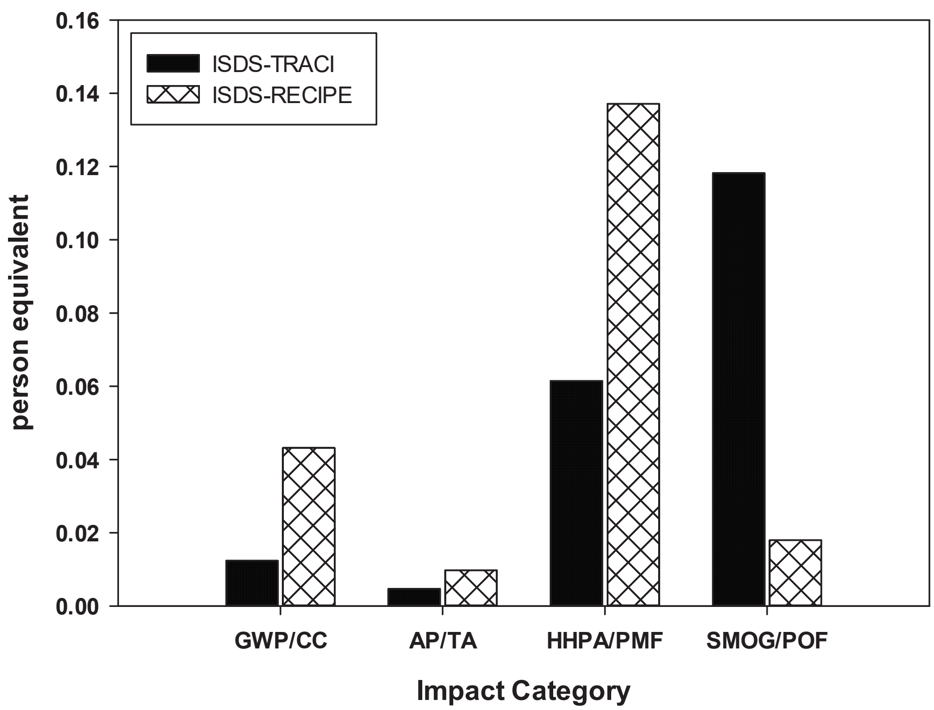


Figure 7.6: Normalized impacts of processing 1 tonne of paddy using ISDS
(Analysed by TRACI 2.1, USA 2008, including biogenic carbon/normalization; and RECIPE Midpoint (H) V1.08/world Recipe H/normalization). GWP/CC = Global Warming potential/Climate Change; AP/TA = Acidification Potential/Terrestrial Acidification; HHPM/PMF = Human Health Particulate Air/Particulate Matter Formation and SMOG/POF = Smog Air/Photo-oxidant Formation

7.3.5.2 Rice husk Availability

The sensitivity of the rice husk availability assumption have also been tested by evaluating the variation of rice husk on the environmental impact. In addition to the 90% availability used in the analysis, 70 and 50% rice husk use in the ISDS was tested. The normalized plot of the environmental impact is displayed in Fig 7.7. Terrestrial Acidification had the least change of 0.6

and 1.17% for 70 and 50% rice husk use, respectively. Photo-oxidant formation on the other hand recorded the greatest variation in the normalised results of 61.1 and 114% for 70 and 50% rice husk availability, respectively. Interestingly, there was a 13.97 and 26.99% decline in the normalised results of particulate matter formation for 70 and 50% rice husk. The observed downward trend can be explained by the fact that, there are more particulate matter emission for rice husk combustion than the wood combustion. Similar decline have been observed in other studies when the fraction of rice husk was decrease in a co-firing experiment with lignite (Mantananont et al., 2012) and bamboo (Chao et al., 2008). Overall, only 5.2% increase in normalised results was observed of a 20% reduction in rice husk use, thus rice husk availability seems not to influence the overall environmental impact greatly. This observed increment however, is only 18.94% of the total normalized emissions from the RPS.

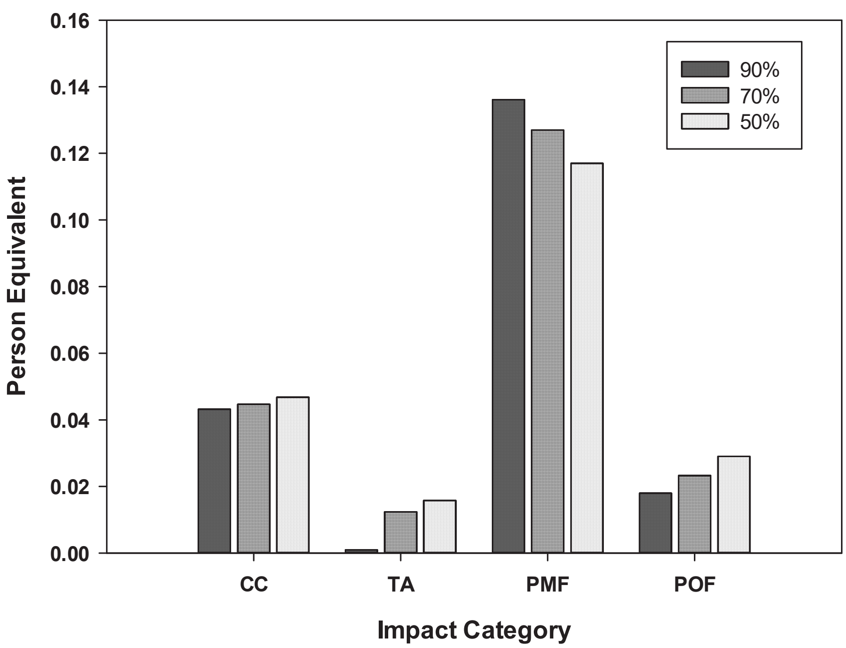


Figure 7.7: Normalized impacts of processing 1 tonne of paddy using ISDS varying rice husk availability (Analysed by RECIPE Midpoint (H) V1.08/world Recipe H/normalization). CC = Climate Change; TA = Terrestrial Acidification; PMF = Particulate Matter Formation and POF = Photo-oxidant Formation

7.4 Conclusion

In this study, a comparative life cycle assessment (LCA) of rural parboiling system (RPS) and an integrated steaming and drying system (ISDS) has been established. The goal of the LCA was to estimate environmental impact when processing a tonne of paddy using the two system. In the

RPS, wood transport, combustion and their associated emissions, as well as rice husk disposal were considered while emissions from system fabrication, fuel combustion (rice husk and wood), and drying process were considered for ISDS. Inventory data used for the LCIA were collection of measured experimental data, published literature, and GaBi databases. Characterised impact results indicate that the four midpoint impact categories - climate change, terrestrial acidification, particulate matter formation and photo-oxidant formation – chosen were 6.8, 14.9, 3.2 and 13.5 times higher for RPS than ISDS. The overall normalized results shows that the overall influence of RPS on the environment is five time more than that of ISDS implying about 80% of the existing total environmental impact can be eliminated by replacing the existing process with ISDS. Process contribution evaluation shows wood combustion was the primary emission contributor for the RPS accounting for 86.8% of total normalised emissions. The sensitivity of the LCA results were tested using an alternative evaluation method and the variation in rice husk availability. The results indicated that the choice of evaluation method matters in LCA results since different normalization factors and midpoint indicators are used for different LCA evaluation methods. The variation in rice husk availability did not influence overall normalized emission as only 5.2% increment in impact was observed for a 20% reduction in rice husk use.

Connecting Text

In chapter 7, environmental gain from the use of the integrated steaming and drying system (ISDS) were established. Characterized and normalized impact category indicators namely climate change, terrestrial acidification, particulate matter formation and photo-oxidant formation were used to quantify environmental impact. The results have indicated that up to 80% of environmental impact and effect on human health can be minimized with the use of ISDS.

Having established the potential energy efficiency improvements (chapter 4, 5 and 6) and the environmental benefits (chapter 7), the next chapter (8) seeks to establish the economic viability of the system. Regardless of energy and environmental improvement gain, if the system is not economically viable, its acceptability and utilization potential will be low. Chapter 8 presents the technoeconomic assessment of the improved system from a potential buyer's perspective through a profitability analysis and the overall systems' worth evaluated through a benefit-cost analysis.

Chapter 8 has been submitted for publication as

- **Kwofie, E. M** and Ngadi, M. (2016). Technoeconomic of an integrated steaming and drying parboiling unit. *Bioresource Technology*, (under revision)

CHAPTER 8 Technoeconomic and Analysis of an integrated parboiling system

Abstract

Rice parboiling energy in West Africa is met by wood while rice husk generated is openly burn without energy recovery. In this study an integrated steaming and drying system (ISDS) fired with rice husk is examined for it economic viability. Financial have been performed to examine the systems' cost-effectiveness from a potential buyer's perspective using four financial criteria. An economic analysis have also been used to evaluate the systems' worth from societal point of view. The profitability evaluation shows that even without subsidy/grants the system is attractive with a net present value of $9900 and a profitability index of 2.25. The cost-benefits analysis considered benefits from wood saving, income generation, environmental damage cost reduction, and forest preservation in addition to profits from the system use. A benefit-cost ratio of 1.74 – 6.5 when cost and benefits are discounted at different rate (5-25%) were found. Overall, ISDS has demonstrated the potential of lessening the burden on rice processors in collecting wood, and a possible reality of reducing processing time and increasing parboiler's income, thus enhancing their livelihood.

8.1 Introduction

Parboiling is an important pre-milling technology employed to enhance the quality of rice. In most local rice processing communities in West Africa, energy for the process is supplied from combustion of wood. The wood is either purchased from wood retailers or collected from local wood collection points around the villages (Houssou & Amonsou, 2004; Ndindeng et al., 2015). The wood are combusted in a three-stone fire (TSF) stove with efficiency of 13 -15% (Ayoub & Brunet, 1996; Berrueta et al., 2008).

The use of wood in TSF stoves is known for its numerous environmental and health related problems. The world health organization (WHO) reported that over 4 million premature death are recorded annually as a result of household air pollution from wood and solid fuels combustion of which more than 50% of deaths are children under five (WHO, 2014). Reducing impacts associated with energy requires changes in both behaviour, and technology (such as improved cookstoves) (García-Frapolli et al., 2010). In the view of many scholars, the use of improved biomass combustion systems will in addition to decreasing the local and global environmental impact, also enhance the economy, health and overall livelihood of rural households (Gupta & Ravindranath, 1997; Habermehl, 2007; Jones & Williams, 1998; Kanagawa & Nakata, 2007; Mehta & Shahpar, 2004).

In an effort to improve parboiling energy supply and use, an integrated steaming and drying system (ISDS) fired with rice husk was developed which was found to be three times more efficient than the current TSF being used. Although, the ISDS like many other energy based developmental projects in developing countries such improved cookstoves and other biomass project can be assumed to have economic benefits to the society at large, it is important to ascertain whether they are worth their cost (French, 1980). There are subjective evidence that rural energy project have mixed records of success (Johnson & Bryden, 2012a), however, in most cases such projects are meant for domestic use with outsiders footing the bill. Considering the fact that the ISDS is meant for an economic venture with the aim of reducing current cost of doing business while eliminating wood collection and reducing overall emission, its acceptability will be dependent on the simplicity and affordability of the system. It is therefore important to provide primary financial indicators with potential risk and uncertainties evaluation as well as with basic technical information for potential investors to ascertain the economic sustainability of the system.

In this study the ISDS developed for local parboiling is examined for it economic viability. The objectives of the paper are therefore (a) to examine the profitability of ISDS using four financial criteria (b) determine the environmental damage cost reduction compared to current processing method (c) determine the net societal benefits through a cost benefit analysis..

8.2 Local parboiling and ISDS description

8.2.1 Local Parboiling

Data from a study on parboiling energy dynamics conducted in three rice producing communities where parboiling is practiced in the Northern region of Ghana (Mainoo & Kwofie, 2014) was used to establish the baseline for rural parboiling expenditure. In that study, the authors measured parboiling energy consumption with it associated cost and identified factors affecting energy use. They found that, 65% of parboiling energy are purchased at a cost of ¢3.75/kg while the remaining are collected by parboilers. Those who collect wood spend some 6 hours twice every week traveling a round trip of 4 - 8 km. An estimated 973 kg of wood is used for parboiling a tonne of paddy. Meanwhile, the rice husk generated during milling is unused and discarded through open field burning around milling centres.

8.2.2 ISDS Description

The system consists of a continuous rice husk combustor, double-fire tube heat exchangers, a 50 cm high conical chimney and a drying unit. The combustor consist of a firebox (80 x 75 x 55 cm) made from 3/16 inch steel plate with a firebrick (23 x 11.4 x 6.4 cm) lining. The double decker heat exchanger unit produces steam for paddy gelatinization and hot air for drying. The lower steam heat exchanger consists of a 13 standard 1 1/2 inch nominal tubes arranged to achieve a triangular pitch of 9.5 cm length fitted into a 45 cm diameter shell made of gauge 16 metal sheet. The drying unit is made of a wooden drying chamber with 21 V shaped channels. The channels are arranged alternately to deliver inlet air at one level and outlet air in the next. Recirculation is achieved through a pneumatic system.

Experimental investigation performed on the systems shows that a thermal efficiency of 47.8% can be achieved at a rice husk feed rate of 2.8 g/s and a water rate of 7.3 g/s. Again, reduction of up to 10.4 kg of CO and 227.4 kg of CO_2 emissions can be realized from processing a tonne of paddy when compared with current TSF stove being used.

8.3 Materials and methods

8.3.1 Financial analysis of ISDS

The financial analysis have been performed taking into account benefits and cost of operating the systems, risk and uncertainty accountability and credit availability (French, 1980) using four financial criteria. Different sources of funding are assessed using three equity scenarios while risk and uncertainty are assessed using sensitivity analysis.

8.3.1.1 Parameters for financial analysis

Although there are some uncertainties in accounting for unseen contingencies during implementation, since a prototype of the system has been made, actual cost of production is known. Again, considering the fact that the system is expected to be fabricated locally by artisans who will be trained to build, operate and maintain the system at the different communities, a reliable production cost estimate was obtained by collating the actual of materials in Ghana and their equivalent in US dollars used. The total capital expenditure (*Capex*), estimated based on actual cost of fabrication in Ghana was US$ 4460. Capex includes cost of materials (metal sheets, iron bars, bricks, and plywood), auxiliary parts (pipes, fittings, fan, controller, and 12V DC battery), blower and labour cost, during fabrication. The operational expenditures (*Opex*) includes cost of biomass fuel (rice husk and wood), labour for operating the equipment, maintenance cost, rent and depreciation. A straight line depreciation was used with the salvage value assumed to be 20% of the Capex. The labour cost used was taken to be 20% more than the current income of millers ($0.375/h) Table 8.1 provides the general parameters used for the financial assessment.

Biomass energy producing equipment are assumed to last up to 15 years (Grotheim, 2011; Magalhães et al., 2009), however, some conservative studies (Hamelinck et al., 2004) have used 10 years for evaluation. Edwards (2015) recommends a 10-12 economic life for agricultural equipment and 15 years for tractors. In this study a service life of 10 years during which income and outcomes occurs was used.

Table 8.1: Summary of parameters used for profitability assessment

Parameter	Unit	Value
Material		
Paddy processed	Tonne/year	70
Rice husk	c/kg	1.875
Wood	c/kg	3.75
Water	c/kg	0.4
Electricity	$/kWh	0.1481[a]
Labour	$/h.person	0.45
Finacial parameters		
Inflation	%	17[b]
Discount rate	%	12
Debt term	years	5
Debt interest rate	%	24
Service Life	years	10

[a]Based on 2014 approved non-residential electricity tariffs by the public utilities regulatory commission (ECG, 2015), [b]based on average inflation of August 2014 – July 2015 **(GSS, 2014; GSS, 2015)**

ISDS is made to process 500 kg of paddy in a day but for the purpose of this assessment a 50% processing capacity and 280 working days in a year has been used. Currently, rice husk is not used for parboiling but heaped around rice mills and set ablaze to dispose it. However, with the inception of the ISDS, there is a possibility of millers selling the husk to system owners or operators. In the case where the parboilers own the system, rice husk may be used at no cost. The authors have assumed a relatively high rice husk cost (50% of the current cost of wood) for the assessment.

The discount rate chosen for the financial analysis was based on current alternative investment rate including interest on savings, fixed deposits, and treasury bills which vary from 0.5 - 9.1% (Ghana.deposit, 2015). The minimum attractive rate of return (MARR) of 12% was therefore used. It was assumed that this discount rate will not change during the service life.

Considering funds availability which is the most critical for rural developmental projects, three scenarios with different fraction of financing schemes namely equity, grant and debt have been employed in the financial evaluation. Equity implies individual investors' contribution or farmer group financial commitment. The term 'grant' used includes foreign and local support (e.g. through donor agencies or NGOs) as well as government subsidies through supply of components or partial funding to farmer groups. Credit also refers to funding borrowed from special government credit facilities aimed at poverty reduction which targets farmers and low income generating individuals. In this study, loan facilities which identifies and promote community based programmes while enhancing development of decentralised micro financial systems have been used. Specifically, the Microfinance and Small loans Centre (MASLOC), a Government of Ghana (GoG) microfinance unit in charge of disbursing micro and small loans to the poor with the aim of improving livelihood and job and wealth creation (MASLOC, 2010) was used. The debt interest rate reflects the 2015 MASLOC rate. A debt term of five years have been chosen to restrict the repayment of loan to less than 25% of annual revenue. The three scenarios used for funding availability impact is shown in Table 8.2.

Table 8.2: Financing Schemes for ISDS project

Funding Source	**Scenario 1**	**Scenario 2**	**Scenario 3**
Equity	100%	33.3%	33.3%
Grant	0%	33.3%	67.7%
Debt	0%	33.3%	0%

8.3.1.2 Financial criteria

The chosen criteria namely internal rate of return (IRR), net present value (NPV), payback period (PBP) and saving to investment ratio (SIR) are applied to the net fiscal flow taken as the difference in total income and total cost. Initial investor cost (I_{cap}) used in the analysis always refers to investor's input or farmer group's contribution towards the project. For a 100% equity, I_{cap} will be equal to *Capex.*

a. Net present value (NPV)

The net present value of a project compares all cash inflows against cash outflows expressed in the present value using a discount rate, *i*. The discount rate provides the rate at which an alternative safe investment would be profitable. The NPV considers the time value of money in project appraisal and when NPV > 0, the projects profitability is accepted. In this study, NPV was estimated using Eq. (1) (Gousgouriotis et al., 2007)

$$NPV = \sum_{t=1}^{N} \frac{C_t}{(1+i)^t} - I_{cap} \qquad 8.1$$

Where, C_t is the net cash flow at year t and N the project service time.

b. Internal rate of return (IRR)

The internal rate of return is a discount rate that makes NPV equals zero. Thus the rate at which the present value of all cash inflow is equal to cash outflows. In essence it is the annual rate of return of a project to resources committed to it. For the farmers or the investor, it would be the return on each dollar they invest into the project. When IRR is greater than the actual discount rate assumed (IRR>i), the project is considered to be economically viable.

c. Payback Period (PBP)

Payback period is the duration to recoup the initial cost invested in a project or reach break-even point. Although, PBP is known to have limitation because it is a non-discounted measurement metric, thus ignores the time value of money, but it easy to apply and understand irrespective of academic training. Furthermore it provides a quick way to determine the level of risk associated with the project.

d. Profitability Index (PI)

In addition to the absolute profitability evaluation method used (NPV), a relative evaluation method, the profitability Index (PI) was employed to analyse the relative profitability. In this study, the PI compares the NPV of the project with the capital investment, I_{cap}

8.3.1.3 Sensitivity analysis

Sensitivity analysis was carried out considering factors which are uncertain and pose potential risk to investors. These includes rice husk cost, operating capacity and service life of the system. Variation in rice husk cost is uncertain and may vary depending on system ownership, thus influencing the profitability of the project. Currently, it is the responsibility of millers to dispose rice husk. They employ people to load rice husk outside the rice mills and set them ablaze. If the system is owned by parboilers group, there is a possibility of claiming the husk for free assuming the system is sited near milling centre. On the other hand, if the system is owned by an investor other than parboilers, then rice husk may be sold or traded in exchange for a lower service charge. To cater for the uncertainties around the cost of rice husk, the profitability has been re-evaluated varying rice husk cost from 0 – 3.75¢/kg.

Although, parboilers currently spend about $50 as energy cost to process a tonne of paddy, a good incentive to ISDS adoption would be to do the same job for less. However, to what extent could the service charge be reduced while maintaining economic viability? The sensitivity analysis therefore includes variation in service charge to determine the barest minimum which will make the project still attractive.

8.3.2 Environmental damage cost analysis

Environmental damage cost was estimated considering the environmental impact on climate change expressed as CO_2eq based on greenhouse gases emissions from operation of ISDS in comparison with the current TSF stove in use. The environmental damage was determined using the midpoint metric, global warming potential (GWP) which the International Panel on Climate Change (IPCC, 2006) have proposed. The IPCC's recommended 100-year time horizons with the approved GWP of CH_4 (25 tCO_2/cCH_4) and N_2O (298 tCO_2/c N_2O) (IPCC, 2007) was used. The global warming index (final sum) indicating the potential contribution to global warming was estimated using Eq 8.2 (Bare, 2002):

$$\text{Global Warming Index} = \sum_i e_i \times GWP_i \quad 8.2$$

Where, e_i is the emission of pollutant expressed in kg and GWP_i is the global warming potential of the pollutant.

Although wood and rice husk are all outcomes of atmospheric carbon dioxide accumulated during their respective plant growth and are transformed into organic carbon substances (Tarnawski, 2004), their carbon dioxide emissions have been included in the inventory. In estimating the emissions from the ISDS, a CO_2 emission factor per kg fuel was measured experimentally using flue gas analyser (M700, Enerac TM, Holbrook, NY USA) during performance evaluation of the system. CH_4 emission from rice husk combustion was taken from Wang et al. (2012a).

Rural parboiling system (RPS) on the other hand considered emissions from wood transportation, wood combustion and open field combustion of the rice husk. Wood transport was included because 65% of parboiling wood is transported from other districts up to 212 km away. Emission from the combustion of wood were taken from other wood combustion studies in rural setting in other developing countries (Johnson et al., 2008; Preble et al., 2014) while wood transport emissions were taken from the GaBi 6 database (PE International, 2015). The inventory data is shown in Table 8.3.

Table 8.3: Inventory data for parboiling (per tonne of paddy)

Input/output	**Unit**	**RPS**			**ISDS**
		Wood transport	**Wood Combustion**	**Rice husk Disposal**	**Rice husk Combustion**
Inputs					
Wood	kg	0	973.94	0	0
Rice husk	kg	0	0	243	243
Diesel	MJ	8.075	0	0	0
Output					
Carbon dioxide	kg	39.16	1230	228	228
Methane	kg	2.64E-04	2.63	0.0268	0.0268
Nitrous oxide	kg	2.63E-04	0	0	0

The environmental damage cost was estimated by converting the GHG emissions into economic values (García-Frapolli et al., 2010) using an average market value of \$15/tonne of avoided CO_2eq. (2015 carbon price forecast at the time of analysis (August, 2015) was \$15 /tonneCO_2 (Luckow et al., 2015)).

8.3.3 Benefit-cost analysis

In this section a benefit-cost-ratio (BCR) of using the ISDS is examined. Although, a profitability index had been estimated, the BCR takes into account the system's value from society's perspective and considers the wood savings, benefits from forest preservation and income from saved time in addition to the income generated from using the system.

The ISDS is designed to use rice husk and where necessary augment rice husk usage with wood when there is shortage. Currently, 27% rice husk with bran are generated during paddy milling equivalent to 270 kg for a tonne of paddy (Mainoo & Kwofie, 2014). Assuming 90% of this husk is available as fuel in the ISDS, 1645.8 MJ of useful energy would be generated for parboiling (assuming a 47% efficiency and LHV of 14.3). Considering the superior efficiency of the ISDS, the 634 kg of wood (representing 65% of total parboiling wood use) parboilers purchase from retailers can be eliminated completely while the remaining 341.6 kg of wood collected from the local wood collection centres can be reduced to 90 kg. Assuming 70 tonnes of rice (equivalent to 50% system capacity) is processed annually, wood savings of 61.8 tonnes would be realised.

Although, the 73.7% reduction in wood use would imply skipping one day of wood collection (6 hours), a conservative value of 2.5 hour reduction in local wood collection time per batch of 40kg has been used. This translates into gaining a total of 62.5 hours for 25 batches per tonne of paddy processed. Again, considering a typical parboiling practice in Ghana where two batches of 40 kg/batch are processed per day per parboiler within a 9 hour period (though each batch is dried for about seven hours), a total of 112.5 hours would be required to dry a tonne of steamed paddy. However, ISDS would require 44.4% of that time to dry the same amount of paddy meaning 62 hours saved. For the purposes of this analysis, a 30 hour saving per tonne has been used. Therefore, for the 70 tonnes per anum assumed, use of ISDS would result in a total annual time savings of 6,475 hours (4,375 for wood collection and 2,100 for drying). It must be noted that the reported time savings stems from the combined savings from different parboilers using the system.

Certainly, not all saved time would be used for income generating activities, therefore only 25% (García-Frapolli et al., 2010) of saved time was assumed to be invested to generate income.

The shadow price for saved time may be difficult to estimate in rural areas especially in this case where the children and some women who perform the activities do not have access to employment and even if they do, the employment may not be available all year round. In this study an average shadow wage of \$0.375/h was used. This was based on the average daily income of millers and market women selling milled rice, paddy and groundnut.

The benefits from forest preservation have been estimated based on the avoided cost of deforestation in Ghana. The average biomass density was taken as 118,474kg/ha (Damnyag et al., 2011) for natural forest in Ghana which translates to 0.52 ha/year. Again, a total afforestation cost of \$1327/ha (García-Frapolli et al., 2010) including cost of labour, trees and transportation was assumed for estimation of forest reserve benefits.

8.4 Results and Discussions

8.4.1 Profitability Evaluation

The profitability evaluation result is shown in Table 8.4. The result reveals that for all equity scenarios considered, the project is deemed economically viable (NPV>0, IRR>I, PI>1) based on the selected financial criteria. At a 70% system capacity, \$37.5/tonne service charge and rice husk cost of 1.875¢/kg, the ISDS will be economically viable for a 100% equity scenario. Investors can recover their investment in 35 months of operation and receive 41.6% of every dollar invested as a return.

According to the result for scenario 2 as shown in Table 8.4, with a 33.3% funding as grant/subsidies to farmers and a loan covering another third, the payback period is reduced by 13 months and farmers can retrieve their contributions before the end of the second year. Although, the NPV seems to have reduced marginally by 6.8%, the profitability index improved substantially by 182%. The reduction in NPV observed stems from the high interest rate. Although, the MASLOC program appears to support farmers through its credit facility with a relatively lower rate among other options, the 2% monthly interest charges would reduce farmers overall income. Under this equity scenario, 13-24% of annual revenue goes into servicing the loan during the five years debt term, however in the sixth year, net annual cash flow increases by more than 57%. In spite of the high interest rate, profitability of the project looks very attractive.

Scenario 3 offers the best overall performance. With a two-thirds subsidy, the return on investment doubles and the farmer group can recoup their monies in 14 months. The financial attractiveness increases markedly and demonstrates that the profit at the end of the project under such conditions will be equivalent to more than 6 times the initial investment.

Table 8.4: Profitabily evaluation results for different equity scenarios

Financial criteria	**Unit**	**EQUITY SCENERIO**		
		1	**2**	**3**
IRR	%	41.59	44.61	100
NPV	$	9900	9225	12848
PBP	years	2.89	1.83	1.10
PI	-	2.25	6.35	8.85

Service charge = $37.5 (75% of current cost); operating capacity 70 tons/yr (50% system capacity); scenario 1 = 100% equity; scenario 2 = 33.3% equity, 33.3% grant and 33.3% debt; scenario 3 = 33.3% equity, 66.7% grant.

Since the project is viable at a 100% equity (scenario 1) as shown in Table 8.4, the sensitivity analysis was performed for only scenario 1. Fig 8.1 is a 3D plot showing variation of rice husk cost and service charge with NPV when 70 tonnes of paddy are processed annually. The plot clearly shows that, service charge has a greater influence on the NPV than rice husk cost. For instance, a 20% reduction in service charge ($37.5 to $30) results in a 69.4 % decrease in NPV whereas, only 27% decline in NPV is observed even for a 50% increase in rice husk cost (¢1.85 to ¢3.75).

If parboiler groups own the system, implying no rice husk cost, the profitability index increases by 26.7% and the NPV increases by 35.6% ($1629). At this zero cost of husk, the minimum service charge that would make the project viable (NPV>0, IRR>I, PI>1) is $26.5. This implies the parboilers can increase their income if they are supported to own the system which will take away the cost of rice husk. Similarly, when the husk is sold for half the current cost of wood, the project will still be viable (NPV>0, IRR>I, PI>1) as long as the services rendered are not charged less than $30.

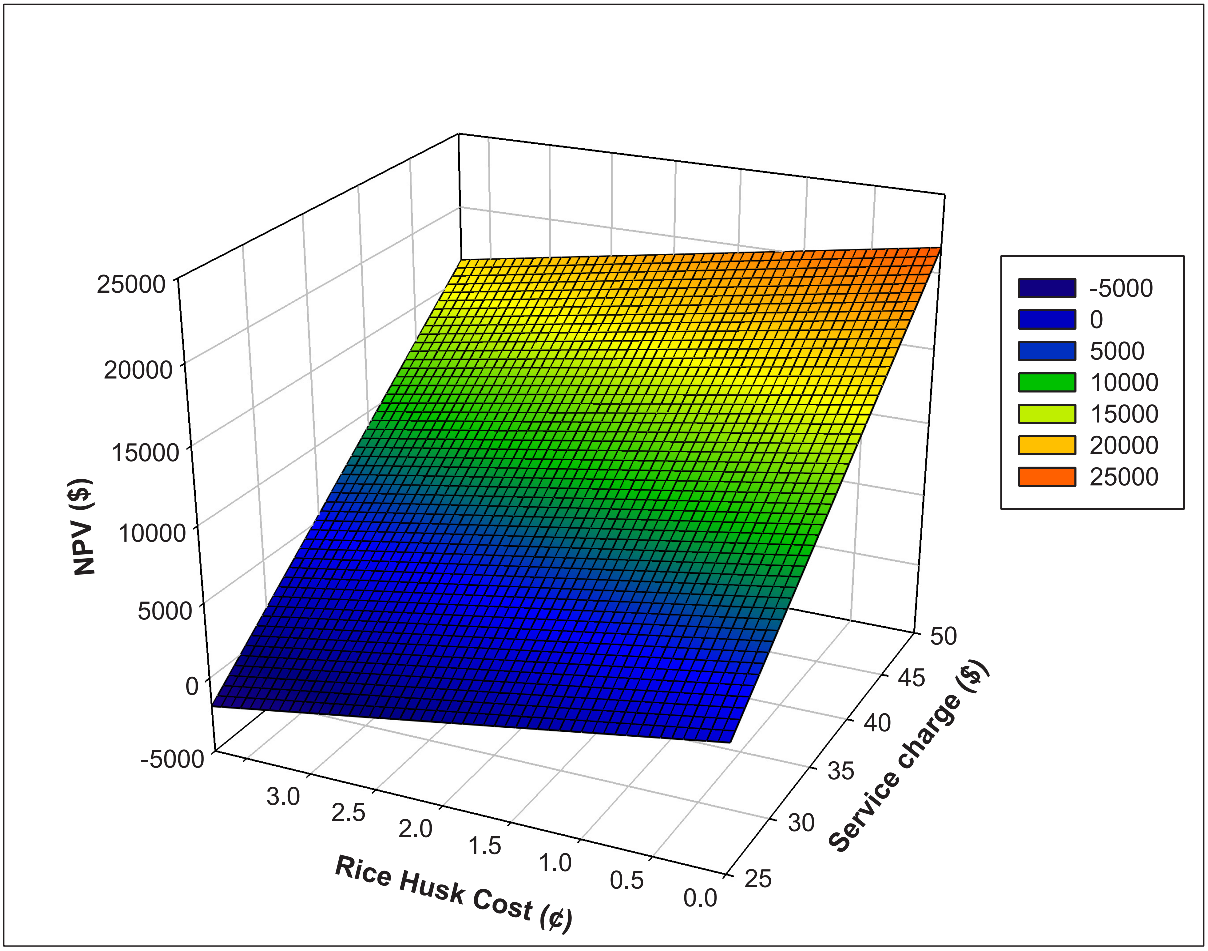


Figure 8.1: Variation of rice husk cost and service charge with NPV at 50% system capacity

Other factors that remain uncertain are the service life owing to the fact that the system is fabricated locally by trained artisan and the overall cost of the system. In case the system does not last the proposed 10 year service life, how much will the profitability be affected? A comparison of the proposed service life to 7 year period shows that despite the 52.4% reduction in both NPV and PI, the project remains attractive (NPV = $4711.84, IRR = 35.29%, PI = 1.07). Also, in the event that the systems costs increased by 20% ($5352) the project is still profitable (NPV = $5606, IRR = 27.61%, PI = 1.05) provided the service charge does not fall below $33.5.

In the above sensitivity analysis, a 50% (70 tonnes/year) system capacity was assumed. At a higher system capacity such as 75% (105 tonnes/year) and 100% (140 tonnes/year) the financial attractiveness even get better. The variation of rice husk cost and service charge at different system capacities is displayed in Fig 8.2. As can be seen from the 3D plot, increasing system capacity significantly increases the NPV. For every 25% increase in capacity a corresponding 81.2% increase in NPV is realised. An annual capacity of 105 and 140 tonnes will require a service charge below 25.1 and $22.8/tonne, respectively, for high rice husk cost (50% of current wood cost) to make the project loose its attractiveness (NPV>0, PI<1). At a zero rice husk cost, the minimum service charge reduces to 21.5 and $19.2/tonne for 105 and 140 tonnes/year.

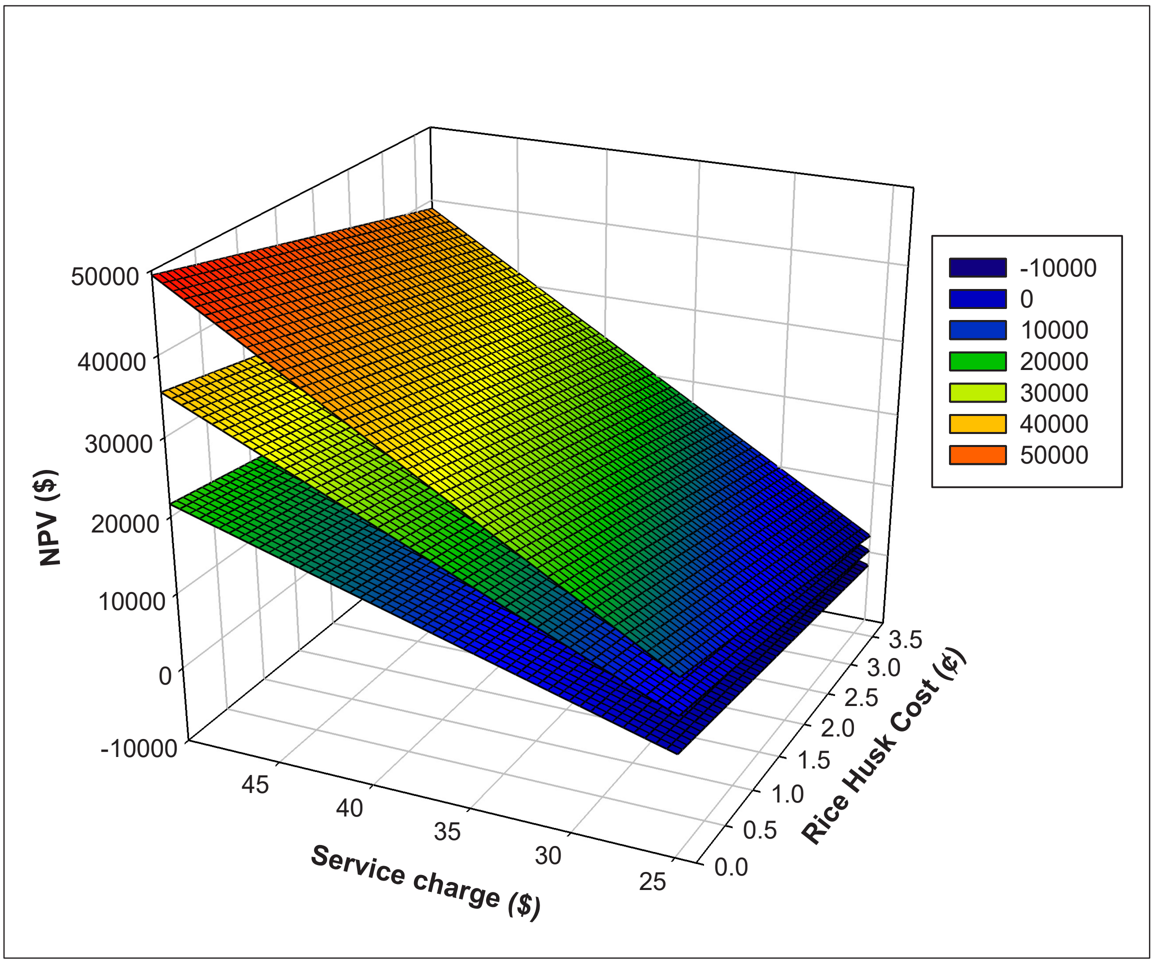


Figure 8.2: Variation of rice husk cost and service charge with NPV at different system capacities. (Plots are displayed as 100, 75 and 50% system's capacity from top to bottom).

8.4.2 Environmental damage cost analysis

The annual global warming index (GWI) for the RPS and ISDS were estimated as 142 and 23.9 CO_2 eq, respectively. The processes contributing to these estimated GWI are displayed in Fig 8.3. The wide variation in the GWI stems from the amount of biomass used in the process and the emission from the biomass. With the use of an inefficient TSF stove, about 68.25 tonnes of wood would be used annually to parboil the 70 tonnes compared to 19.6 tonnes of biomass (87.1% rice husk and 12.9% wood) used in the ISDS. Again, according to the results from the emission test conducted on the ISDS system, for every kilogram of biomass combusted, wood releases 48.5% more CO_2 than rice husk. This is most likely due to the relatively high carbon content of wood (50.17%) compared to rice husk (37.66%). These emissions translates into an annual environmental damage cost of $2130 and $358.5 for RPS and ISDS, respectively. These results imply by using the ISDS for rural parboiling the annual environmental damage cost can be reduced by 83.2%.

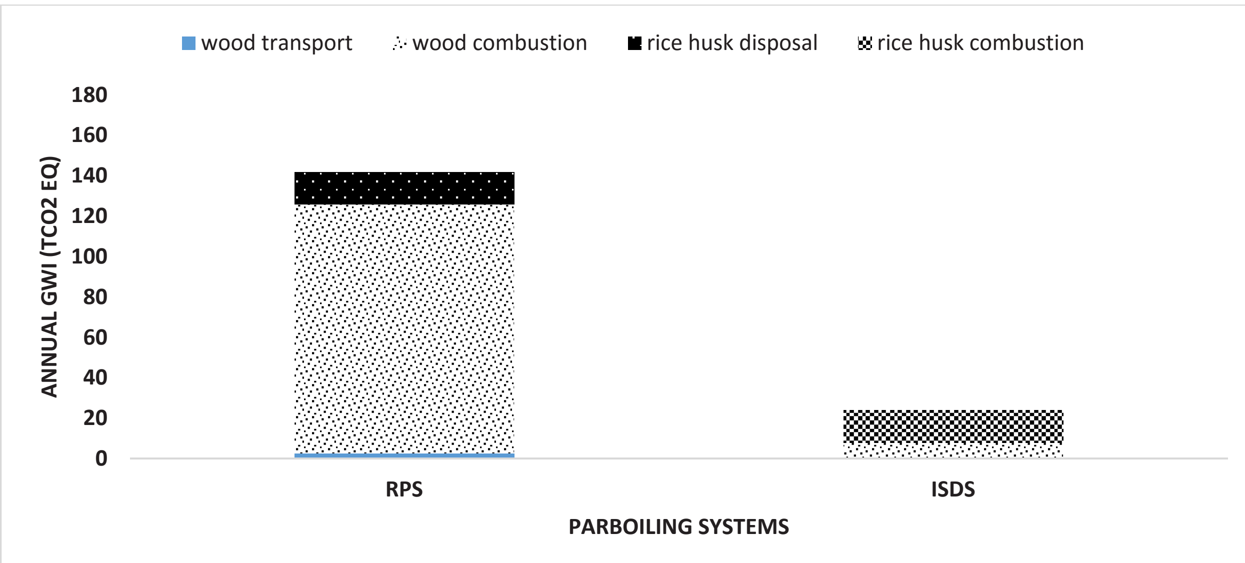


Figure 8.3: Annual Global warming index of rural parboiling system (RPS) and integrated steaming and drying systems (ISDS) as a function of different contribution.

8.4.3 Benefit-cost analysis

Economic benefits from using ISDS is shown in Table 8.5. The total economic cost for fabricating and operating the ISDS are the same parameters used for profitability assessment shown in Table 8.1 and the equity scenario shown in Table 8.2. The economic benefits reported in this study go beyond fuel savings reported in some studies to include other societal benefits like forest preservation and environmental damage cost reduction.

At the assumed discount rate of 12% used for the profitability analysis, NPV of $39,328 and BCR of 2.74 are obtained when 70 tonnes are processed per annum. This increases to $74,580 and 4.77

for NPV and BCR, respectively at the systems' full capacity of 140 tonnes. Varying the discount rate shows a noticeable change between the NPV and BCR. As can be seen from the results of the economic analysis displayed in Fig 8.4, the ISDS demonstrates substantial economic benefits when it replaces existing TSF stove which supports claim of significant benefits from other improved biomass stoves (García-Frapolli et al., 2010; Habermehl, 2008; Habermehl, 2007; Mutamba & Gwata, 2003)

The BCR obtained in this study was between 1.7 and 6.5 which are similar to those obtained in Malawi (Habermehl, 2008) and China (Smith & Haigler, 2008). However, they were lower than those reported in Mexico (García-Frapolli et al., 2010) and Uganda (Habermehl, 2007) which were between 9 - 11 and 25 – 29, respectively. The difference between these results can be accounted for by the fact that besides the cost of the ISDS, additional operational costs such as labour, fuel, electricity, maintenance, and taxes are incurred. Hence a higher cost component compared to other improved domestic cookstoves which are much cheaper and comes with little or no operational cost.

Parboiling communities in the north are within a degraded forest region (based on ITTO definition (ITTO, 2002)) as a result excessive wood harvesting, poor management and the impact of climate change has furthered desertification in the region, therefore, any attempt to reduce deforestation within the region would be very beneficial. The use of ISDS could therefore help reduce the rate of desertification within the region. This programme could further be pursued with introduction of rice husk stove for domestic use in rice producing communities.

Table 8.5: Economic benefits from ISDS

Economic Benefits	**Annual Benefits ($/year)**	**Benefit over Service life ($)**
Income from ISDS usage	2,625	58,787[d]
Wood savings	2,318	23,180
Income generated from saved time	604	13,520[d]
Benefits of preservation of forest reserves	692	6,920
Environmental Damage cost saved	1,772	17,720
Total Economic benefits	**8,011**	**120,127**

[d]Takes into account inflation

Although, no measurement of the health effect was made, the observed reduction in environmental damage (83% reduction in global warming index) and ISDS's safety rating of 83 points (estimated according to the biomass stove safety protocol version BSSP 1.1 (Global Alliance for Clean Cookstoves, 2012)) compared to 44 points for TSF (Johnson, 2005) is expected to reduce health impact. This would imply reduction in number of lost hours due to poor health, avoided public health system cost and avoided cost of diseases at household level.

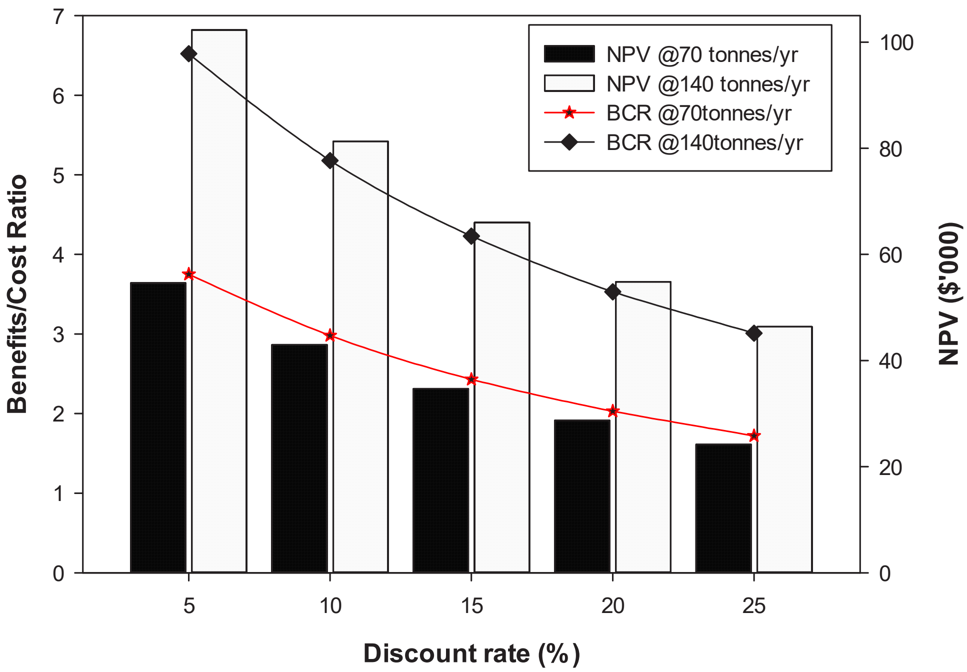


Figure 8.4: NPV and Benefits/Cost ratios at discount rates 5, 10, 15, 20 and 25

Finally, rice being the most rapidly growing source of food within the sub Saharan African region (Mohanty, 2013; Solh, 2005), implies that every effort ought to be made to improve its handling locally. Already this agenda have been pursued vigorously at both national and international level to boost local rice production. For instance, the Government of Ghana received $100 million and $45 million from the World Bank and USAID, respectively, all geared towards rice value chain development. Elsewhere in Dakar, the Government of Senegal (GOS), through its PRACAS program allocated a 32 billion CFA ($64 million) for rice production in the 2014/15 production year, 14 billion CFA ($28 million) for farmer's debt payment through Credit Bank (CNCAS) and another 6.5 billion ($13million) for off season rice production (Sylla, 2015). While these efforts are mostly geared towards increase in paddy productivity, a corresponding effort in processing such as subsidies for improved processing equipment such as the ISDS can aid in achieving not only improved quality but also make local rice competitive and also reduce the burden on rice processors in collecting wood and increase their income and overall enhance their livelihood considering the fact that more than 80% of local rice is produced by smallholder farmers (Angelucci et al., 2013).

8.5 Conclusion

The study presents benefits of using an integrated steaming and drying system (ISDS) for rice rural parboiling. It evaluates benefits from an investor perspective through a profitability assessment as well as from societal point of view through a cost benefits analysis including fuel saving, forest preservation and environmental damage reduction. It is clear that, the proposed ISDS is not only economically viable with or without subsidy/grant, but its use demonstrates a tremendous reduction of environmental damage (83%) which has huge local and global benefits besides the improved health implication. It would reduce overall time by 92 hours per tonne of paddy processed in wood collection and processing. Overall, benefits from the ISDS outweigh its cost by at least 3 folds and its use will positively impact the livelihood of parboilers.

Connecting Text

Chapters 3–6 provided information about development of two thermochemical conversion systems – their development, performance evaluation and their energy efficiency improvement. Chapter 7 provided results of the environmental gains from the system and chapter 8 assessed the financial and economic viability of the system.

In the final chapter of the thesis, a summary of all the results in earlier chapters are presented. Chapter 9 also presents the contribution made from this work both to scientific knowledge and rural development. The chapter concludes with further research work needed to reach the realization of energy economy and improve the environment in rural rice processing communities.

CHAPTER 9 General Conclusion and Recommendations

9.1 General Summary

Rice parboiling is a pre-milling technology employed in rice processing to enhance the quality and competitiveness of rice. The process as practiced in rice producing communities is time consuming, arduous and energy intensive. Combustion of wood collected over long distances or purchased from wood vendors supplies thermal energy for the process using a three stone fire (TSF) stove which is known for its inefficiency and impact on human health. With an objective of improving both energy supply and use, an alternative improved energy supply system powered with rice husk has been developed and evaluated for energy and environmental improvement as well as economic viability.

The work began with an assessment of the thermochemical pathway of harnessing rice husk energy within a rural community context. This was achieved by first determining thermal characteristics of rice husk and briquettes made with local binding materials. This was followed by examining the potential of selected conversion pathways in meeting the annual energy demand in a typical rice producing community. The results of the thermogravimetric evaluation indicated that the thermal behaviour of rice husk does not differ from its briquettes irrespective of the binder used. The kinetics and reactivity of all the samples were similar, however, briquettes made with corn and cassava starch binder had relatively lower ignition temperatures and higher ignition index indicating their ease of ignition during combustion processes. This results implied that, combustion behavior would not be so different irrespective of the binder choice or whether the husk is combusted directly or densified. Following these results, three rice husk thermochemical conversion pathways – direct combustion, briquette combustion and gasification, were examined for their energy replacement, environmental impact reduction and economic potential in meeting the annual parboiling energy requirement. Direct combustion of available rice husk presented the cheapest way of harnessing rice husk energy achieving about 34.0, 43.3 and 38.0% reduction in energy expenditure, emissions and energy use, respectively. Although, briquetting had the highest energy replacement potential, its use will increase energy cost and impact the environment more. Overall, using the current available rice husk has the potential of reducing emissions by 23.57% 36.85 and 62.94% using direct combustion, briquetting and gasification, respectively.

Two pathways from the above results were therefore selected for the next step of the project. A bottom lit downdraft gasifier stove operating in a continuous mode was developed. The 6.5 kW gasifier was found to be 52.7% efficient. A thermochemical equilibrium model to envisage the performance of the gasifier at different operating conditions was developed. A second system was developed to directly combust rice husk continuously in excess air. The 4.5kg load capacity system had a continuous feeding and ash removal system and had also the ability to use wood when there is a shortage of rice husk. A water boiling test (WBT) revealed a thermal efficiency of 28.67±2.7%, a fire power of 15.9±3.2kW and a specific energy consumption of 0.141±0.01kg/kg rice husk.

The primary purpose of the parboiling system was to produce hot water and steam for the process, therefore, the next part of the project concentrated on improving energy use of the newly developed system. The first approach towards achieving energy economy was to improve the heat transfer process to enhance efficiency. A 23-inch high fire tube heat exchanger made of 13 standard pipes fitted to a 17-inch diameter galvanized sheet steel was incorporated onto the combustor. The performance of the new system was evaluated by estimating the initial energy supplied and the thermal efficiency using the indirect method for boiler evaluation. The extension, in addition to continuous steam production, further increased thermal efficiency by 61.67% (thus, from 28.67±2.7% to 46.35±0.43). The combustion efficiency (CE) observed for the stove was in the range of 97.2 - 98.8% for rice husk and 96.9 – 98.1% for wood. CO and CO_2 emission factors for rice husk combustion were also in the range of 10.6-12 and 785-793 g/kg rice husk, respectively and were much lower than fuel wood (36.3 – 42.7 and 1519-1531 g/kg wood). This implied a reduction of up to 10.4 kg of CO and 227.4 kg of CO_2 could be realized from processing a tonne of paddy when compared with the TSF stove currently being used.

The second energy improvement strategy used was the addition of a waste heat recovery unit incorporated into a recirculating drying system. The heat recovery unit was another fire tube heat exchanger which extract heat from the flue gas leaving steam heat exchanger to produce hot air for drying. A thermodynamic performance evaluation of the complete integrated steaming and drying unit (ISDS) showed an average logarithmic mean temperature difference (LMTD) of 344.6 and 128.9 °C for the steam and hot air generators, respectively. The average temperature efficiencies of the hot combustion products, water, and air were found to be 72.9, 32.5 and 35.6%, respectively. Of all the operating conditions, the effect of water flow rate was most prominent affecting both steam generation and efficiency. The first law and second law efficiencies were found to be 47.8 and 10.93%, respectively. Maximum heat loss and exergy destruction occurred at the steam production unit and in the combustor, respectively. The large amount of ash with its high chemical exergy added to the high anticipated exergy loss within the combustor contributed more than 60% of total exergy destroyed. The reference temperature was found not to significantly influence the second law efficiency of the system. Based on the results of the thermodynamic evaluation, an excel-based energy and exergy assessment framework was developed for quick evaluation of rural parboiling systems.

To evaluate the extent of the environmental improvement achieved through this work, a comparative life cycle assessment (LCA) was performed. Using a functional unit of processing 1 tonne of rice, an LCA goal of determining the environmental impact of the integrated steaming and drying system (ISDS) in comparison with the current rural parboiling system (RPS) was set out. Four impact category indicators were selected to estimate the environmental impact using the ReCiPe evaluation methodology available in the GaBi 6 LCA software. Inventory data were collected from emission experiment results, literature and Gabi database. Characterised impact results show that the four chosen midpoint impact categories namely climate change, terrestrial acidification, particulate matter formation and photo-oxidant formation were, respectively, 6.8, 14.9, 3.2 and 13.5 times higher for RPS than ISDS. The normalized results shows that the overall influence of RPS on the environment is five times more than that of ISDS implying, about 80% of the existing total environmental impact can be minimized by replacing the existing process with ISDS. In a sensitivity analysis to ascertain the impact due to variation in rice husk use, it was observed that variation in rice husk availability does not influence overall normalized emission as only 5.2% increment in impact was observed for a 20% reduction in rice husk use.

Finally, the economic viability of the ISDS was evaluated from a potential buyer's perspective and from a societal viewpoint using profitability analysis and benefit to cost ratio, respectively. Using four financial criterial – internal rate of return (IRR), net present value (NPV), payback period (PBP) and profitability index (PI), ISDS was attractive even without subsidy/grants earning a net present value of $9900 and a profitability index of 2.25. Benefits from wood saving, income generation from saved time, environmental damage cost reduction, and forest preservation in addition to profits from the system use showed a benefit-cost ratio of 1.74 – 6.5 when cost and benefits are discounted at different rates (5-25%). Overall, ISDS has demonstrated the potential of lowering the burden on rice processors in collecting wood, reducing processing time and increasing parboiler's income, thus enhancing their livelihood.

9.2 Contribution to knowledge

The study presents information and tools for improving rural rice parboiling energy supply and use, geared towards advancing rice processing in Africa. The outcome of this study has contributed to both scientific knowledge and particularly to rural development in more ways than one. A few of the several commendable contributions are as follows:

1. This study provides rural rice processing stakeholders a broader perspective (energy, economic and environmental standpoints) of rice husk utilization options. This can be a useful information for rural energy supply intervention within rice processing communities.
2. The study also provides comprehensive data on general combustion behavior, kinetics, reactivity, and ignition performance of rice husk and its briquettes. This is the first thermogravimetric assessment of rice husk briquettes with local African binders which was crucial in evaluating the replacement potential of rice husk for rice parboiling. The study also establishes the fact that the thermal behavior or rice husk and its briquettes do not considerably differ regardless of the type of binder used and that whether rice husk is combusted directly or densified their devolatilization characteristics will not change
3. The present work is expected to contribute towards expanding current data on rice husk gasification and specifically direct application in rice parboiling. Information on simplified design and operating parameters of the throatless downdraft gasifier stove working in a continuous mode has been made available for rural artisanal training. Again, the investigation of syngas application to rice drying will expand the knowledge base of thermochemical processing of agricultural biomass for drying with an overall aim of increasing operational efficiency and improving rice quality. This is in order to enhance local rice productivity and competitiveness.
4. For the first time, a complete thermodynamic assessment has been performed on a parboiling system which led to the development of an excel-based Thermodynamic

framework for assessment of parboiling energy systems for a quick determination of energy consumption, exergy destruction, and first and second law efficiencies.

5. For the first time, a life cycle assessment of a local parboiling system has been conducted revealing how the different stages of the current process impact the environment. This provides rice processing stakeholders the needed background to take informed decision in addressing the impact of the current process on parboilers.
6. The techno-economic analysis has provided basic data for potential buyers of the system and farmer groups, but more importantly data on community level benefits have been presented. This contribution is critical for rural energy development and possible dissemination of ISDS which could improve the livelihood of rural farmers.

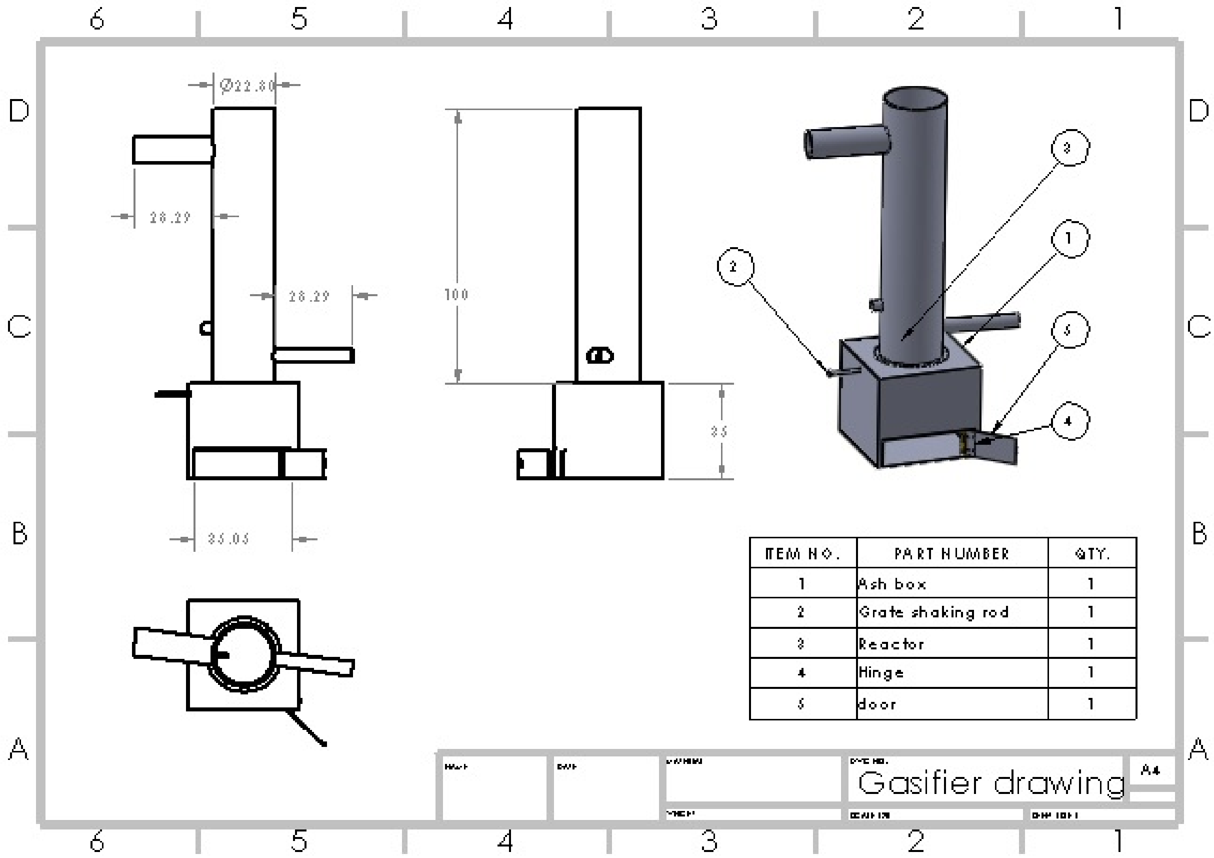
9.3 General Recommendation

This study focused on the development and evaluation of improved thermochemical conversion systems for enhancing rural rice parboiling in West Africa. Some of the recommendation for future work are as follows:

1. ISDS has been tested for steam and hot air production. However, due to the unavailability of paddy, the entire system have not been tested for actual paddy parboiling. It is therefore recommended that onsite evaluation of the system should be carried out to (a) identify areas requiring improvement (b) obtain farmers/parboilers input to be incorporated in later modified designs.
2. A longitudinal studies is recommended before and after the implementation of the ISDS in rice producing communities. This will help quantify the changes in livelihood including human health, resource availability and use, income and wealth as well as education and gender differences.
3. The improved system developed is expected to improve both energy and product efficiency. A study of the impact of ISDS on rice quality and competitiveness is therefore recommended.
4. To fully estimate the economic benefits of the system developed, actual system performance data including actual time savings and health improvement measurement should be used. Re-evaluation on the system a year or two after implementation is recommended to establish the actual benefits-cost ratio.

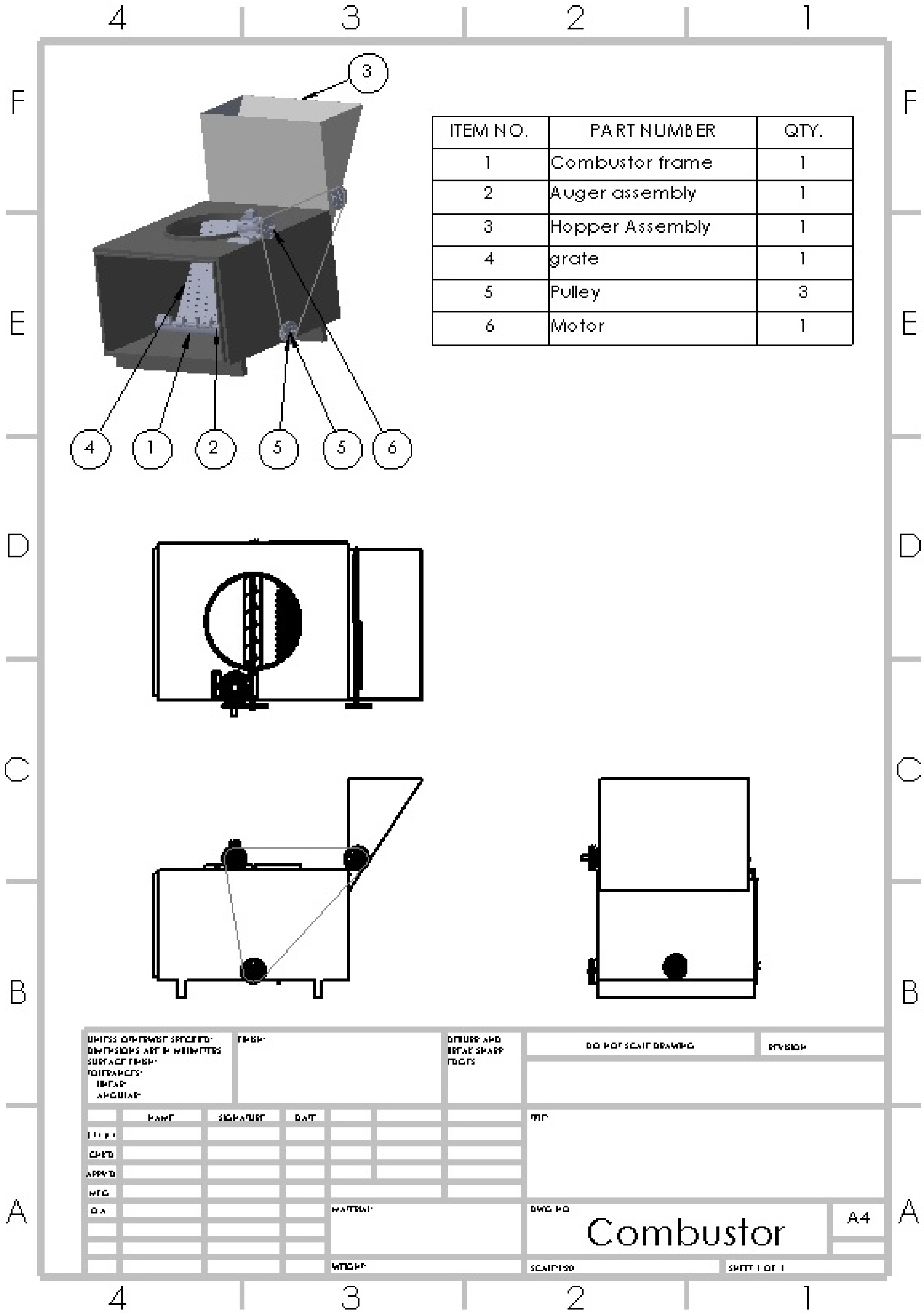
5. Rice husk ash produced from the gasifier stove may be used as biochar or rural building material. Investigation of the use of ash is recommended to explore the full potential of the system.

APPENDIX A - GASIFIER DESIGN DRAWING

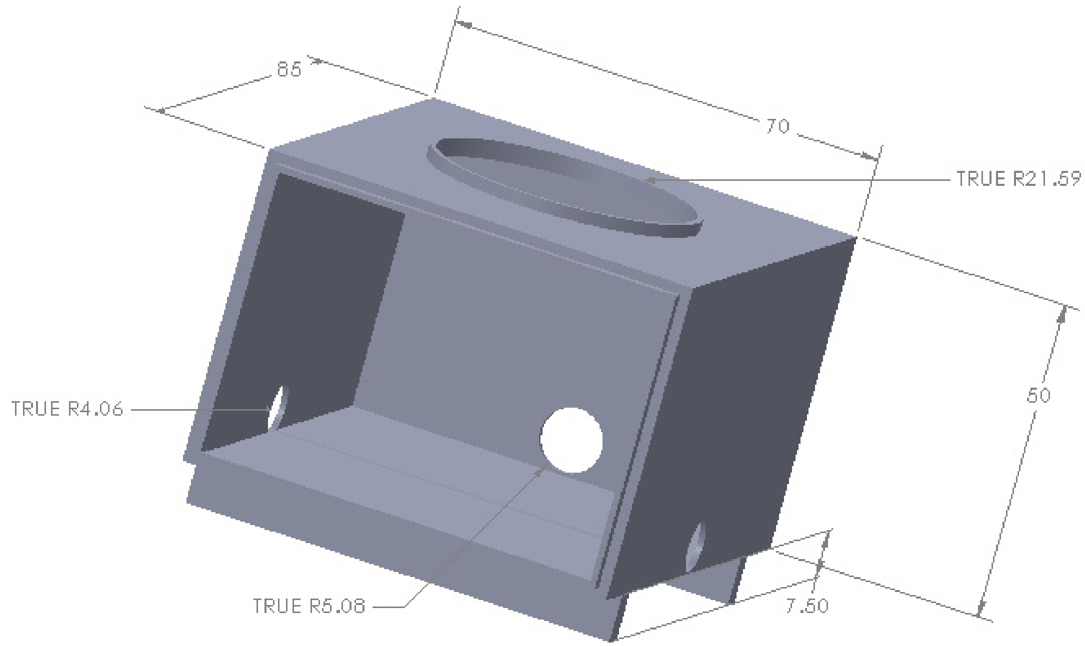


ITEM NO.	PART NUMBER	QTY.
1	Ash box	1
2	Grate shaking rod	1
3	Reactor	1
4	Hinge	1
5	door	1

APPENDIX B – RICE HUSK COMBUSTOR DESIGN DRAWING



ITEM NO.	PART NUMBER	QTY.
1	Combustor frame	1
2	Auger assembly	1
3	Hopper Assembly	1
4	grate	1
5	Pulley	3
6	Motor	1



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APPV'D					
MFG					
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				WEIGHT:	

TITLE:

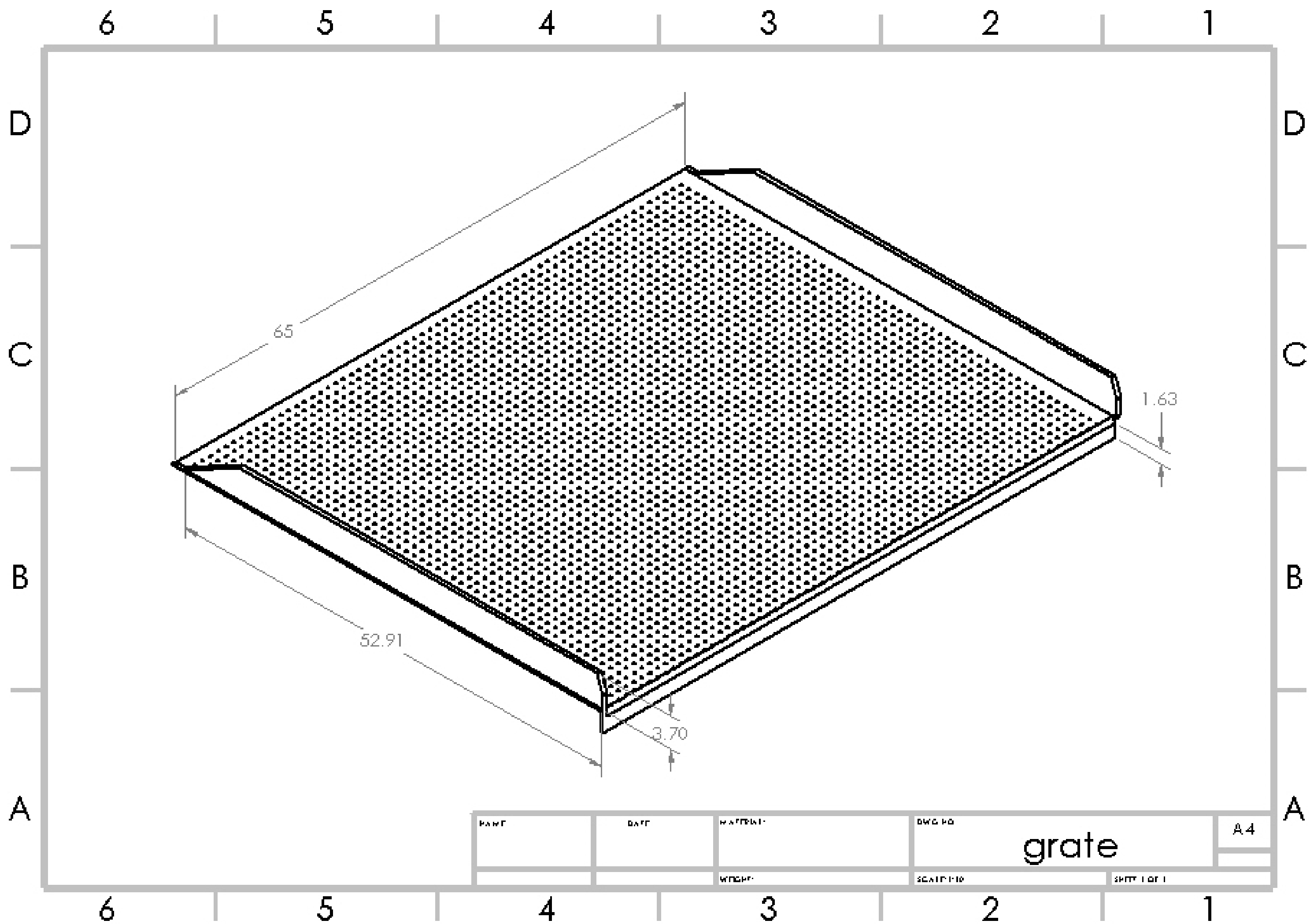
DWG NO.

Combustor frame

A4

SCALE:1:20

SHEET 1 OF 1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grate
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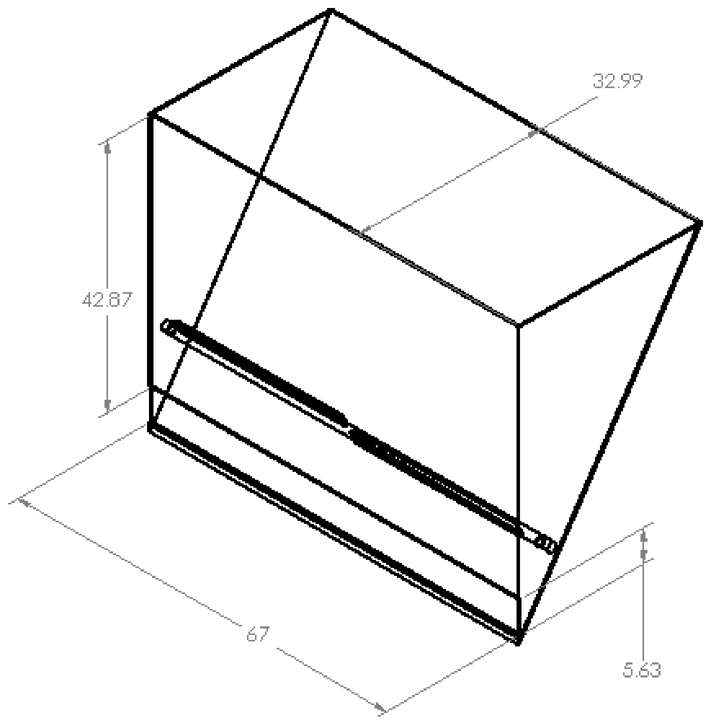
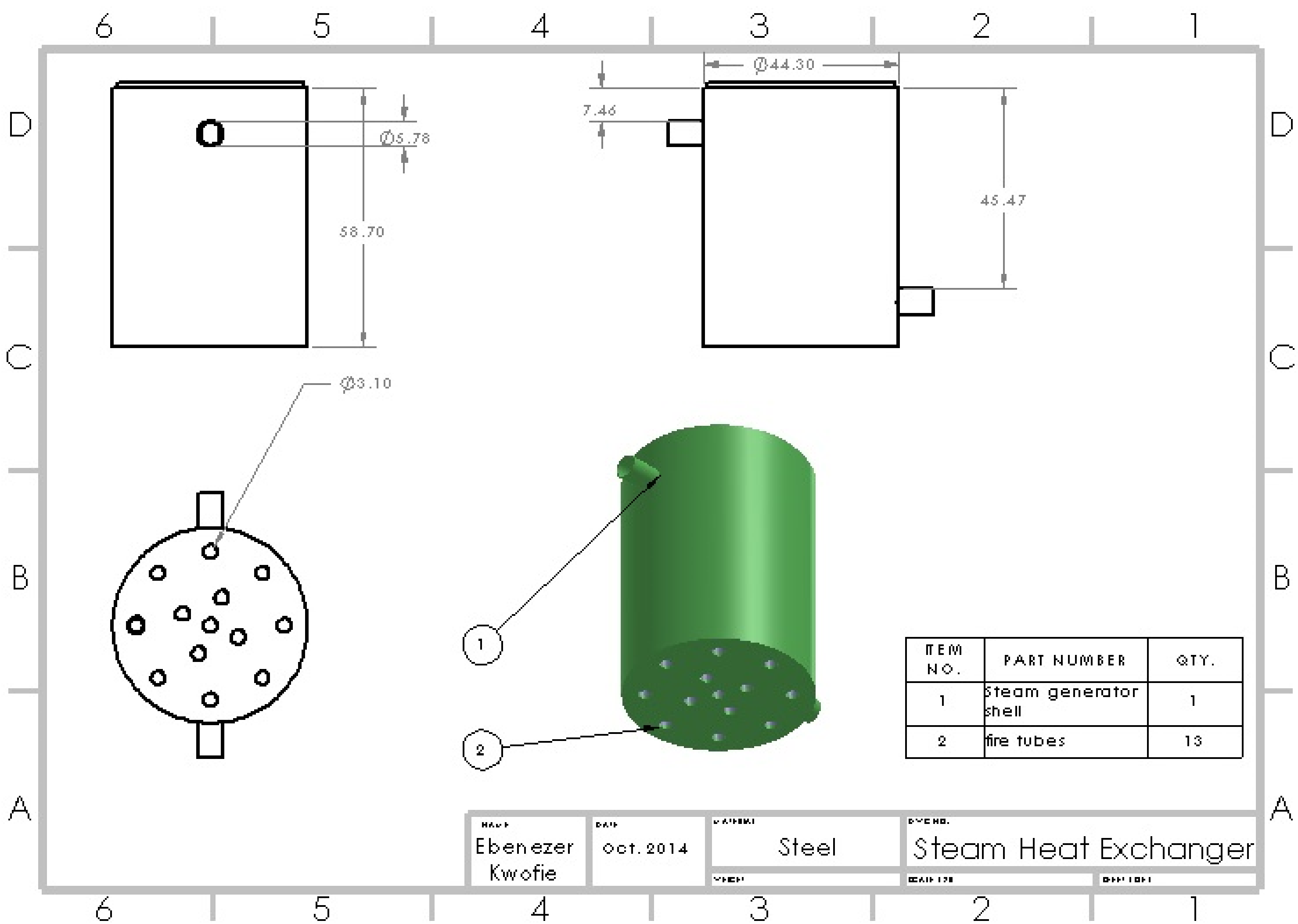
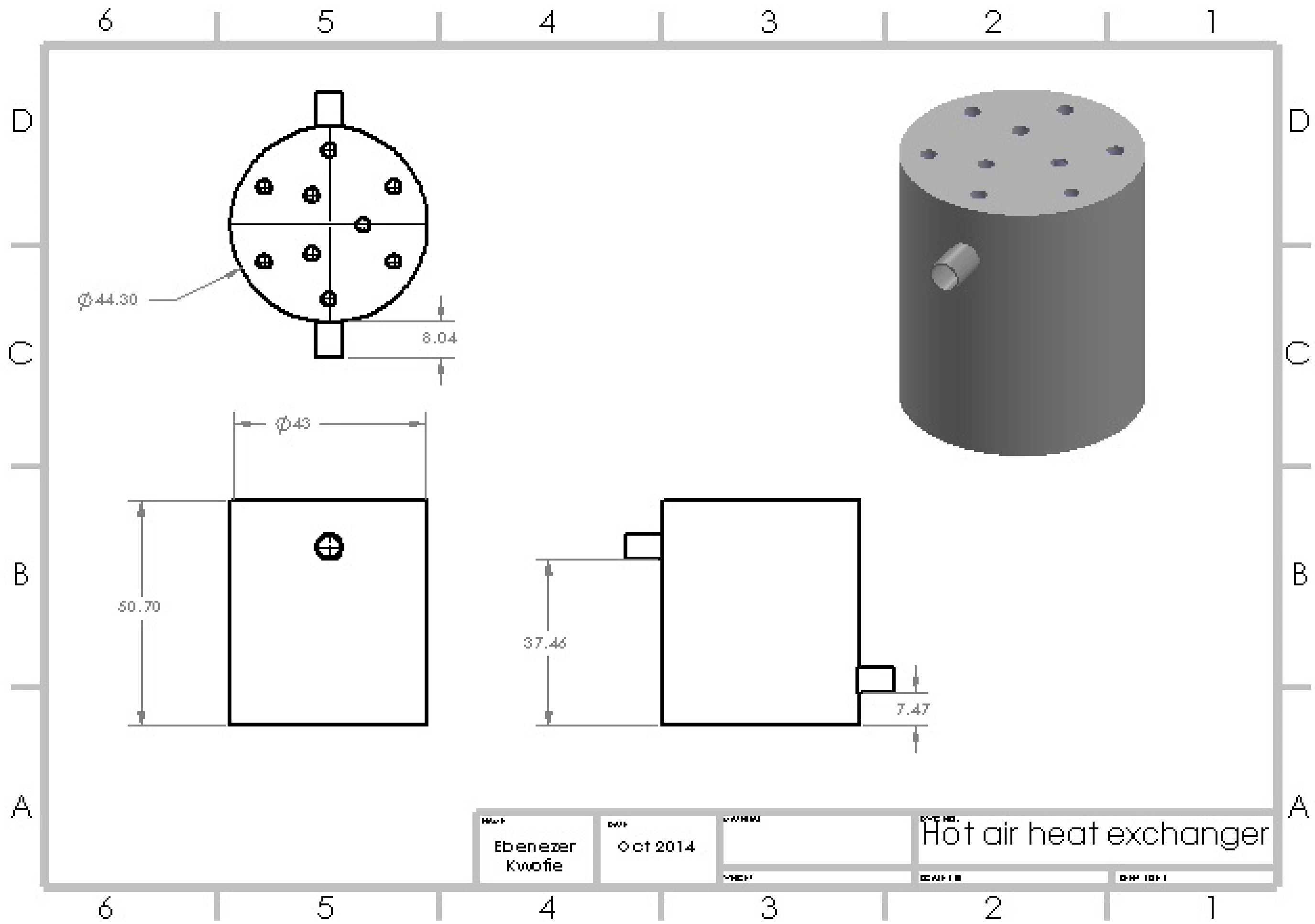
WEIGHT:
SCALE:1:10
SHEET 1 OF 1



NAME	DATE	MATERIAL:	DWG NO. Hopper Assembly	A4
		WEIGHT:	SCALE:1:10	SHEET 1 OF 1

APPENDIX C - HEAT EXCHANGER DESIGN DRAWINGS





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Ebenezer Kwofie
Oct 2014
Hot air heat exchanger

APPENDIX D – EXCEL FRAMEWORK DEVELOPMENT (VBA SCRIPT)

```
Sub Type_of_stove_selection()

' Type_of_stove_selection Macro
    Range("E12").Select
    With Selection.Validation
        .Delete
        .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
        xlBetween, Formula1:="='Fuel Data'!$D$23:$D$26"
        .IgnoreBlank = True
        .InCellDropdown = True
        .InputTitle = ""
        .ErrorTitle = ""
        .InputMessage = ""
        .ErrorMessage = ""
        .ShowInput = True
        .ShowError = True
    End With
End Sub


Sub Type_of_fuel()
' Type_of_fuel Macro
    Range("E14").Select
    With Selection.Validation
        .Delete
        .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
        xlBetween, Formula1:="='Fuel Data'!$C$4:$C$18"
        .IgnoreBlank = True
        .InCellDropdown = True
        .InputTitle = ""
        .ErrorTitle = ""
        .InputMessage = ""
        .ErrorMessage = ""
        .ShowInput = True
        .ShowError = True
    End With
End Sub
Sub Type_of_parboiling_system()
' Type_of_parboiling_system Macro
```

```
    Range("E16").Select
    With Selection.Validation
        .Delete
        .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
        xlBetween, Formula1:="='Fuel Data'!$D$29:$D$32"
        .IgnoreBlank = True
        .InCellDropdown = True
        .InputTitle = ""
        .ErrorTitle = ""
        .InputMessage = ""
        .ErrorMessage = ""
        .ShowInput = True
        .ShowError = True
    End With
End Sub


Sub fuel_rate_estimation()
' fuel_rate_estimation Macro
    Range("D11").Select
    ActiveCell.FormulaR1C1 = "=R[-2]C/(R[-4]C*60)"
    Range("D12").Select
End Sub


Sub Water_rate_estimation()
' Water_rate_estimation Macro
    ActiveCell.FormulaR1C1 = "=R[-2]C/(R[-5]C*60)"
    Range("D13").Select
End Sub


Sub fuel_LHV_estimation()
' fuel_LHV_estimation Macro
    Range("D26").Select
    ActiveCell.FormulaR1C1 = _
        "=VLOOKUP(R21C3,'Fuel Data'!R[-24]C:R[-8]C[10],2,FALSE)"
    Range("D27").Select
End Sub
```

```
Sub Percentage_carbon_estimation()
' Percentage_carbon_estimation Macro
    ActiveCell.FormulaR1C1 = _
        "=VLOOKUP(R21C3,'Fuel Data'!R[-24]C:R[-10]C[10],6,FALSE)"
    Range("D29").Select
End Sub



Sub Percentage_hydrogen_estimation()
' Percentage_hydrogen_estimation Macro
    Range("D29").Select
    ActiveCell.FormulaR1C1 = _
        "=VLOOKUP(R21C3,'Fuel Data'!R[-27]C:R[-11]C[10],7,FALSE)"
    Range("D30").Select
End Sub



Sub Percentage_oxygen_estimation()
' Percentage_oxygen_estimation Macro
    ActiveCell.FormulaR1C1 = _
        "=VLOOKUP(R21C3,'Fuel Data'!R[-28]C:R[-12]C[10],8,FALSE)"
    Range("D31").Select
End Sub



Sub Enthalpy_of_air()
' Enthalpy_of_air Macro
    Range("I9").Select
    ActiveCell.FormulaR1C1 = _
        "=VLOOKUP(R[5]C[-5],'Steam and Air Tables'!R[-4]C[3]:R[37]C[5],2,TRUE)"
    Range("I10").Select
End Sub



Sub Entalpy_of_water()
' Entalpy_of_water Macro
    Range("I10").Select
    ActiveCell.FormulaR1C1 = _
        "=VLOOKUP(R[5]C[-5],'Steam and Air Tables'!R[-4]C[-7]:R[36]C[-3],3,TRUE)"
    Range("I11").Select

End Sub
```

```
Sub Enthalpy_of_steam()
' Enthalpy_of_steam Macro
    ActiveCell.FormulaR1C1 = _
        "=VLOOKUP(R[5]C[-5],'Steam and Air Tables'!R[-5]C[-7]:R[35]C,5,TRUE)"
    Range("I12").Select
End Sub


Sub Enthalpy_of_fuel()
' Enthalpy_of_fuel Macro
    ActiveCell.FormulaR1C1 = _
        "=VLOOKUP(R21C3,'Fuel Data'!R[-6]C[-5]:R[10]C[5],2,FALSE)"
    Range("I16").Select
End Sub


Sub Entropy_of_air()
' Entropy_of_air Macro
    Range("I16").Select
    ActiveCell.FormulaR1C1 = _
        "=VLOOKUP(R[-2]C[-5],'Steam and Air Tables'!R[-11]C[3]:R[30]C[5],3,TRUE)"
    Range("I17").Select
End Sub


Sub Entropy_of_water()
' Entropy_of_water Macro
    Range("I17").Select
    ActiveCell.FormulaR1C1 = _
        "=VLOOKUP(R[-2]C[-5],'Steam and Air Tables'!R[-11]C[-7]:R[29]C,6,TRUE)"
    Range("I18").Select
End Sub


Sub Entropy_of_steam()
' Entropy_of_steam Macro
    ActiveCell.FormulaR1C1 = _
        "=VLOOKUP(R[-2]C[-5],'Steam and Air Tables'!R[-12]C[-7]:R[28]C,8,FALSE)"
    Range("I19").Select
End Sub
```

```
Sub Exergy_Estimation()

' Exergy_Estimation Macro

    Range("G20").Select

    ActiveCell.FormulaR1C1 = "air"

    Range("I20").Select

    ActiveCell.FormulaR1C1 = "=R[-11]C-((R[-6]C[-5]+273)*R[-4]C)"

    Range("G21").Select

    ActiveCell.FormulaR1C1 = "water"

    Range("I21").Select

    ActiveCell.FormulaR1C1 = "=(R[-11]C-((R[-7]C[-5]+273)*R[-4]C))"

    Range("G22").Select

    ActiveCell.FormulaR1C1 = "steam"

    Range("I22").Select

    ActiveCell.FormulaR1C1 = "=R[-11]C-((R[-8]C[-5]+274)*R[-4]C)"

    Range("G23").Select

    ActiveCell.FormulaR1C1 =
    "fuel" Range("I23").Select
    ActiveCell.FormulaR1C1 =
    "=R[-15]C*0.99"
    Range("G24").Select
    ActiveCell.FormulaR1C1 =
    "flue gas"
    Range("I24").Select
    ActiveCell.FormulaR1C1 = _

        "=R[2]C*((R[-7]C[-5]-R[-10]C[-5])-(R[-10]C[-5]*(LN(R[-7]C[-5]/R[-
    10]C[-5]))))" Range("G25").Select

    ActiveCell.FormulaR1C1 =
    "Hot products"
    Range("I25").Select
    ActiveCell.FormulaR1C1 = _

        "=R[2]C*((R[-7]C[-5]-R[-11]C[-5])-(R[-11]C[-5]*(LN(R[-7]C[-5]/R[-
    11]C[-5]))))" Range("I26").Select

End Sub



Sub Fuel_Analysis()

' Fuel_Analysis Macro

    Range("L8").Select

    ActiveCell.FormulaR1C1 = "Stoichiometric air supplied"

    Range("O8").Select

    ActiveCell.FormulaR1C1 = _

        "=((2.9978*R[21]C[-11]%)-(0.3747*R[22]C[-11]%)+(0.374*R[24]C[-11]%)+(R[20]C[-
        11]%))*11.445"

    Range("L9").Select

    ActiveCell.FormulaR1C1 = "Actual Air supplied"

    Range("O9").Select

    ActiveCell.FormulaR1C1 = "=R[-1]C+(1-(R[16]C[-11]/RC[-11]))"
```

```
    Range("L10").Select
    ActiveCell.FormulaR1C1 = "Mass of dry flue gas"
    Range("O10").Select
    ActiveCell.FormulaR1C1 = _
        "=((2.9978*R[19]C[-11]%)-(0.3747*R[20]C[-11]%)+(0.3747*R[22]C[-11]%)+(R[18]C[-
        11]%))*(11.445*'
Fuel Data'!R[27]C[-3])+('Input Data'!R[-1]C[-11]-'Input
    Data'!R[15]C[-11])" Range("O11").Select
End Sub



Sub Energy_losses_estimation()
' Energy_losses_estimation Macro
    Range("L12").Select
    ActiveCell.FormulaR1C1 = "Loss in flue gas"
    Range("O12").Select
    ActiveCell.FormulaR1C1 = _
        "=((R[-2]C*0.23*(R[5]C[-11]-R[2]C[-11])/(R[14]C[-11]*0.239))*100)"
    Range("L13").Select
    ActiveCell.FormulaR1C1 = "Loss due to H2"
    With ActiveCell.Characters(Start:=1, Length:=13).Font
        .Name = "Arial"
        .FontStyle = "Regular"
        .Size = 9
        .Strikethrough = False
        .Superscript = False
        .Subscript = False
        .OutlineFont = False
        .Shadow = False
        .Underline = xlUnderlineStyleNone
        .ThemeColor = xlThemeColorLight1
        .TintAndShade = 0
        .ThemeFont = xlThemeFontNone
    End With
    With ActiveCell.Characters(Start:=14, Length:=1).Font
        .Name = "Arial"
        .FontStyle = "Regular"
        .Size = 9
        .Strikethrough = False
        .Superscript = False
        .Subscript = True
        .OutlineFont = False
```

```
        .Shadow = False

        .Underline = xlUnderlineStyleNone
        .ThemeColor = xlThemeColorLight1
        .TintAndShade = 0
        .ThemeFont = xlThemeFontNone
    End With
    Range("O13").Select
    ActiveCell.FormulaR1C1 = _
        "=((9*(R[16]C[-11]/100)*(584+(0.45*(R[4]C[-11]-R[1]C[-
        11]))))/(R[13]C[-11]*0.239))*100"
    Range("L14").Select
    ActiveCell.FormulaR1C1 = "Loss due to moisture"
    Range("O14").Select
    ActiveCell.FormulaR1C1 = _
        "=(((R[10]C[-11]/100)*(584+(0.45*(R[3]C[-11]-RC[-
        11]))))/(R[12]C[-11]*0.239))*100"
    Range("L15").Select
    ActiveCell.FormulaR1C1 = "Loss due to ash"
    Range("O15").Select
    ActiveCell.FormulaR1C1 = "=(R[10]C[-11]*R[12]C[-11])/(R[11]C[-
    11])"
    Range("L16").Select
    ActiveCell.FormulaR1C1 = "Total combustors energy losses"
    Range("O16").Select
    ActiveCell.FormulaR1C1 = "=R[-4]C+R[-3]C+R[-2]C+R[-1]C"
    Range("O17").Select
End Sub


Sub Energy_Analysis()
' Energy_Analysis Macro
    Range("L18").Select
    ActiveCell.FormulaR1C1 = "Energy loss to the parboiling
    vessel"
    Range("O18").Select
    ActiveCell.FormulaR1C1 = _
```

```
        "=VLOOKUP('Fuel Data'!R[-2]C[-10],'Fuel Data'!R[12]C[-
        11]:R[14]C[-10],2,FALSE)"

    Range("O18").Select

    ActiveCell.FormulaR1C1 = _

        "=VLOOKUP('General Information'!R[-2]C[-10],'Fuel
        Data'!R[12]C[-11]:R[14]C[-10],2,FALSE)"

    Range("L19").Select

    ActiveCell.FormulaR1C1 = "Evaporation ratio"

    Range("O19").Select

    ActiveWindow.SmallScroll Down:=-3

    ActiveCell.FormulaR1C1 = "=R[-9]C[-11]/R[-10]C[-11]"

    Range("L20").Select

    ActiveCell.FormulaR1C1 = "Energy Consumption"

    Range("O20").Select

    ActiveCell.FormulaR1C1 = "=(R[-11]C[-11]*R[6]C[-11])+(R[-
    11]C*R[-11]C[-6])"

    Range("L21").Select

    ActiveCell.FormulaR1C1 = "Combustor Efficency"

    Range("O21").Select

    ActiveCell.FormulaR1C1 = "=100-(R[-5]C+R[-3]C)"

    Range("O21").Select

    ActiveCell.FormulaR1C1 = "=100-(R[-5]C)"

    Range("L22").Select

    ActiveCell.FormulaR1C1 = "Parboiling Thermal Efficiency"

    Range("O22").Select

    ActiveCell.FormulaR1C1 = "=100-(R[-6]C+R[-4]C)"

    Range("O23").Select

End Sub



Sub Exergy_Analysis()

' Exergy_Analysis Macro

    ActiveCell.FormulaR1C1 = "Combustor Exergy Destroyed"

    Range("O24").Select

    ActiveCell.FormulaR1C1 = _

        "=(R[-15]C[-11]*R[-1]C[-6])+(R[-15]C*R[-4]C[-6])-(R[-
        14]C*R[1]C[-6])"

    Range("L25").Select
```

```
    ActiveCell.FormulaR1C1 = "Steam Generator exergy destroyed"

    Range("O25").Select

    ActiveCell.FormulaR1C1 = _

        "=R[-15]C*(RC[-6]-R[-1]C[-6])+R[-15]C[-
    11]*(R[-4]C[-6]-R[-3]C[-6])"
    Range("L26").Select

    ActiveCell.FormulaR1C1 =
    "Total exergy destroyed"
    Range("O26").Select

    ActiveCell.Formul
    aR1C1 = "=R[-
    2]C+R[-1]C"
    Range("L27").Sele
    ct

    ActiveCell.FormulaR1C1
    = "Combustor
    Efficency"
    Range("O27").Select

    ActiveCell.FormulaR1C1 = _

        "=((R[-17]C*R[-2]C[-6])/(R[-18]C[-11]*R[-4]C[-6]))*100"

    Range("L28").Select

    ActiveCell.FormulaR1C1 = "SteamGenerator Efficiency"

    Range("O28").Select

    ActiveCell.FormulaR1C1 = _

        "=((R[-18]C[-11]*(R[-6]C[-6]-R[-7]C[-6]))/(R[-18]C*(R[-
        3]C[-6]-R[-4]C[-6])))*100"

    Range("L29").Select

    ActiveCell.FormulaR1C1 = "Exergy Efficiency"

    Range("O29").Select

    ActiveCell.FormulaR1C1 = _

        "=((R[-19]C[-11]*(R[-7]C[-6]-R[-8]C[-6]))/(R[-20]C[-
        11]*R[-6]C[-6]))*100"

    Range("O30").Select

End Sub
```

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