Low Pressure Densification of Rice Husk and Direct Combustion of Biomass in Improved Cookstoves

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Abstract

Biomass densification and combustion is gaining popularity in the energy sector to reduce the dependency on fossil fuel and the environmental footprint of energy production. This research investigated the densification of rice husk generated in post-harvest transformation as a biomass for direct combustion to offer a new use for a waste product and an alternative fuel to reduce wood consumption and rice post-harvest activities in rural areas of developing countries. Improved biomass stoves were studied to assess the increase in efficiency, the fuel saving and the reduction in emissions compared to the 3-stone stove currently used. The energy requirements of the stoves over their life cycle were also assessed. The influence of the type of binder, the binder and bran content, and the amount of water added to the initial mixture on the final densified briquettes was investigated and physical tests provided results on the density, moisture content, calorific value, durability and compressive strength. The stoves were tested to assess the thermal and combustion efficiency, the fuel consumption, the time to boil water, and the emission factors in function of the design, the air supply and the type of fuel burned. The rice husk briquettes had a durability between 0 and 91.9% and a calorific value of 16.08 MJ kg^{-1} dry basis. The highest compressive strength and density were 2.54 kN and 441.18 kg m^{-3}, respectively. As for the improved stoves, the boiling time was reduced by 31% at cold start and by 45% at hot start and the fuel reduction was 28% at both phases. The specific fuel consumption varied from 126.7 to 249.9 g L^{-1}. The overall thermal efficiency of the improved stoves varied between 19 and 25.1%. The overall emission factor of carbon monoxide (CO) for the 3-stone stove was 4.9 g MJ^{-1} and varied from 3.8 to 12.6 g MJ^{-1} for the improved stoves. It was found that the energy required to build the improved stoves could be recovered in 6.78 and 10.15 days for the Noflay and AM stove, respectively.

Résumé

La densification et la combustion de la biomasse prend de plus en plus d'ampleur elle permet de réduire la dépendance envers les combustibles fossiles et l'empreinte écologique de la production d'énergie. Ce travail de recherche a étudié la densification de la balle de riz destinée à la combustion directe afin d'offrir une utilisation alternative pour ce déchet et de réduire la consommation de bois dans la cuisson quotidienne et les activités d'après récolte des zones rurales des pays en voie de développement. L'influence d'agents liants, de la teneur en son de riz et de la quantité d'eau ajoutée au mélange pour fabriquer les briquettes a été étudiée. La densité, le taux d'humidité, la valeur calorifique, la durabilité et la résistance à la compression des briquettes ont été mesurés. Des foyers améliorés à la biomasse ont aussi été étudiés afin d'évaluer l'amélioration de l'efficacité énergétique, l'économie de combustible et la réduction des émissions par rapport au foyer à trois pierres présentement utilisé. L'efficacité thermique et de la combustion, la consommation de bois, le temps d'ébullition et les facteurs d'émission des foyers ont été mesurés en fonction du model, de l'apport en air et du type de combustible. Les besoins énergétiques des foyers au cours du cycle de vie ont été évalués. Les briquettes ont présenté une durabilité entre 0 et 91,9% et une valeur calorifique de 16,08 MJ kg^{-1}. La plus grande densité et résistance à la compression était de 441,18 kg m^{-3} et de 2,54 kN respectivement. Le temps d'ébullition des foyers améliorés a diminué de 31% au démarrage à froid et de 45% à chaud. Les deux phases ont réduit l'utilisation de combustible de 28%. La consommation de bois a varié de 126,7 à 249,9 g L^{-1} et l'efficacité thermique de 19 à 25,1%. Le facteur d'émission de monoxide de carbone (CO) pour le foyer à trois pierres était de 4,9 g MJ^{-1} et de 3,8 à 12,6 g MJ^{-1} pour les foyers améliorés. L'énergie nécessaire pour la construction les foyers améliorés a été recouvrée après 6,78 et 10,15 jours d'utilisation pour les deux modèles, soit le Noflay et le foyer AM.

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Authorship and Manuscript

Dr. Michael Ngadi, Dr. Robert Kok, Audrey Yank and a number of other graduate and undergraduate students were involved in a five year project (planned to finish in 2015), 'Enhancing food security through the improvement of rice post-harvest handling, marketing and the development of new rice-based products' in collaboration with CIDA, Africa Rice and different National Agricultural Research partners in different West African countries. Dr. Ngadi and Dr. Kok supervised the contribution of McGill University in this research project. Audrey Yank was responsible to prepare and conduct the experimental work and analysis related to the outputs 130 and 131 on the development of improved stoves and briquettes from rice by-products. The thesis follows the manuscript format with two manuscripts and a course report.

Chapter 3: This chapter is a manuscript that was submitted, peer reviewed, revised and re-submitted to the journal *Biomass and Bioenergy*.

Yank, A., M. Ngadi, R. Kok. Physical properties of rice husk and bran briquettes under low pressure densification for rural applications.

Chapter 4: This chapter is a manuscript in that was submitted to the journal *Energy for Sustainable Development*.

Yank, A., M. Ngadi, R. Kok, S. A. Ndindeng. Thermal and combustion efficiency of improved clay brick stoves for rural rice parboiling

Chapter 5: This chapter is a report on that was submitted for the course *BREE 608: Special Problems in Bioresource Engineering* and will be eventually adapted for submission to a journal.

Yank, A., M. Ngadi. Life cycle analysis of improved clay brick stoves

Table of Content

List of Tables

List of Figures

List of Abbreviations

AM	Africa Rice/McGill Stove
CCT	Controled Cooking Test
CH_4	Methane
CS	Cold Start phase
C_xH_y	Hydrocarbon
EC	Elemental carbon
E-LCA	Environmental life cycle analysis
EPA	Envrionmental Protection Agency
FAO	Food and Agriculture Organisation of the United Nations
GHG	Greenhouse gases
HS	Hot Start phase
HHV	Higher Heating Value
ICs	Improved cookstoves
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standard Organisation
KPT	Kitchen Performance Test
LCA	Life cycle analysis
LCC	Life cycle cost
LCEE	Life cycle energy efficiency
LCI	Life cycle inventory
LCIA	Life cycle inventory assessment
LCM	Life cycle management
LHV	Lower Heating Value
LP	Low Power phase
LPG	Liquefied petroleum gas
NF	Noflay
NOx	Nitrogen Oxides
PAH	Polycyclic aromatic hydrocarbons
PICs	Products of incomplete combustions
PM	Particulate matters
SETAC	Society of Environmental Toxicology and Chemistry
S-LCA	Social life cycle analysis
WARDA	Africa Rice Center
WBT	Water Boiling Test
WHO	World Health Organization
UNEP	United Nations Environment Program
VOC	Volatile organic compound

Chapter 1: General Introduction

1.1 Problem Statement

1.1.1 Global Energy Supply

A majority of the greenhouse gas (GHG) emissions responsible for climate change emanate from the energy sector, with energy demand constantly increasing. About 85% of the primary energy consumed worldwide is presently derived from fossil fuels and almost 60% of all anthropogenic emissions come from the combustion of those fossil fuel in developed countries for the majority (Moomaw, 2011). In about 15 years from now, the global energy demand is predicted to surpass the current demand by 44% assuming business as usual (Lim et al., 2012). The global population is also increasing at a fast pace especially in emerging economies of the developing world (Lim et al., 2012). However, developing countries face challenges to access fossil fuel energy. Most of these countries greatly depend on biomass, either wood or charcoal as more than 80% of their primary energy source is obtained from forests (UNEP, 2012). About three billion people around the world use wood on a daily basis as a fuel for cooking, heating and post-harvest processing, especially in rural areas (FAO, 2012; WHO, 2011).

Table 1.1 – Number of people relying on biomass as their primary cooking fuel as of 2004 (Sagar & Kartha, 2007)

	Total population		Rural		Urban	
	Million	%	Million	%	Million	%
Sub-Saharan Africa	575	76	413	93	162	58
India	740	69	663	87	77	25
China	480	37	428	55	52	10
Indonesia	156	72	110	95	46	45
Rest of Asia	489	65	455	93	92	35
Latin America	83	19	75	60	33	8
Global	2528	52	2147	83	461	23

However, the fuel supply is decreasing as deforestation rates remain high, a growing concern in Africa. The shift in land use for agriculture, cattle grazing, and to accommodate the population growth are amongst the main drivers of rapid deforestation (Geist & Lambin, 2002), which brings a number of environmental and socio-economical impacts. Deforestation is an important precursor to land degradation as it increases soil erosion and reduces at the same time soil fertility (Bationo et al., 2007). Deforestation also contributes to climate change with about 17% of global CO_2 emissions (Moomaw, 2011). Sub-Saharan countries are already vulnerable to environmental changes and mitigation efforts are required. Recent climatic disturbances along with rapid desertification have affected agriculture, horticulture and forestry (Jekayinfa & Scholz, 2009) which already affects food supply (Bationo et al., 2007).

Deforestation also impacts rural community facing energy shortages as fuelwood becomes less available (Ndiema, 2002; Panwar, 2011). Traditionally, women and children collect wood from the surrounding forest, except during the rainy season when they mostly buy wood at a local market. Increasing demand relative to the availability raises the price of fuelwood which becomes less affordable for most low income households (Wamukonya, 1995). Women and children can spend up to 3 to 4 hr per day walking up to 5 to 10 km to collect wood (Sagar & Kartha, 2007). Animal dung and other garbage found at hand sometimes become the available source of fuel. Fuel scarcity reached a point in areas of SSA where some families reported to go without a hot meal for a number of consecutive days (Ayoub & Brunet, 1996). Therefore, there is a growing need to find alternatives to fuelwood as the main energy supply and to move towards new sources of renewable energies to decrease dependence over fuelwood, reduce pressure of remaining forests and increase household livelihoods.

1.1.2 Agricultural Residues: Rice Husk

Approximately 80% of West Africans depend directly on subsidence agriculture which accounts for more than 20% of their GDP (Dixon et al., 2001). Rice is the third most important crop in the world (Zhang et al., 2012) and about 2% of it is produced in West Africa (Diagne et al., 2007). Rice milling leads to the production of a significant amount of by-products mainly husk and bran. It has been estimated that 137 million tons of rice husk are produced annually in the world (Lim et al., 2012), from which a majority is generated in developing countries (Armesto et al., 2002). Rice husk and bran are usually considered as waste. They are piled and burnt in open fires when too much accumulate (Oladeji, 2010). Those piles, the improper combustion of the waste and the remaining ash lead altogether to water and air contamination while also representing a major handling issue (Thao et al., 2011). Yet, these by-products could be managed differently and transformed into a new source of energy (Jekayinfa & Scholz, 2009; Oladeji, 2010). Rice husk is presently used in Asia in different large scale energy generation systems or in heavy mechanized densification processes (Lim et al., 2012), though these processes are not easily applicable in the context of smaller rice producing communities.

1.1.3 Parboiling and Cooking Stoves

A number of Asian and African countries are involved in rice parboiling, a post-harvest process which consists of steaming the rice before it is milled. This common practice has been carried for centuries. It would allow to increase the nutritional value (Kossou, 2008) and the period of storage of the rice (Zossou, 2008). Parboiling takes place on a 3-stone stove which consist of three rocks or clay stands set in a triangular shape to support a cooking pot. An open fire is then initiated under the cauldron. This basic stove is still used on a daily basis by nearly three billion people worldwide despite its low thermal efficiency ranging between 5 and 15%

(Alakali et al., 2011; Bhattacharya & Salam, 2002). This non-effective combustion burns much more wood than what would normally be required. Improved wood burning devices have the potential to reduce by 10 to 50% the amount of fuelwood presently consumed (IEA, 2006). Moreover, the 3-stone fire produces considerable amount of smoke which directly affects the respiratory health of the stove users, women and young children for the vast majority. The World Health Organization (WHO, 2011) estimates that respiratory health diseases attributable to indoor air pollution are responsible for the premature death of two million people every year.

1.2 Objectives

This study had the objective of improving the overall energy efficiency of the small-scale rice parboiling system used in rural areas. To achieve so, the study focused firstly on the fuel and secondly on the combustion device and its overall energy assessment.

Objective 1: Investigation of low pressure densification of mixtures of rice husk, rice bran, and various binding agents to produce briquettes that can be used as energy source.

Objective 2: Investigation of improved biomass clay-brick stoves to improve the efficiency of combustion and reduce the emissions compared to the traditional 3-stone stove.

Objective 3: Assessment of energy and resource requirements of the stoves over the life-cycle.

1.3 Scope of Work

This study was conducted at the McGill Macdonald campus (Ste-Anne-de-Bellevue, Qc, Canada). In Chapter 1, the rice husk and bran briquettes were investigated as a source of potential energy in the rural context of developing countries, especially in rice producing communities where those by-products accumulate. The briquettes were made under low pressure densification using a manual double-lever press. Low pressure densification was chosen as it does not require other energy input than the manual force of lowering the lever by the operator. This technology was studied as it has the potential to be readily accessible and available in the rural communities. The annual amount of rice husk produced worldwide, estimated at about 137 million tons (Lim et al., 2012), can be considered meaningful enough to develop such method to valorize this by-product. Binders were investigated to assist the densification, namely okra stem gum, rice dust and cassava waste water. These binders were selected as they are waste products resulting of other post-harvest processing activities and they would not compete with the food supply. The work in Chapter 1 follows a previous undergraduate research project in Benin (May-Aug 2009) at the Africa Rice Center where the manual press was first designed and built.

In Chapter 4, four improved brick stoves were investigated for small-scale rice parboiling in rural communities as well. Clay is readily available and the brick production is already a process established locally. Clay bricks stove were selected for this study as a type of improved cookstoves which could potentially be built easily at low cost in rice processing communities and could be robust enough to sustain the weight of the cauldrons filed with rice during parboiling. The interest to investigate the Noflay stove design came from an internship in West Africa with the organisation REAP-Canada (Oct 2011 - May 2012) where the first version of the Noflay domestic cookstove received positive feedback from Gambian and Senegalese women groups. The interest for the AM stove designs came from a rice parboiling stove that was previously built in Cameroun by the Institute of Agricultural Research for Development (IRAD) as part of joint project between McGill University and the Africa Rice Center.

For Chapter 5, the life-cycle approach was selected to assess the energy requirements of the stoves, namely to determine if the energy required to build the improved stoves can be recovered during the parboiling process using the improved parboiling.

1.4 Thesis Outline

The following thesis comprises of four chapters. Chapter 1 presents a brief introduction along with the general context and objectives behind the research conducted. A detailed literature review about biomass densification and improved stoves (ICs) is presented in Chapter 2. Chapter 3 covers the methodology and results from the production and testing of the rice husk and bran briquettes while Chapter 4 focuses on the experimental comparisons in terms of efficiency and emissions of the different improved clay brick stoves compared to the traditional 3-stone stove.

Chapter 2: Literature Review

2.1 Biomass Energy

Biomass can be defined as any carbon based material that is available on a renewable basis to produce energy and that was derived from a direct or indirect photosynthesis reaction (IEA, 2012; Loo & Koppejan, 2012). It is the organic material originating from living or recently expired living organisms. Fossil fuels are also a form of biomass, but the vital difference between the two is that of timescale. Fossil fuels are a consequence of biomass being compressed under high temperature and pressure in the earth's crust and decomposed into chains of hydrocarbons. Biomass is normally processed within a short timescale and can maintain a closed carbon cycle with no net increase of CO2 in atmosphere if managed sustainably. Biomass is attractive from a sustainability perspective. It can be considered a renewable energy as it regenerates itself, especially if the resource is not used faster that the regeneration rate (Jekayinfa & Scholz, 2009). A decade ago, the total amount of biomass on the planet was equivalent to the two-thirds of known fossil fuel total reserves (Hall & Rao, 1999). In 2011, biomass represented 10% of the world's primary energy consumption, including biofuels and waste, but the share of biomass energy in developing countries reached 85% (IEA, 2012).

2.1.1 The Context of Developing Countries

In developing countries, biomass is used for cooking, water heating, household heating, and for heat generation in a number of small-scale industries, including post-harvest processing (gari production, rice parboiling, palm oil production, etc), pottery firing and brick making (Berrueta et al., 2008). About 7% of the world primary energy would be biomass that is used at the household level alone, as 52% of the population in developing countries rely on fuelwood for cooking (IEA, 2012). More than half of those people live in India, China, and Indonesia.

However, the percentage of the people relying on biomass is the highest in rural SSA where more than 90% of the population depend on fuelwood and charcoal (IEA, 2012). Adkins et al. (2010) noted a reliance level as high a 99% in 300 households in Uganda and Tanzania. The majority is collected by hand and the remaining purchased at the local market where up to 15-20% of the family income is spent buying fuelwood (Berrueta et al., 2008).

2.1.2 Types of Biomass: Agricultural Residues

Wood is the most common biomass and it would account for about 80% of the biomass energy on earth (Hall & Rao, 1999). Biomass also includes residues and derivatives of the forest industry, dedicated crops, and agricultural or animal by-products (Loo & Koppejan, 2012). Crops containing carbohydrates and sugars can also be converted into energy in (biofuels). Agricultural wastes or residues such as straws, shells, stalks, cobs, husks, and pumaces or by-products generated from post-harvest and transformation processes are another interesting source of biomass. Table 2.1 presents the annual waste production from main crops.

Table 2.1 – World annual residue production from agricultural crops (Zhang et al., 2012)

Crop	Biomass (Mtons)	Crop	Biomass (Mtons)
Corn	1729.92	Soybean	416.62
Wheat	763.42	Cotton	107.13
Rice (Straw)	698.10	Sugarcane	16.85

Agricultural residues are an inexpensive biomass as they are generated as waste products. The disposal issue can also be solved if they are used as a feedstock to produce energy. But overall, agricultural residues still remain underutilized though new opportunities emerge with energy conversion technologies. Recently, agricultural residues have received growing attention for energy generation in direct combustion, especially in developing countries where agricultural production is expanding considerably (Mansaray & Ghaly, 1997). The supply of agricultural residues can be considered secure because of the constant agricultural production and transformation. Also, the use agricultural residues as non-edible biomass such to produce energy have the advantage of shifting away from the food versus fuel debate (Lim et al., 2012). Agricultural residues represent an opportunity to meet growing energy demand while moving away from fossil fuels and reducing the dependency on fuelwood (IEA, 2012; Panwar, 2011).

2.1.3 Energy Conversion

Biomass can be converted using either thermochemical or biochemical processes to generate useful energy, i.e. heat or electricity, or biomass can be transformed into a different energy carrier (charcoal, liquid fuel or gas). Biochemical conversion include biological processes such as fermentation to produce alcohol, anaerobic digestion to produce gases that are rich in methane (CH_4) or hydrolysis to break down the sugar molecules (Loo & Koppejan, 2012). The thermochemical conversion uses heat and a chemical process to produce energy and is achieved by pyrolysis, gasification, liquefaction and combustion or co-combustion (Figure 2.1). This current work will focus on the direct combustion of agricultural residues to produce heat.

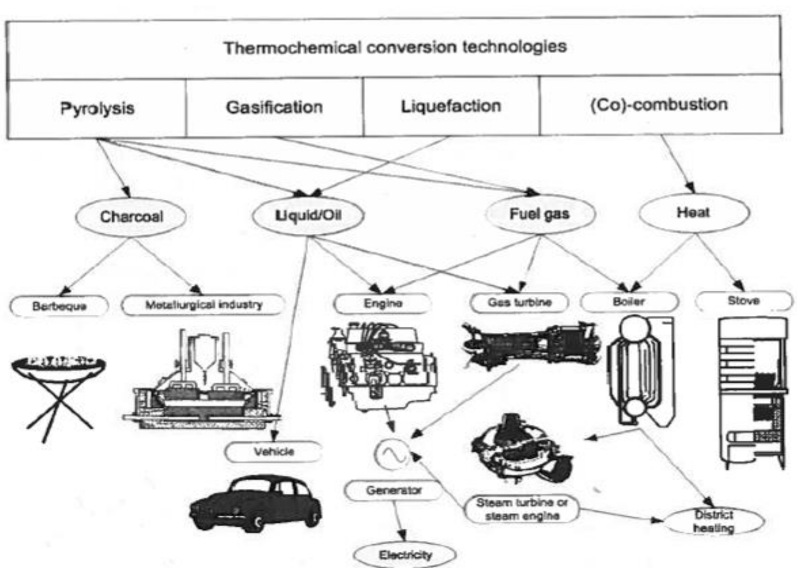


Figure 2.1 – Thermochemical conversion of biomass into energy (Loo & Koppejan, 2012)

However, the use of agricultural residues for energy production presents some challenges. Agricultural residues are difficult to utilize in their original form because they naturally have irregular shapes and sizes, low bulk density, and high volatility (Kaliyan & Morey, 2009b). These characteristics increase the cost and the requirements of handling, transportation and storage and reduce the volumetric energy density and combustion efficiency (Singh & Kashyap, 1985). The combustion of a low density material leads to poor thermochemical conversion because of non-uniform temperature distribution and poor mixing within the heterogeneous fuel (Zhang et al., 2012). Densification of residues is then required to optimize energy production.

2.2 Biomass Densification

Densification consists of agglomerating fine particles together into a larger and solid homogeneous shape of higher density. The process, which is also often appied to the animal feed industry, has the potential to increase the initial bulk density of loose or baled material typically around values of 40-200 kg m^{-3} to a final bulk density of 600-800 kg m^{-3} (Mani et al., 2002; Obernberger & Thek, 2004). This higher bulk density increases at the same time the energy density, improves the combustion performance, controls the uniformity and quality of the product, and reduces the transportation, storage and handling challenges.

2.2.1 Densification Technologies

Densification is achieved using pressure or tumble agglomeration. Tumbling composes of the movement of particles containing binder in balling equipment; either balling discs, cones, or drums. Pressure agglomeration involves a force to compress the particles in a confined volume, either in the form of cubes (12x12 to 38x38 mm in cross-section, 25.4 to 101.6 mm in length), pellets (Ø 6-20 mm, 12.7 to 25.4 mm in length) for automatically fed stoves or briquettes (Ø 30-100 mm) for manual feeding (Loo & Koppejan, 2012). The process can take place at very high pressure, at medium pressure (usually along with heating as pre-treatment or during compression), or at low pressure using a binder. Extruders and presses are common pressure agglomeration technologies. In all cases, an initial densification can be done with a tapered auger in the feed mechanism to first remove air from the low density biomass.

Extrusion consists of feeding the raw material continuously into a cavity from which it is forced through a die by a screw or a rotating roller to obtain a compact product. For the rotating roller, the movement of one to three rollers pushes the feed material against a perforated die (ring die or flat die) and through the holes of the die from the inside towards the outside. For both the screw and rotating roller, adjustable knifes at the outer face of the ring cut the densified product at the chosen length. The friction between the particles and the wall of the die prevents the feed to flow freely through the holes and allows for compaction when the pressure is applied. This friction combined to the internal friction in the material and high rotational speed of the rollers or the screw (~ 600 rpm) raises the temperature and assists the compression. Extruders and rollers are mechanically powered and the rollers are usually the preferred method to produce pellets.

On the other hand, press systems compact biomass in a mould using pistons or rolls and are common to make briquettes. High pressure presses are often mechanically or hydraulically driven while low pressure mechanisms such as levers are often manually operated. The piston can be run as a batch process or continuously with a reciprocating ram. In a roll press, the feed material is compressed while flowing between two counter-rotating rolls that have pockets of the desired size. The roll pressed biomass are usually pillow-shaped (like coal briquettes).

A major drawback to densification is the energy and equipment required. The energy to of pellet sawdust with a roller is about 2.5% of the net calorific value of the wood, but this number rises up to 20% if the raw biomass has to be dried beforehand (Loo & Koppejan, 2012).

Extrusion is also more energy intensive than press densification methods of the friction that needs to be overcome. Tumuluru et al. (2011) stated two equations to measure the work performed during densification and the frictional forces in function of the dimension of the die:

Work performed $$W = A\int_0^x P dx \tag{2.1}$$

Frictional force $$F = F_0 \exp(4\mu L/D) \tag{2.2}$$

Where P is the applied pressure, x the sample thickness, F the frictional force, F_0 the initial friction, μ a constant, A the cross-section of the die, L the length of the die and D the diameter of the die. The impact of the type of equipment chosen would be minimal compared to the total effect of the type of biomass, pre-treatments and densification treatments (Mani et al., 2006).

2.2.2 Characteristics of Raw Biomass

Certain material properties are desirable to obtain optimal results during densification. Apart from availability and cost, the biomass should have the following attributes:

- **Moisture content** – The moisture of the raw biomass should be as low as possible to avoid excess energy for drying or grinding. Moist biomass creates more friction during grinding and will tend to clog when pelleting. The moisture of fresh wood is around 50 % wet basis (w.b.) while the one of waste wood or straws is around 15% w.b. (Loo & Koppejan, 2012).
- **Ash content** – Agricultural residues have relatively low ash content (1-8%), except straws with 0-15% and rice husk with about 20% (Grover & Mishra, 1996), but the composition is high in alkaline minerals which tend to devolatilise during combustion. This contributes to the fouling and slagging which occurs with fuels of ash content above 4% (Grover & Mishra, 1996). Overall, low ash content is desired for ease of handling and maintenance.
- **Size** - Fine particles (< 1 mm) are desirable when making pellets to increase the surface area and bonding during compression (Kaliyan & Morey, 2009b). Very fine particles tend to clog

the pellet roller. Bigger particles (> 6 mm) are recommended for briquettes to increase durability and favour interlocking between particles (Tumuluru et al., 2011). A mixture of particle sizes would also improve densification by filling inter-particle space.

- **Composition -** The constituents of the biomass may experience compositional changes during densification and influence the quality of the final product. Common transformations that enhance binding are the gelatinization of starch, the denaturation of protein, and the solubilisation and crystallization of sugars an salts (Kaliyan & Morey, 2009b).

  a) Starch: Under damp and hot conditions, starch gelatinizes. It acts as a binder and as a lubricant for the material to flow well through the die. However, raw starch does not really contribute to binding. The minimal recommended water to starch ratio is 0.3:1 and 1.5:1 for complete gelatinization (Kaliyan & Morey, 2009b).

  b) Protein: The protein plasticizes under heat, moisture and shear and form bonds. The effect is optimal with raw protein (not previously denatured). Sokhansanj et al. (2005) noted that biomass containing protein gave better results compared to a mainly cellulosic material. They also suggested a moisture content of 20% to pellet starch and protein material. The densification of protein-rich material is mostly relevant to the animal feed industry.

  c) Lipids: The presence of oily components would reduce the durability of densified products. Fat reduces friction between particles instead of creating bonds and inhibits bonding of water-soluble constituents (starch, protein, etc). However, small fat/oil content (< 1.5%) would be beneficial (Kaliyan & Morey, 2009b).

  d) Fibers: Fibers can be either water-soluble or insoluble. The soluble fibers increase the stability of the densified material in a similar way as starch while the insoluble ones you no help creating bonds. Insoluble fibres are also elastic in nature and would oppose the compression force. Moisture content above the fibre saturation point (20-26%) is not recommended (Faborode & O'Callaghan, 1987). Some chemical agents (NaOH, CaO, and urea) can be added to brake down the structure of the insoluble fibres.

e) Lignin: Lignin plays a role at high temperatures as it softens above 140°C (Chen et al., 2009; Mani et al., 2004b). It acts as an adhesive between particle when it solidifies, though the effect would be beneficial only up to a lignin content of 34% (Tumuluru et al., 2011). A ligneous biomass is a good fuel since lignin has a higher calorific value than cellulose.

f) Cellulose and Hemicellulose: Cellulose has a semi-crystalline structure highly bonded with hydrogen with no interesting adhesive properties. Hemicellulose has a more random and amorphous structure that could present more binding sites. However, both constituents require to be degraded to increase the flexibility and the branching capacity.

2.2.3 Pre-treatments of Biomass

Raw biomass can be subjected to one or more pre-treatments to improve the densification process and the quality of the final product. However, pre-treatments add to the total cost and should be selected in function of the properties of the raw biomass to be used and in function of the desired attributes of the end product to be formed. Common pre-treatments include:

- **Drying:** The raw biomass is dried when the water content is high. A moisture content of 10-20% is recommended before densification (Chen et al., 2009; Grover & Mishra, 1996; Missagia et al., 2011), and closer to 10% for pellet production (Loo & Koppejan, 2012). The least expensive method is to dry the biomass in piles outside over a summer which can bring the moisture down from 50 to 30%. Belt dryers, drum dryers, tube dryers, superheated steam dryers are other technologies that also exist to further lower the moisture content if required.

- **Grinding:** Some biomass particles are too large to be densified properly. Then, the size is reduced for ease of compression, homogeneity and stability of the final product. Singh and Kashyap (1985) found that reducing the size of the rice husk particles from 5.14 to 4.05 mm increased the durability of briquettes from 84.1 to 95%. Hammer mills are common for grinding. Mani et al. (2004a) studied the specific energy requirements during grinding.
- **Conditioning:** Biomass can be softened and braked down at the molecular level either with steam or with the addition of chemical agents to improve the adhesion between the particles. Biomass is sometimes leached to reduce the mineral content.
- **Binder:** The addition of binder that acts as glue in the biomass is common for low pressure densification though some biomass may still require a binder at high pressure. The binder forms bridges, a matrix or initiate chemical reactions to bond particles. The type of binder and concentration depends on the cost and availability, the composition of the raw biomass, the end use and desired quality of the final product, and the temperature and pressure of densification. A binder may not be required with ligneous material compressed above 140 ºC. Taulbee et al (2009) investigated over 50 types of binders to briquette coal and sawdust. Binders can be organic, either hydrophobic (resins, wax) or hydrophilic (starch, molasses), or inorganic, either insoluble (clay) or soluble (lime). The binder should also be selected in function of its influence on the combustion and emissions. Inorganic binders tend to increase the ash content but not the organic ones. Water can also be combined to a binder for gelatinization and uniform binder distribution throughout the biomass. A minimum level of moisture is required to reduce the friction between particles, but beyond a certain point, the additional moisture occupies the pore space and increases the resistance to compression.

2.2.4 Densification Treatments

A number of factors influence the compression process. Several densification treatments can be used at once and should be adjusted according to the characteristics of the biomass and the pre-treatments selected. Densification treatments can be used along with pre-treatments, though densification treatments can overcome the need for certain pre-treatments. For instance, increasing the densification pressure and temperature reduces milling and binder requirements.

- **Temperature:** Hot compression (> 60-70 ºC) induces more permanent deformation in the molecular structure of the biomass and reduces the expansion of the final product. Rhén et al (2005) suggest that temperature is one of the most important factors to improve the strength of sawdust pellets. Faborode (1989) reported that bonding increases as the temperature rises and that the outcome is similar to creep deformation in non-linear visco-elastic solids.
- **Pressure:** Pressure reduces the air voids in the biomass and increases the contact between particles. High pressure also forces out the natural constituents (starch, protein, and lignin) that enhance bonding. Tumuluru et al. (2011) mentioned that density is proportional to the natural logarithm of the applied pressure. Panwar (2011) reported a relationship between pressure and density given by Kaminski:

  $$\rho = kP \exp(n) \qquad (2.3)$$

  Where ρ is the bulk density (kg m $^{-3}$), k and n constant, and P the applied pressure.
- **Dwell time:** The dwell time refers to the retention time in the die or the time for which the piston is held down during briquetting. This time allows for more permanent deformation relative to an impact pressure, though the effect of dwelling was reported as minor especially at high pressure (Li & Liu, 2000; Taulbee et al., 2009). At 103 MPa, Li and Liu (2000) measured a 5% increase in sawdust briquette density with a 10s dwell time. Chin and

Siddiqui (2000) observed a reduction in the briquette expansion with a dwell time of 20-40 s and an increase in strength until 60 s when the effect became asymptotic. They also developed a relationship between the dwell time and combustion rate $\dot{m}$:

$$\dot{m} = at \exp(-b) \tag{2.4}$$

Where t is the dwell time (s), and a and b are empirical constants specific to each biomass.

- **Die geometry:** The dimension of the die influences the stability of the product. The applied pressure can be increased by reducing the diameter. If the die is loo long, the friction between the particles and the wall of the die will opposes the compression force. The pellet durability would increase with a length to diameter ratio around 8-10% (Kaliyan & Morey, 2009b).

2.2.5 Compression Mechanisms

The densification process induces changes within the molecular structure of the biomass. Mani et al. (2004b) studied different compaction models: the Heckel model and the Cooper-Eaton model for powdered and cellulosic materials, and the Kawakita-Lüdde model for softer materials. On the whole, three stages were identified for time independent and room temperature compression described by Faborode & O'Callaghan (1987;1989). The inertia stage is the initial compression that expulses the air out of the voids and rearranges particles more closely together. The upper elements are subjected to a totally irreversible deformation and the fractures in the middle elements are partially reversible. The inertia stage accounts for 14 to 38% of the specific energy of compression. The second stage consists of the dense stage also referred to as the elastic stage and starts after the critical density point. Beyond the critical point, there is resistance to compression from the elasticity of the particles. However, the particles are more in contact with each other creating short-range bonds. The elastic stage induces recoverable deflection until the pressure further increases to reach the third and irrecoverable stage. During the elasto-plastic deformation, the particles fracture leading to mechanical interlocking. The compressed height to the recovered height is the relaxation ratio which assesses the residual deformation after densification and accounts for 54 to 77% of the total deformation. In the case of very high pressure or hot compression, the biomass can reach the visco-elastic stage which is recoverable but time dependant, and finally the irrecoverable and time independent visco-plastic stage.

2.2.6 Bonding Mechanisms

The compression and reduction of inter-particle space leads to the formation of different types of linkages between the particles depending on the amplitude of the applied pressure (Figure 2.2). The bonding mechanisms are also influenced by the densification treatments and the constituents in the material. The analysis of the micro-structures can be achieved using light microscopy, scanning electron microscopy and UV auto-fluorescence imaging. The bonding mechanisms consist of short range bonds, solid bridge, cohesive bonds, and mechanical bonds which have been described by Kaliyan and Morey (2010) and Tumuluru et al. (2011).

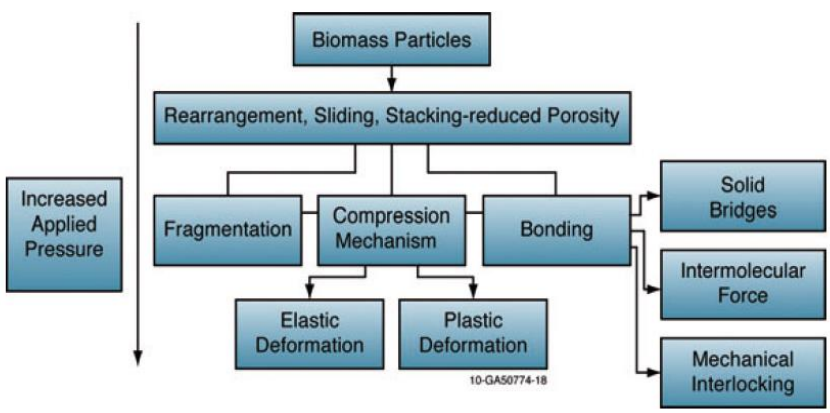


Figure 2.2 – Bonding and compression mechanisms of particles (Tumuluru et al., 2011)

At the inertia stage, short range bonds take place which highly rely on the attraction forces between particles that are close enough together. The effect can be molecular with valance forces (i.e., free chemical bonds), hydrogen bridges, and van der Waals' forces. Van der Waals' forces would act when particles are less than 0.1 μm apart (Kaliyan & Morey, 2010). The covalent bonds would be the strongest, followed by the hydrogen one and finally the van der Waals'. Though each individual van der Waals' bond may be weaker, their total contribution is believed to be amongst the most important intermolecular attractions. The presence of water also contributes to the creation of molecular forces. Water creates a film like binders, increases the contact area between particles and offers hydrogen bonding sites. Other short range bonds come from electrostatic and magnetic attractions. Electrostatic is a result of excess charge from the grinding or inter-particle friction while magnetic forces occur in powdered material.

On the other hand, solid bridge mechanisms result from high pressures and temperatures and the subsequent chemical reactions and cooling and drying of both the densified product and the additional binders if any. Those bonds can be a product of diffusion at points of contact between molecules. Applying pressure lowers the melting point of particles and allows them to move towards each other and fuse together. Solid bonds are also formed with the solidification and crystallisation of melted constituents. Those natural binders present in the biomass are activated at a minimum temperature called the glass transition temperature which is specific for each biomass. For instance, the glass transition temperature of corn stover and switchgrass is about 75 ºC (with 10 to 20 % moisture content w.b.) (Kaliyan & Morey, 2010).

As well, mechanical processes act on fibres, flat and bulkier particles which can no longer change position. Brittle particle will fracture since the particles have no more free space to adjust under deformation. The compression causes them to fold on each other or interlock. Mechanical interlocking bonds are strong enough to resist the counter-acting forces of elastic recovery during relaxation after densification. The presence of liquids promotes the formation of interfacial and capillary forces. An adsorption layer as thin as 3 nm is beneficial. It increases the contact area (by evening out the surface of the particles), reduces inter-particle space and favours molecular attraction forces. Liquids also spread between non-soluble elements and help to hold them together by capillarity. Soluble particles are also dispersed along with the liquid and will create solid bridges in the form of necks after the liquid evaporates. Finally, adhesion and cohesion forces result from highly viscous binders. Adhesion takes place when the viscous substance is sticking to the surface of solid particles. Bonds are also formed from the cohesion happening within the binder itself. Then, solid bridges will be formed upon hardening and cooling. Overall, the effectiveness of inter-particle bonds is the main indicator of the final quality of the densified product. The bonding level can be measured by performing physical tests.

2.2.7 Properties of Densified Biomass

A number of mechanical and chemical properties can be tested to measure to quality of the densified biomass. These properties are also useful to determine whether the briquettes, cubes or pellets are adequate for combustion, but also and for handling, transportation and storage. The 'green' properties are measure immediately after densification or the 'cured' properties after relaxation and a certain period of time usually around one week. The final bulk density and relaxation ratio are indicators of the degree of densification. The final bulk density is compared to the initial one while the unit density is the measure of how close the particles are to each other inside the briquette, cube or pellet. The relaxation ratio measures the increase in volume once the product is removed from the die after densification. Chin and Siddiqui (2000) found that relaxation usually occurred for 2 h after compression with the maximum relaxation in the first 10 min. They also noted that the time of relaxation was smaller with increasing pressure.

Different forces can act to deteriorate the final product (Mina-Boac et al., 2006). Impact forces shatter the material after collision with a plane surface. Compression forces can crush the product until it fails along planes and shear forces causes abrasion at the edges and surface. The physical integrity to oppose those forces is measured in terms of durability (resistance to abrasive resistance), compression strength (resistance to compression), impact strength (resistance to drop and shattering) and water resistance (resistance to penetration by water and moisture).

Other properties are indicators of the quality of combustion such as moisture content, ash content, heating value, ignitability, and combustion rate. Low moisture content is recommended not to substantially decrease the heating value of the material because of the energy required to evaporate the water during combustion. A fuel with a high heating value will release more energy per unit of mass burned. A biomass fuel should also ignite easily without spontaneous ignition during storage. A low combustion rate will reduce the number of refuelling required to accomplish given task and would be related to the density of the product (Zhang et al., 2012).

2.3 Cookstoves

The direct combustion of solid biomass can take place at the industrial scale either for thermal applications or electricity production via steam generation. The combustion technologies are either batch or continuous systems and include fixed beds, fluidized beds (bubbling or circulating combustion) or pulverized fuel beds. Fixed beds, commonly referred to as fuel bed combustion, have wider applications and simply consist of the biomass burning in piles. The last two technologies consist of pulverizing the fuel and are barely applicable in small scale combustion. At the household level, biomass combustion provides energy for heating or cooking with the device being optimized for the end use. Household biomass heating appliances (fireplaces, stoves, central heating furnaces or boilers) are designed to provide a relatively constant rate of heat-output into the living space for as long as possible with one batch of fuel to reduce the refuelling frequency. The heat output is often controlled by limiting the supply of primary air in the fuel. The heat dispersion can be assisted with a fan, heat exchanger and/or air circulation system throughout the house. On the other hand, cookstoves are usually smaller as the heat is meant to be directed specifically towards a pot. Cookstoves are often operated at higher intensity to achieve a cooking task in a short time and require frequent refuelling and tending. Cookstoves designs are intended to reduce at the maximum the heat loss to the surrounding.

A variety of cookstoves exist according to the context in which they are used, the material and fuel available, the type of food to cook, and the end user preferences. The 3-stone stove is the most common stove found around the world, mostly in developing countries. This stove is simply made of three rocks set in a triangular shape to hold a cooking pot over an open fire. This basic system is still used on a daily basis by nearly three billion people in the world despite its low thermal efficiency (5 to 15% (Alakali et al., 2011; Bhattacharya & Salam, 2002)). This instigated the development of improved cookstoves (ICs), starting in the 1980's. The objective is to increase the energy efficiency to reduce the amount of fuelwood used while cooking, and to improve the combustion efficiency to reduce the production of smoke, both for environmental and health purposes. Prasad et al. (1985) expressed that the access to ICs should be a basic right as eating is a fundamental need and staple foods have to be cooked to be edible.

Table 2.2 provides an overview of the stoves and fuels available worldwide, including traditional stoves, improved biomass stoves, and other ICs using fossil fuels, electricity or renewable energies. The energy efficiency of liquid, gas and electricity is appealing, though the system efficiency (over the life-cycle) provides a better indication as it includes the energy required during the production. Also, the efficiency of electric stoves largely depends on the primary energy used to produce the electricity (hydropower or fossil fuel). This current work will focus on the direct combustion of biomass (wood and agricultural residues) in ICs.

Table 2.2 – Efficiency of cookstoves and fuels (Baldwin et al., 1985)

Technology	Efficiency (%)		Technology	Efficiency (%)	
	Stove	System		Stove	System
Traditional stoves			**Liquid Stoves**		
Dung	11-15	10-14	Kerosene Wick	40-45	36-41
Agricultural Residues	13-17	12-16	Kerosene Pressure	45-50	41-45
Wood	15-19	14-18	Alcohol Wick	40-45	33-37
Charcoal	19-23	8-12	Alcohol Pressure	45-50	37-42
Improved Biomass Stoves			**Gas Stoves**		
Wood	27-32	26-31	Central Gasifier	55-60	39-42
Charcoal	29-34	13-17	Site Gasified	40-45	39-44
Wood II	40-44	38-42	Biogas	55-60	54-59
Electricity			LPG	55-60	48-53
Resistance	60-65	17-21	Natural Gas	55-60	53-58
Microwave	55-60	16-20	**Solar**		
			Solar Box Oven	25-30	25-30

2.3.2 Types of Improved Biomass Cookstoves

Over the past 40 years, hundreds of ICs have been designed by different organisations and research institutions. There are an estimated 220 million ICs in use worldwide, with a significant number in China and India (Sagar and Karhta, 2007). Thornburn and Moeliono (1982) classified biomass ICs in function of the fuelling method: packed stoves and natural draft stoves. First, packed stoves are made in a hollow vessel (mud, fired clay, bricks or metal) tightly filled with loose agricultural residues. At the time of filling, a stick is held vertically inside the middle of the vessel and a second one horizontally at the bottom to leave an air channel to fire the biomass once the sticks are removed. Secondly, natural draft stoves burn densified biomass or wood placed on a fuel bed at the bottom of a combustion chamber that acts like an internal chimney. The hot gas rises and the draft draws air from the bottom through the burning fuel. The forced draft stoves operate on the same principle but with a mechanically powered fan.

Alternatively, De Lepeleire et al. (1981) categorised the biomass ICs according to their visual aspect: closed heavyweight, shielded heavyweight and shielded lightweight. These categories can be further subdivided according to the size (household or institutional size, staple or sauce cooking pot cooking pot), number of pot holes (one or more), type of fuel (charcoal, wood, agricultural residues) and type of food (to roast tortillas, boil water, grill meat, etc).

2.3.2.1 Shielded Heavyweight Stoves

Shielded heavyweights are made of mud, clay, bricks, concrete, sand, or a combination of those. These mud and clay stoves are mostly an attempt to protect the fire from the wind which is responsible for a large fraction of the heat dissipated, and do not allow controlling the air flow in the fire bed. Heavyweight stoves can not be moved once they are built, though smaller versions have been built in old metal basins. Modified traditional stoves (Figure 2.3a) and u-shaped stoves (Figure 2.3b) are shielded heavyweight stoves, the most accessible ICs because of material availability, ease of the construction, and resemblance with the traditional cooking method. Simple modifications to the 3-stone stove can be beneficial. Ballard-Tremeer and Jawurek (1996) measured a 7% increase in the thermal efficiency only by adding a grate. Yet, the lack of air supply in the enclosed fire can result in incomplete combustion (Alakali et al., 2011). The u-shaped stove was reported more pollutant than the 3-stone stove and not necessarily more efficient (5 to 17%) (Berrueta et al., 2008). Thus, ICs can potentially increase harmful emissions compared to the 3-stone stove and should be carefully assessed before implementation.

Figure 2.3 – The traditional (a), modified traditional (b) and the u-shaped (c) shielded heavyweight stoves.

2.3.2.2 Closed Heavyweight Stoves

Closed heavyweight stoves are made with similar material but processed in the form of bricks (either sundried of fired). They are often square or rectangular and can present more than one pot holes. The construction is somewhat more extensive than the shielded heavyweight stoves and is also made in-situ. Closed heavyweight stoves are often built following the principles of an insulated circular combustion chamber, a feeding channel at the bottom to insert the wood and preheat the air, and devices to control the air flow such as chimneys, baffles, grates and doors (Witt et al., 2006). The closed heavyweight stoves are usually built inside the house with the smoke directed outside with a chimney (Ballard-Tremeer & Jawurek, 1996; De Lepeleire et al., 1981). The Plancha (Boy et al., 2000), the Patsari (Berrueta et al., 2008) and the Lorena (Wallmo & Jacobson, 1998) are common models. Alvarez et al. (2004) measured fuel savings between 50 and 67% compared to the 3-stone stove, but others reported no fuel saving (Baldwin et al., 1985; Ballard-Tremeer & Jawurek, 1996) or even an increase in fuel use (Jetter & Kariher, 2009; McCracken & Smith, 1998; Wallmo & Jacobson, 1998) as heat is captured by the in high-mass stove body and some escapes from the chimney with the natural draft induced.

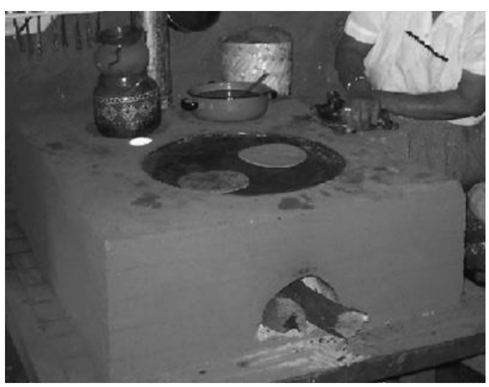


Figure 2.4 – The Patsari stove (closed heavyweight stove) in South America to roast tortillas (Berrueta et al., 2008)

2.3.2.3 Shielded Lightweight Stoves

Shielded lightweight stoves are often manufacture ex-situ, and are smaller and easily moveable, which is convenient though less stable with larger pots. A wider variety of lightweight stoves exist (according to the type of fuel: charcoal, densified or loose biomass, liquid fossil fuel, wood) compared to the heavyweight stoves made to burn wood and agricultural residues (densified or in the form of stalks or sticks). The simplest shielded lightweight stoves are made of fired clay to burn charcoal (Figure 2.5a). Others are made using a ceramic insulator and a metal outer wall (Figure 2.5b) or with light-gauge steel for both the inner and outer walls (Figures 2.5c), though metal stoves are sometimes criticized not to last as long. The efficiency of such stove was reported between 20 and 24% (Ballard-Tremeer & Jawurek, 1996) and from 12 to 27% (Bhattacharya et al., 2002). More sophisticated biomass ICs such as gasifier stoves present greater thermal efficiencies between 30 and 54% (Jetter et al., 2012). Gasifiers (Figure 2.5d) burn pelletezed biomass or even loose agricultural residues in the apparent shape of pellets (rice husks, peanut shells, etc) because they are equipped with a powered fan to increase airflow through the fuel. Gas stoves (LPG, kerosene, natural gas) even reach 57 to 62% (Akter & Hossain, 2001). Biomass gasifiers can reduce fuel consumption by 25 to 50% (Sagar & Kartha, 2007) and emissions by more than 10 folds (Jetter et al., 2012) tough this may not be fully appreciated at first by the users compared to the change in cooking habits.

Figure 2.5 – Shielded lightweight stoves, the a) Rungsit (Bhattacharya et al., 2002), b) Jilko (MacCarty et al., 2008) and StoveTech, c) Vita, and d) Philips (MacCarty et al., 2010).

2.3.3 Combustion Principles

Figure 2.6 represents the stove reduced to the schematic interactions within the open system. The system is basically formed by the heat source (fire), the cooking pot and the walls of the combustion chamber. The arrows illustrate the relationships between the elements and the flow of heat from the fire to the pot, the walls and to the surrounding. The actual efficiency of conversion of wood into heat is relatively high (above 90%), but the challenge is to optimize the amplitude of the heat flow to the cooking pot (from the fire or from feedback from the wall and surrounding) while reducing the heat losses as much as possible. The peak temperature of combustion in the system is determined from the balance between the exothermic combustion of CO and CO_2, the absorption of heat by the reduction of CO_2 and the heat losses from the system.

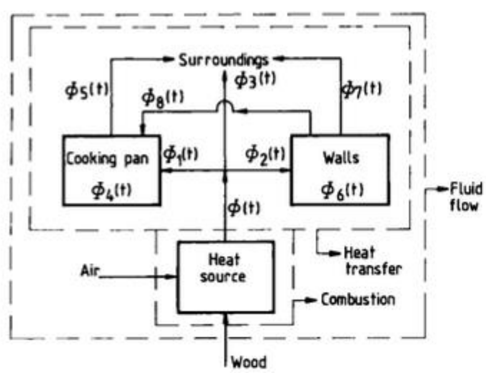


Figure 2.6 – The cookstove system and heatflows. The heavy lines are system elements, the arrows are interaction paths and the dashed lines processes (Prasad et al., 1985).

Three distinct processes are involved in the direct combustion of solid biomass on fixed beds: the pyrolysis, the burning of char, and the burning of volatiles. All three occur somehow at once and contribute to feed the reaction with feedback from the flame zone (exothermic reaction from the burning of the char) to maintain the pyrolysis in the fuel bed which is an endothermic.

During pyrolysis, the volatile matters in the wood are liberated and the remaining forms what is known as char. Moisture is the first one to evaporate (until 110 °C) and the chemical changes in the wood increase along with the temperature. Hemicellulose decomposes between

200 and 260 °C, followed by cellulose and lignin from 240 to 350 °C (Prasad et al., 1985). The pyrolysis step is usually complete by the time the wood reaches about 500 °C (Prasad et al., 1985). Then, the burning of the char consists of the combustion reaction itself (glowing combustion) of the fixed matters remaining (mostly carbon). The reaction can be simplified in three steps. The heterogeneous combustion occurs first with the oxygen travelling through the fuel bed and reacting with the solid fuel according to the chemical reaction: $2\ C + O_2 \rightarrow 2\ CO$. The second step is the homogeneous combustion when the CO migrates between the particles and reacts with oxygen: $2\ CO + O_2 \rightarrow 2\ CO_2$. The heterogeneous reduction follows with the CO_2 reacting with the carbon molecules to give: $CO_2 + C \rightarrow 2\ CO$. The combustion reaction is continuous as long as there is sufficient oxygen and heat.

Finally, the burning of the volatiles (flaming combustion) takes place above the fuel bed and involves complex chemistry with the release of more than 200 separate compounds participating in the reaction process (Prasad et al., 1985). During biomass combustion, the volatiles burn with a diffusion flame where the fuel burns by entraining air from the surrounding without external assistance. A second type of flaming combustion consists of premixed flames and is found in jet planes when the fuel and the air are mixed together before the combustion.

2.3.4 Design Parameters

2.3.4.1 Improving the thermal efficiency

Increasing the thermal efficiency reduces the amount of fuel consumed and reduces the time required to accomplish a cooking task. First, the flue gases touching the pot should be as hot as possible. Therefore, the combustion chamber should be insulated with low mass and heat resistant material and enclosed to protect from the wind not to decrease the temperature of the fire (Baldwin et al., 1985). Secondly, if there is no fan, a good natural draft should be maintained through the burning fuel with a vertical combustion chamber above the fuel bed or a tunnel-shaped opening to feed the fuel. A draft increases the flame height and the flue gas velocity for proper heat transfer (Bryden et al., 2005). Alakali (2011) showed a reduction of 4 min in the required time to boil 4.5 L of water by increasing the air flow rate from 0.13 to 0.16 m^3/s. If an external chimney is used, the draft can be controlled with a baffle not to loose heat from unnecessary high draft (Baldwin et al., 1985). Finally, the convective heat loss from the pot to the surrounding can be reduced by adding a pot skirt. This shield will force the hot flue gases to remain close to the side of the pot and increase heat transfer (Adkins et al., 2010). Bryden et al. (2005) shared guidelines to measure the adequate gap size (G) between the pot and the skirt in function of the size of both the pot and stove:

$$\text{Gap Size} : G = A_c / C_p \tag{2.5}$$

with C_p the circumference of the pot and A_c the cross-sectional area of the combustion chamber (which depend on the desired power output). Also, the cross-sectional area of the flow of the hot flue gases should be constant.

2.3.4.2 Improving the combustion efficiency

Different design principles to improve the combustion efficiency can help to reduce the production of smoke and harmful emissions. First, the cold air entering the fire should be limited (e.g. small door opening), so the primary air passing through the fuel should be pre-heated either by adding a grate to elevate the fuel bed (Ballard-Tremeer & Jawurek, 1996). The primary air is the one that allows to the combustion reaction of the fuel to take place. The secondary air should also be preheated and in adequate proportion (usually a ratio of about 6:1 for secondary to primary air). The secondary air is the one entering the system above the fuel bed to oxidize the volatiles in the flue gas. The air and flue gas should then be mixed in the appropriate proportion.

If the air is too cold or too much in excess, it will cool down the flue gas and negatively affect the efficiency of the combustion. If the power output at which the stove should operate and the velocity of the air entering the stove are known, the amount of air per unit of time and the area of the air holes required for complete combustion of the wood can be calculated using stochiometry. Complete combustion is visually assessed by a blue flame, similar to natural gas combustion. A yellow flame indicates the presence of unburned volatiles. If we assumed complete stoichiometry (all the air used in the combustion reaction), the only end products would consist of CO_2, H_2O, 0_2 and N_2. However, the flue gas still contains CO, unburned particles, and H_2 and a certain amount of excess air is necessary. Operating at lean combustion, slightly above stochiometric conditions (i.e. air rich combustion with an air to fuel ratio slightly above 1) will provide enough air, but not too much, to oxidize the volatiles and the CO as much as possible. The excess air factor is the ratio of the total amount of air involved in the combustion to the amount of stoichiometric air. Designing a stove to reach optimal combustion efficiency is the art of fine-tuning the gaps and dimensions of the combustion chamber to find the right balance between the secondary and primary air. Prasad et al. (1985) proposed an equation to derive the stoichimetric amount of air, V_{st} in moles, from the ultimate analysis of wood:

$$V_{st} = \frac{1}{0.21}\left[\left(1-\frac{1}{2}f\right)\frac{p}{12}-\frac{y}{32}\right] \qquad (2.6)$$

Where f is the combustion efficiency, the ratio of carbon emission $CO/(CO + CO_2)$; p is the carbon content in the fuel (%); x the hydrogen content (%); and $(8x + y)$ the oxygen content (%).

Moreover, the combustion chamber should be high enough for proper flame development and residence time, and avoid quenching (Akter & Hossain, 2001). Quenching occurs if the combustion reaction stops as the flame hits the pot. If the residence time is too short, the amount of unburned volatiles will increase. The optimal volume of the combustion chamber can be calculated from the power output of the stove to maximize the radiant heat transfer.

Beyond the design aspects, the way the fire is tended by stove users also influences the combustion efficiency. The air should be well distributed and able to flow easily at the surface of the fuel. It is recommended to burn only the tip of the fuel, to increase the surface area of the fuel (smaller pieces of fuel), and to leave space between the pieces instead of having a random stack. The moisture content of the biomass at time of combustion also significantly influences the emissions. If the fuel is moist, more heat is required to evaporate the water which in turn lowers the temperature of combustion and increase the release of particulate matters (PM) and CO.

2.3.5 Stove Emissions: Implications on Climate and Health

The general reaction of complete combustion of a carbon based reactant is well known as: $C\text{-}H_2 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O$. Yet, complete combustion is hardly achieved in cookstoves resulting in some products of incomplete combustions (PICs) which have a greater impact on climate (GWP) than CO_2. Emitted in concentration often 10 to 15% higher than CO_2, CO is a result of lack of oxygen, poor fuel-air mixing and lower combustion temperatures. Non-methane hydrocarbons (NMHCs) are mostly composed of hydrogen and carbon. Elemental carbon (EC), which includes soot and black carbon, are carbon particles that do not volatize around 600 °C, temperatures of the char burning phase (MacCarty et al., 2008). EC is one of the main aerosols in the atmosphere which impact the global climate by scattering and absorbing sunlight. About 20% of the EC come from biomass combustion (Roden et al., 2009). The single scattering albedo measures the effect of one particle, with a net warming force below 0.85. Typical values for EC are between 0.3 and 0.5 (Roden et al., 2009). MacCarty et al. (2008) found that rocket-type or fan-powered ICs can reduce the climate impact of PICs by 50 up to 95%.

Emission	Global warming potential, 100-year CO_2 equivalent
CO_2	1
CO	1.9
CH_4	25
NMHC	12
N_2O	298
PM - EC	680

Figure 2.7 – Global warming potential of products of incomplete combustion (MacCarty et al., 2008)

PICs also have adverse effect on human health. The exposure level of stove user depends on the type of fuel and stove, the cooking frequency/length, and the ventilation. The indoor air pollution associated with incomplete combustion in developing countries would be directly responsible for more deaths than malaria, almost as many as tuberculosis and almost half as many as HIV/AIDS (IEA, 2006). There would be about 4 000 deaths per day attributed to indoor air pollution, with more than half being children under fiver year old and 95% living in developing countries. The main PICs affecting human health are PM, CO, polycyclic aromatic hydrocarbons (PAHs), nitrogen oxides (NOx), volatiles organic compounds (VOCs), and sulfur oxides (SOx), arsenic and fluorine for coal combustion more specifically. The main resulting health diseases include acute lower respiratory infections (pneumonia, tuberculosis), chronic obstructive pulmonary disease (bronchitis, asthma), and lung cancer. PICs would also have non-respiratory impacts such as stillbirth, lower cognitive development and visual impairments. Smith et al. (2004) also described the mechanisms of air pollution on low birth weight.

The risk level is directly correlated to the concentration of the pollutant. There would be roughly a 0.7 to 1.1% increase in daily mortality for every increase of 10 mg m^{-3} in PM in ambient air (Larson & Rosen, 2002). The WHO (2006) listed a series of standards for exposure limits to keep the level of pollutants in the blood below 2.5%. The maximum recommended level of CO is 10 ppm for an 8 h period and 5 000 ppm for CO_2. Battacharya and Salam (2002) compiled emission factors of which ranged between 13 and 624 g kg^{-1} of dry fuel for CO. Masera et al. (2000) even observed a concentration in PM two time higher in lower incomes household (449 lg m^{-3} compared to 845 lg m^{-3}). The main categories of interventions to reduce health impacts are either from changes in behaviour (keep young children away from the fire), in ventilation (more windows, cook outside), in fuel (from solid fuel to a lower emitting fuel), and in cookstoves (IC instead of 3-stone stove). In terms of ICs, different studies have demonstrated the effectiveness in reducing the emission of pollutants. Albalak et al. (2001) measured a 85% reduction in PM emissions using the Plancha stove over the 3-stone stove. MacCarty et al. (2010) reported a reduction of 75% in CO and 46% in PM emission. They also mentioned how gasifier and forced air stoves can reduce even more substantially the PM, sometimes up to 90% compared to the 3-stone stove. However, the laboratory settings to tests the ICs are somewhat ideal compared to the field. ICs do not always perform as well when tested in household settings. It was previously found that the average PM emission factor in the field was four times higher that the one in the lab (6.1 compared to 1.5 g kg^{-1}) (Roden et al., 2009). Also, epidemiologists would argue that substantial emission reduction of airborne pollutants is still required. The actual emission reduction in many biomass stoves may still not be significant enough to considerably reduce the health response, as even a small level of exposure over time is enough to trigger adverse health effects.

Connecting Statement to Chapter 3

The main goal of this study was to assess the potential of using rice husk as a raw material for the production of biomass fuel briquettes for rural West Africa. After an overview in Chapter 2 of the principles of biomass densification and energy generation via direct combustion, Chapter 3 now examines more specifically different parameters that influence the production of rice husk briquettes under low pressure and different tests to asses to quality of the briquettes produced.

The following chapter is drawn from a journal article that was prepared for publication in *Biomass and Bionergy*. The manuscript was co-authored by Audrey Yank, M.Sc. Candidate at McGill University, Dr. Michael Ngadi and Dr. Robert Kok, supervisor and co-supervisor, and professors at McGill University. The format has been changed to be consistent with this thesis.

Chapter 3: Physical Properties of Rice Husk and Bran Briquettes under Low Pressure Densification for Rural Applications

3.1 Abstract

Agriculture generates large amount of by-products that could be used to produce energy and reduce the amount of fuelwood required to meet the daily cooking needs, especially in developing countries. Rice is a major crop grown in West Africa and rice husk is a by-product of the milling process. The goal of this study was to develop a low cost system to produce biomass briquettes from rice husks in the context of a rural village. A manual press generating 4.2 MPa of pressure was developed and used. The influence of the briquette formulation (type of binder, binder content, water addition, and bran content) was studied. The binders investigated were cassava wastewater, rice dust, and okra stem gum. The physical properties (density, moisture content, calorific value, durability, and compressive strength) were tested to identify the briquettes with the highest quality, i.e. greatest physical integrity. The briquettes made with rice dust had the highest durability (91.9%) and compressive strength (2.54 kN), while the briquettes made with cassava starch wastewater had the greatest density (441.18 kg m^{-3}). Water added to the rice husk before densification positively influenced the briquette quality while bran seemed to mostly increase the density, but not necessarily the briquette quality. The briquette formulation did not significantly influence the calorific value. With a higher heating value of 16.08 MJ kg^{-1} dry basis, rice husk briquettes represent an interesting alternative to fuelwood.

3.2 Introduction

Worldwide, up to three billion people cook using fuelwood on a daily basis (FAO, 2012). Biomass represents 80% of the energy supply in developing countries (UNEP, 2012). There is an increasing need to source alternative fuels, especially for cooking so as to reduce deforestation as a result of trees being cut for fuelwood. More than 14 MT of rice paddy is produced in West

Africa every year (Diagne et al., 2007) along with a significant amount of by-products. Paddy contains about 25% husk and 10% bran (Saunders, 1985). Rice husk and bran are mostly considered as waste and are left to accumulate in big piles, which represent a handling issue and a source of water contamination (Lim et al., 2012). When too much accumulates, the piles are usually burned in open fires and become a major source of air pollutants and greenhouse gases (Thao et al., 2011). The majority of the rice mills in the developing world involve a one-stage process, with both the husk and bran being removed simultaneously. Otherwise, a two-stage mill separates the by-products. These by-products could be managed as a new domestic fuel to replace fuelwood. Rice husk does not compete with food sources (Lim et al., 2012) and receives stable supply as rice is the third crop in importance in the world in terms of tonnes harvested (Zhang et al., 2012). With the majority of rice husk produced in developing countries, it represents an opportunity for greater energy sustainability in this part of the world (Jekayinfa & Scholz, 2009; Lim et al., 2012; Mansaray & Ghaly, 1997; Thao et al., 2011).

Different studies have recognized the qualities of rice husk (and bran which has 10 to 23% oil content (Saunders, 1985)) as a combustion fuel. Despite its high ash content (up to 25%) (Mansaray & Ghaly, 1997), rice husk has low moisture content (Missagia et al., 2011), satisfying calorific value and low sulfur content (Armesto et al., 2002; Lim et al., 2012)). However, agricultural residues, including rice husk, present low bulk densities usually under 200 kg m^{-3} (Tumuluru et al., 2011). Densification into pellets (less than 2.5 cm in diameter) or briquettes (2.5 to 10 cm in diameter) is required to overcome this challenge. The advantages of densified biomass include: increased calorific value, improved ease of handling, transportation and storage, improved combustion and lower particulate emissions, and reduced volatility along with uniform size, density and quality (Kaliyan & Morey, 2009b; Tumuluru et al., 2011).

Energy can be obtained from biomass through direct combustion, gasification, pyrolysis, anaerobic digestion, hydrolysis, hydrogenation or fermentation (Chen et al., 2009). Lim et al. (2012) provided an overview of the technologies available to produce heat, electricity or value added products (ethanol composites, absorbents) from rice husk and straw. However, such processes are energy and equipment intensive. Briquetting remains the most applicable technology to produce energy in the form of solid fuel for cooking at the household level in rural settings (Oladeji, 2010; Sotannde et al., 2010).

The characteristics of briquettes made of grass (Kaliyan & Morey, 2009c), wood (Li & Liu, 2000), fibers (Faizal et al., 2010), straws (Mani et al., 2004a), leaves (Panwar, 2011), stalks (Zhang et al., 2012) and husks, including rice husk alone (Missagia et al., 2011; Oladeji, 2010; Shrivastava et al., 1989) and in combination with other biomass (Bhattacharya et al., 1984; Islam et al., 2004), have been previously studied under high pressure. Limited studies have been conducted on rice bran, and mostly in combination with rice straw (Chou et al., 2009a). The quality of the biomass densification can be determined by testing the physical properties of the briquettes (Bhattacharya et al., 1989). Kaliyan and Morey (2009b) discussed how the final product is affected by the pre-treatments and the initial characteristics of the biomass, namely particle size, moisture, temperature, and binder content. The high quality of a briquette indicates the effectiveness of inter-particle bonds (Kaliyan & Morey, 2010). Particle size reduction is usually recommended in order to reduce inter-particle space and create strong bonds during compression (Bhattacharya et al., 1989; Missagia et al., 2011). High temperature and pressure are also widely agreed to enhance binding mechanisms (Chou et al., 2009a; Faborode & O'Callaghan, 1987; Suhartini et al., 2011). Yet, these processes require important energy input.

Few studies have been conducted on the densification of rice husk at low pressure and room temperature. Low pressure densification of rice husk presents an opportunity to reduce energy input although it requires using a binding agent to create sufficient cohesion and briquette durability. Binders have been used for low pressure densification of biomass. Taulbee et al. (2009) investigated over 50 different binders for coal and sawdust briquettes. Water is also suggested to play a role to reduce friction and void space during compression (Bhattacharya et al., 1989; Faborode, 1989). Carbohydrates, proteins and lignin are considered excellent organic binders, but proteins and lignin only melt and bind under high temperature densification (above 140 °C) (Tumuluru et al., 2011). Also, binders should ideally consist of waste by-products. For example, West Africa produces 84 MT of cassava annually and the subsequent processing discharges about 250-300 L of wastewater per tonne of tuber, which affects the water streams with high biological oxygen demand (25,000 to 50,000 mg L^{-1}) (FAO, 2001). The cassava wastewater is rich in cassava starch as the tubers present a starch content typically around 20-30% (Osunsami et al., 1989; Safo-Kantanka & Owusu-Nipah, 1992). Another waste by-product consists of rice dust. Rice kernels are often milled to produce flour. Large amount of rice dust accumulates on the floor of milling facilities and is then swept and discarded. Finally, the okra fruit is known for its high mucilage content used in pharmaceuticals because of its binding properties (Ameena et al., 2010; Ogaji & Nnoli, 2010). The roots and stems of the okra plant also contain mucilage (Ogaji & Nnoli, 2010) but are barely used, though the stems may be collected sometimes for fiber or rope.

The objectives of this study were firstly to develop a village scale low pressure densification method to use rice husk for briquette production for cooking purposes; secondly, to investigate the impact of bran and water addition on low pressure and temperature densification of rice husk, and thirdly to identify high quality briquettes based on a range of combinations of rice bran, water addition, types of binder and binder content.

3.2 Material & Methods

3.2.1 Rice Husk

Approximately 50 kg of dried two-stage rice husk grinds (imported from USA) was purchased from Moût International (Montréal, QC, Canada). The experiments took place at the Macdonald Engineering shop. The rice husk was ground in a hammer mill (Thomas no. 4275-210, PA, USA) fitted with a 2 mm mesh to simulate the one-stage grinds usually found in the area of interest targeted by this study. Grinding is also recommended when two-stage rice husk is to be used for low pressure densification (Chou et al., 2009b; Faborode & O'Callaghan, 1987).

The fraction size distribution of the rice husk samples was determined using a sieve shaker (RoTap, Soiltest CL 305A, USA) for 10 min at a constant speed of 3.6 Hz according to the ASABE standard S319.3 (2006a). The fraction size distribution of two rice husk samples sourced in Nigeria, a first one from a one-stage mill and a second one from a two-stage mill, was also determined for comparison purposes. The bulk density was measured using a scale and a graduated cylinder according to the ASABE standard S269.4 (2007). Unless specified, RH will be used to refer to the ground rice husk that was used to make the briquettes in the present study.

3.2.2 Rice Bran, Water and Binders

Briquettes were made according to different formulations of binder content, bran content and water addition. Rice bran (RB) was purchased (Bob’s Red Mill Rice Bran, OR, USA) and refrigerated until used. The bran was added to the RH at levels of 0, 5 and 10% weight by weight (w/w). Water was added in proportions of 50, 60 and 70% (w/w) to the mixture of RH and RB . Tap water was preferred over distilled water as the water available in the boreholes and wells naturally presents high mineral content. The binders were added individually in proportions of 0, 5, 10 and 15% (w/w). Three binders were investigated namely cassava starch wastewater (CSW), rice dust (RD), and okra stem gum (OSG). The binders were selected for their non-edibility, availability and low-cost as waste products. All binders were refrigerated until used.

3.2.3 Mixture preparation

For each sample, 360 g of RH was weighed (Denver Instrument TR-4102D, CO, USA) and mixed with RB. The binder and water were measured, mixed, and added to the RH and RB. For each binder, the binding solution was prepared according to the following procedures:

CSW was produced by dissolving tapioca starch (La Maison Canelle, QC, Canada) in the appropriate amount of water (see section 2.2 for details on the proportions) at room temperature. The CSW solution was slowly heated using a hotplate with constant mixing until 70 °C for the starch to gelatinize and act as a binder (Thomas et al., 1998; Tumuluru et al., 2011). The homogenized paste was then poured to the RH and RB, and mixed by hand using rubber gloves to evenly distribute the binder through the biomass. The completed mixture (RH, RB, binder, and water) was left to cool down around 35 to 40 °C and used immediately for densification so as to prevent moisture evaporation.

RD was produced by grinding rice kernels (Selection™ Parboiled Rice, USA) using a 0.5 mm sieve in hammer mill (Thomas no. 4275-210, PA, USA). The RD was poured into water, heated up to about 72 to 75 ºC using a hot plate with constant mixing. This temperature, which is slightly higher than for CSW, allowed the starch contained in the RD to gelatinize as well. Rice starch gelatinizes at a temperature slightly higher than cassava starch (Thomas et al., 1998). The solution was mixed with the RH and RB, and left to cool down following the same procedure as CSW until densification.

Dried chopped okra stems purchased from a local market in Nigeria were ground (Sumeet Multi grind No.964, TN, India) and sieved through a 0.85 mm mesh. The particles remaining in the sieve were ground again until all particles passed through the sieve. The OSG was obtained by rehydrating the powdered stems by pouring and mixing 70ºC water. The viscous OSG solution was added to the RH and RB following the same procedures as CSW and RD.

3.2.4 Experimental Set-up for Briquette Production

A manual hand press with a double lever (Figure 3.1a) was designed, built and used for the densification of the RH. The press provided a mechanical advantage of 12. Briquettes were produced at room temperature and constant pressure of 4.2 MPa with a fixed uniaxial output force of 8.7 kN. The force applied was measured with a load sensor (Futek LCF400, CA, USA) embedded in the piston. A cylindrical mold 63.6 mm high with a 52.1 mm inner diameter was used with a central rod of 9.3 mm outside diameter to create a hole in the middle of the briquette. This hole increased the oxygen supply during combustion (Shrivastava et al., 1989). The mold was filled with the RH mixture and placed under the piston on the plinth. The lever was lowered at horizontal position and the load was held down for a 10 s dwell time to optimize compression and minimize briquette relaxation (Panwar, 2011; Tumuluru et al., 2011). The briquettes (Figure 3.1b) were left to air dry on a flat surface in a closed room with adequate air ventilation for seven days before testing the physical properties (Kaliyan & Morey, 2009a; Taulbee et al., 2009).

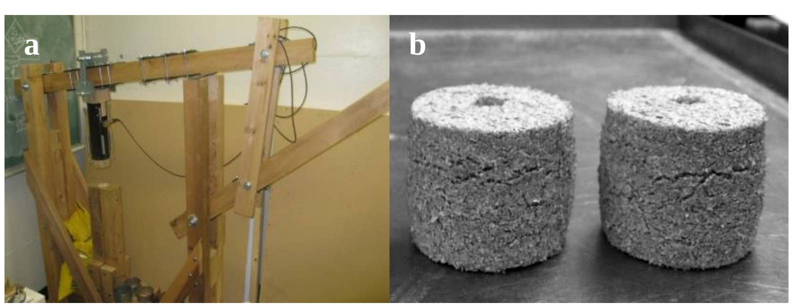


Figure 3.1 – a) The manual press and b) the rice husk briquettes

3.2.5 Briquette Testing and Characterisation

The briquettes were weighed (Denver Instrument APX-100, CO, USA) and the density was calculated from mass and volume according to the ASABE standard S269.4 (2007). The volume was determined from three repeated measures of diameter, height and central whole diameter at different points using a calliper. The moisture content was measured by drying the briquettes during 24 h in an oven (Fisher Scientific 750F, USA) at 104 ºC based on the ASABE standard S358.2 (2006b). All the physical tests were conducted seven days after densification.

The durability was determined by placing the briquettes in a sieve shaker (Soiltest CL 305-A, USA) for 2.5 min at 3.6 Hz on a 1.3 cm mesh to simulate mild handling in a small scale production (Kaliyan & Morey, 2009b). The particles remaining on the mesh were weighted. The durability was calculated as the percentage of mass retained on the mesh divided by the initial mass (Kaliyan & Morey, 2009a; Mina-Boac et al., 2006). The compressive resistance, or compressive strength, is the maximal load applied for a briquette to crack. This load estimates the weight a briquette can withstand during storage (Kaliyan & Morey, 2009b). The compressive strength was measured axially using the universal testing machine (Instron 4500, MA, USA) with a crosshead speed of 50 mm min^{-1} (Mani et al., 2004b) and a load cell of 50 kN +/- 0.5%. A bomb calorimeter (Parr Oxygen Bomb Model 1341EB, Calorimeter Thermometer Model 6772, IL, USA**)** was used to determine the higher heating value (HHV), i.e. calorific value of the briquettes, according to the ASTM standard D5865 – 11a (ASTM, 2010a).

3.2.6 Experimental Design

The briquettes were produced consecutively as no variations of external factors required randomizing the densification process. The briquettes were made following a complete factorial design with four independent variables at three levels with ten replicates each. The physical properties of the briquettes, i.e. response variables (density, moisture content, durability, compression strength, and calorific value) were tested and replicated three times on samples randomly selected. Analysis of variance (ANOVA), univariate analysis (Student-Newman-Keuls Test) and multi-regression analysis were conducted using SAS 9.3 and JMP 8 to test for the significance (p<0.05) of the influence of the independent variables on the briquette properties. All significance tests in this study were conducted with p<0.05. Statistical analyses were conducted after the non-significant terms of the factorial design were removed.

3.3 Results and Discussion

The initial moisture content of the rice husk (RH) before grinding was 9.2% wet basis (moisture content in this paper are expressed as wet basis). The HHV of the RH alone before densification was 16.08 MJ kg^{-1} dry basis (db). The two-stage RH in this study had a particle size distribution similar to a two-stage RH sample collected in Nigeria (Table 3.1). This similarity was also obtained between the ground RH and a one-stage milling sample from Nigeria. This validated the use of a 2 mm sieve in the grinder to simulate one-stage milling residues.

Table 3.1 – Particle size distribution and bulk density or rice husk (RH)

Particle size diameter (mm)	Unground RH[a] (wt. %)	Ground RH[b] (wt. %)	Two-stage RH[c] (wt. %)	One-stage RH[d] (wt. %)
$d \geq 2$	29.64	0.00	34.48	0.32
$2 < d \leq 0.85$	64.91	17.67	29.50	22.05
$0.85 < d \leq 0.5$	4.15	49.21	1.21	33.77
$0.5 < d \leq 0.25$	0.86	23.86	0.35	26.74
$0.25 < d \leq 0.15$	0.29	5.72	0.10	13.43
$0.15 < d \leq 0.106$	0.05	1.32	0.04	2.41
$d < 0.106$	0.13	1.86	-	0.46
Density (kg m^{-3})	129.6	367.1	102.2	370.6

[a] The particle size distribution of the two-stage RH used in the present study before grinding and [b] after grinding with a 2 mm sieve to simulate one-stage milling residues.
[c] For comparison purposes, the particle size distribution of a Nigerian two-stage RH sample (rice husk only) and [c] one-stage RH sample (rice husk with bran).

3.3.1 Calorific Value

The HHV of the briquettes ranged from 16.01-16.45 MJ kg^{-1}. Varying the bran and binder content, the binder type, and the water addition did not significantly influence the calorific value. This agrees with Suhartini et al. (2011) and Sotannde et al. (2010) who observed that increasing the binder content (starch) from 8 to 12% and 15 to 35%, respectively did not significantly affect the HHV. Chou et al. (2009a) mentioned that increasing the bran content from 0 to 20% and 40% increased the calorific value of rice straw briquettes as bran has a higher HHV (20.5 MJ kg^{-1}) than straw (16.1 MJ kg^{-1}). This compares with the HHV of the RH briquettes in this study (16.08 MJ kg^{-1} db). Thus, higher bran content may have increased the HHV of the briquettes. However, adding more than 10% bran may not be sustainable as rice paddy contains only about 10% bran (Lim et al., 2012; Saunders, 1985) and rice bran potentially has other uses based on its nutritional values (Abdul-Hamid et al., 2007; Saunders, 1985).

3.3.2 Moisture Content

Seven days after densification, the moisture content of the briquettes varied between 4.64-7.42% inclusively with an average of 5.86%. Table 3.2 shows that briquettes with 70% water addition had an average moisture of 6.00%, while the moisture content was equally and slightly lower (5.78%) with 60% and 50% water. Bran did not significantly affect the moisture content. Moisture generally increased with the binder concentration, though it was not significant most of the time (with the exceptions of 10 and 15% OSG, and 5, 10 and 15% RD, all at 70% water). In terms of binder, the briquettes made with CSW had the highest moisture content while the lowest was found with RD. The moisture content of the CSW briquettes decreased with an increasing amount of water addition, with opposite trends for RD and OSG. This could be caused by the greater water absorption of cassava starch compared to rice (Hongsprabhas et al., 2007).

The OSG also absorbed less water than the binders containing starch because of the fibrous nature of the stems. More water probably remained in the inter-particle space after the compression which could explain the formation of mold in the central hole of some of the OSG briquettes (mostly with 70% water). This presence of water between the particles lead to slower drying and to favorable conditions for mold growth, even if the final moisture content of the briquettes containing mold was suitable for combustion.

Table 3.2 – Moisture content (% dry basis) of the rice husk (RH) briquettes

Binder Content (w/w)	50% (w/w) water addition	60% (w/w) water addition	70% (w/w) water addition	Mean
No binder				
0	5.37	5.90	6.43	5.90
CSW				
5	6.52^{ad}	6.11^{bde}	5.66^{ce}	6.10^{a}
10	6.49^{a}	5.95^{bf}	5.49^{cf}	5.98^{a}
15	6.70^{ag}	6.35^{bgh}	5.99^{ch}	6.35
Mean	6.57	6.14	5.71	6.14
OSG				
5	5.62^{ad}	5.82^{bd}	5.89^{d}	5.78
10	5.68^{ae}	5.56^{be}	6.58^{c}	5.94
15	5.71^{af}	5.82^{bf}	6.80^{c}	6.11
Mean	5.67^{a}	5.73^{a}	6.42	5.94
RD				
5	5.11^{ad}	5.33^{bd}	5.44^{d}	5.29
10	5.07^{a}	5.58^{b}	6.00	5.55^{a}
15	5.19^{ae}	5.54^{be}	6.16	5.63^{a}
Mean	5.13	5.49	5.87	5.50
Mean	5.78^{a}	5.78^{a}	6.00	5.86

Values displaying the same letter on a column or a row for the same binder are not significantly different (p<0.05).

After seven days of drying, all briquettes had a moisture content below the recommended value of less than 10% (at the time of combustion) (Chen et al., 2009; Kaliyan & Morey, 2009b; Missagia et al., 2011), even with 70% water addition to the RH. Energy is required to vaporize the water contained in a fuel when it is burned, so a high moisture content reduces the net calorific value and the combustion performance of a fuel (Obernberger & Thek, 2004; Zhang et al., 2012). Altun et al. (2003) observed that coal briquettes with higher moisture contents presented higher values of activation energy. However, stability may be reduced if the moisture content is too low (less than 4-5%) since a densified product expands if it absorbs humidity from the air (Li & Liu, 2000; Missagia et al., 2011; Tumuluru et al., 2011). Studies also identified lower durability (Tabil, 1996; Temmerman et al., 2006; Tumuluru et al., 2011) and density (Panwar, 2011) with moisture contents over 10 to12%. Li and Liu (2000) measured increasing briquette density with moisture content from 0 to 5 or 6%. The optimal briquette moisture content would then lie between 5 and 10%, a range for which moisture content did not significantly affect the briquette's physical properties.

3.3.3 Density

The type of binder, the bran and the binder content (but not the water addition) significantly influenced the density. The briquettes with the highest density (471.3 kg m^{-3}) were made from 15% CSW and 10% bran (Figure 3.2). This represents an increase of 3.6 times the initial bulk density of the RH. This agrees with a value (around 400 kg m^{-3}) previously measured for RH briquettes with no binder at a densification pressure of 4.0 MPa (Chin & Siddiqui, 2000). The lowest density (382.4 kg m^{-3}) was observed with 5% OSG and 0% bran. Okra stems are less compressible as they contain elastic fibers (Thomas et al., 1998; Tumuluru et al., 2011). This could explain the briquette relaxation that lead to lower densities. Overall, density increased with binder content (372.72, 405.10, 427.80, and 445.06 kg m^{-3} with 0, 5, 10, and 15% (w/w), respectively). A similar trend was previously observed for RH at 7.8 MPa (Singh & Kashyap, 1985). Density also increased with bran content (415.44, 424.49, and 438.02 kg m^{-3} with 0, 5, and 10% (w/w), respectively). Chou et al. (2009a) reported that rice straw briquettes with 20 and

40% bran had the same density, which suggests there is a limit to which bran increases density. The variations in water addition did not significantly affect the density. Mani et al. (2002) also noted no statistical difference when the water in the biomass was increased from 12 to 15%.

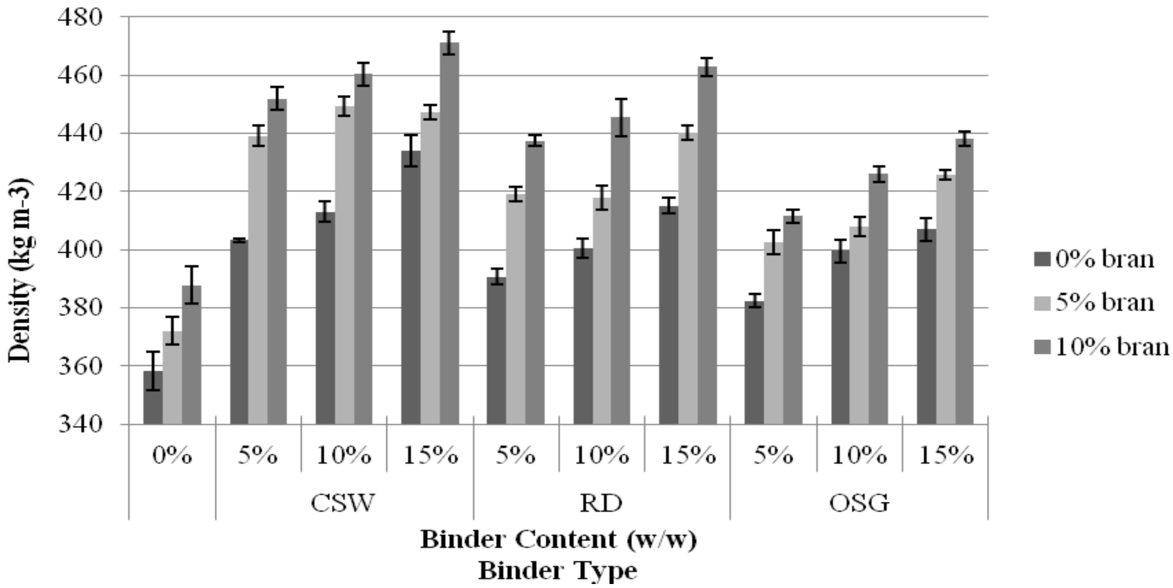


Figure 3.2 – Briquette density (kg m^{-3}) as a function of the bran content, type of binder and binder content. The effect of water addition was not significant.

Overall, the density increase was most notable when the binder content was raised from 0 to 5% and from 5 to 10%, especially with CSW (Figure 3.2). In most cases (for CSW and OSG), increasing the binder content from 10 to 15% did not significantly increase density (except for CSW at 10% bran and OSG at 5% bran). For sawdust briquettes, Sotannde et al. (2010) measured higher densities with cassava starch than with gum as a binder. With 15% binder, they also reported lower briquette density (310.0 kg m^{-3}) than in the present study, which may be explained by the lower densification pressure (1.05 MPa instead of 4.2 MPa).

The effect of bran was not well defined even though it generally increased the density. The briquettes with no binder and 10% bran had a higher density than briquettes with 5% OSG and no bran. At fixed binder content and increasing bran content, the increase in density was not significant in most cases, though there was usually a significant difference between the densities at 0 and 10% bran, but not from 0 to 5% or 5 to 10% separately. The bran, which is finer than the RH, may somewhat improve densification and enhances bonding as it fills inter-particle spaces (Kaliyan & Morey, 2009b). Finer particles would mostly improve the quality of briquettes and not necessarily of pellets, as fine particles (< 0.25 mm) have more risk of jamming a pellet mill than a hand press (Tumuluru et al., 2011).

The effect of water addition on density was not significant. However, the water reduced the density of the OSG briquettes (416.2; 410.6; 406.9 kg m^{-3} at 60, 50, and 70% water, respectively) while it increased the density for RD (422.4; 425.2; 429.0 kg m^{-3}) and CSW (437.3; 438.5; 446.8 kg m^{-3}). Fibers are less water absorptive (Kaliyan & Morey, 2009b), so water remained at the surface during compression. This additional water between the OSG particles most likely reduced the density because of the incompressible nature of water. In contrast, water was beneficial for the uniform distribution of the binders containing starch, as confirmed by Kaliyan and Morey (2010). Chin and Saddiqui (2000) found that briquettes had less relaxation with 20% water addition (varied 5 to 30%), but this was without the use of a binder that would further reduce the relaxation at a higher water content. Optimal water content strongly depends on the nature of the binder (Taulbee et al., 2009).

3.3.4 Durability

Figure 3.3 illustrates the interactions between the independent variables influencing the durability. The highest value (91.9%) was observed with 10% RD, 70% water and 0% bran, though it was not significantly different from the highest value (91.8%) observed with 15% CSW, 70% water and 0% bran. Durability, or abrasive resistance, is an indication of briquette quality, i.e. ability to produce fewer fines during manipulations (Kaliyan & Morey, 2009b; Kaliyan & Morey, 2009c). At 70% water, 15% binder and 10% bran, the difference between the

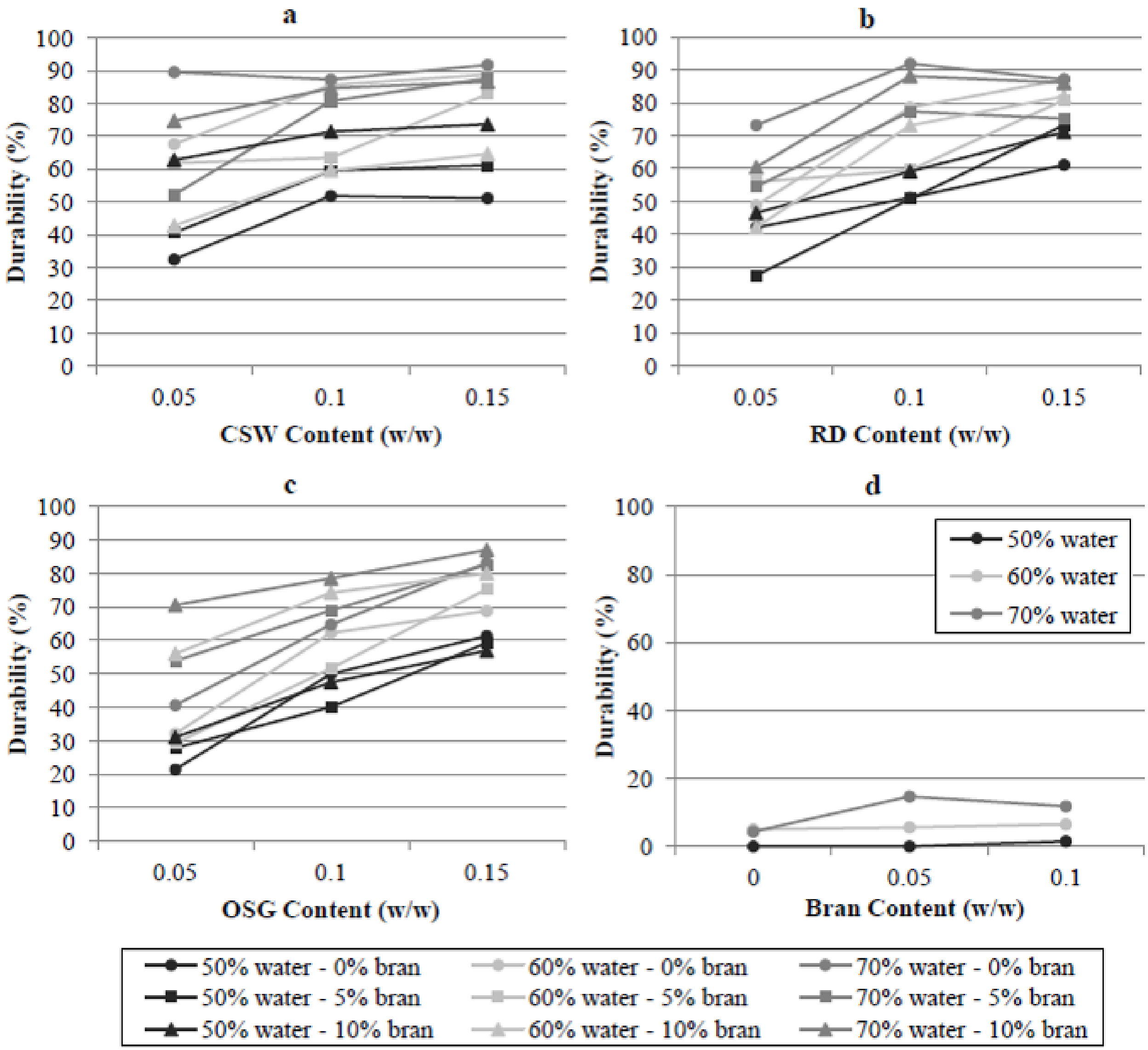


Figure 3.3 – Durability (%) of briquette as a function of water addition, bran and binder content with (a) cassava starch wastewater (CSW), (b) rice dust (RD), (c) okra stem gum (OSG), and (d) control briquettes (0% binder). The same legend is used for graphs a, b and c.

binder had durability values below 15%. The durability was even 0% for the briquettes with 0% bran and 50% water (Figure 3.3). The durability increased with the binder content, but the increase after raising the binder content from 10 to 15% was usually not significant for CSW and RD (except at 5% bran, 50 and 60% water for RD). High binder content is said to increase durability (Kaliyan & Morey, 2009b; Sotannde et al., 2010), but it was observed that water addition can reduce the amount of binder required. The briquettes with 70% water and 10%

binder had similar (around 80% or higher) durability than the ones with 60% water and 15% binder. The binders containing starch were considered more suitable as similar durability was achieved with 10% CSW or 10% RD, than with 15% OSG. This means less input and potentially lower briquette cost. No standard procedure exists to define quality, but high, medium and low quality were previously associated to durability values above 80%, between 70 and 80%, and below 70%, respectively (Kaliyan & Morey, 2009b; Tabil, 1996).

The effect of water addition depended on the nature of the binder (Figure 3.3). The durability increased significantly for CSW when water was raised from 50 to 60%, with 0% bran at all three levels of binder and did not significantly increase when water was added at 70% (except at 5% binder and 5% bran). Also, the durability for CSW (10 and 15%) was almost the same (around 85%) at 60% water and 0% bran than at 70% water and 10% bran. Water addition up to 60% may be sufficient if there is no bran. Adding 70% water significantly improved the durability of the RD briquettes only when the binder content was less than 15%. This implies that water enhanced cohesion between particles and reduced the need for higher binder content.

Water would reduce inter-particle friction, but beyond a certain limit it would create resistance as water is incompressible (Faborode, 1989). Some authors mentioned how excess water can impede biomass densification (Kaliyan & Morey, 2009c; Missagia et al., 2011; Tumuluru et al., 2011), but these studies were conducted under high pressure. Heavy compression creates solid bridges between particles (Chou et al., 2009b; Kaliyan & Morey, 2010; Mani et al., 2004b), but this binding mechanism is not as predominant under low pressure densification. At low pressure, more importance is given to water in generating van der Waals bonds (Chin & Siddiqui, 2000; Kaliyan & Morey, 2010; Tumuluru et al., 2011). Faizal et al. (2010) added up to 80% water to palm oil mill residues before densification at 3-11 MPa. At 5

MPa, Mani et al. (2006) measured higher briquette durability with 10% water than with 5%. Also, since RH naturally has a low moisture content, RH would require more water for densification compared other biomass residues (Missagia et al., 2011).

The durability of OSG briquettes was positively affected by water addition when bran was present (5 or 10%). Bran may have absorbed the additional water present between the particles when OSG was used, which could explain the increase in durability at higher bran content. The density of OSG briquettes also followed this similar trend. The density reduced with water addition, but increased with bran. The effect of bran content and water addition on the compressive strength of OSG briquettes was not significant.

Increasing the bran content up to 10% did not have a significant impact on the durability of CSW briquettes and the increase to 5% bran was only significant at 5% binder content. For RD, the presence of bran was only significant when the binder content was below 15%. This suggests that the simultaneous effect of high bran and binder content may not be required with stronger binders, such as the ones containing starch. If the RH is milled in a two-stage operation, 15% binder content would be recommended. Otherwise, 10% binder content would be sufficient. The trend is different for OSG, since an increase in durability was observed with bran content. This effect was mostly significant with an increase in bran of 5 to 10%. Bran also did not have an impact at 50% water and 15% OSG. Interestingly, CSW and RD briquettes with 5% bran had lower durability compared to 0 and 10% bran.

3.3.5 Compressive Strength

The interactions between the type of binder, the water addition, and the bran and binder content were significant to determine the compressive strength. The highest compressive strength (2.54 kN) was observed with 15% RD, 60% water and 0% bran. Therefore, the briquettes can be considered strong enough to handle stacking for storage purposes. This value (2.54 kN) is also equivalent to 0.0306 N mm^{-3}, which meets the acceptance level of 0.0271 N mm^{-3} for compressive strength of coal briquettes (Raghavan & Conkle, 1991). The OSG briquettes had lower strength than the CSW and RD briquettes (Figure 3.4). However, higher strength was observed with 15% binder content for all binders. Suhartiniet al. (2011) also measured an increase in strength with 10% binder compared to 8%. Figure 3.4 shows that the variation in binder content only significantly affected the strength of OSG briquettes while more interactions existed for the CSW and RD briquettes.

For RD, the simultaneous interaction between water, bran and binder content was not significant. Increasing water addition from 50 to 60% improved briquette strength, while further raising it to 70% reduced compressive strength. However, the difference in strength between 50 and 70% water addition was not significant. At fixed amount of water, increasing the binder content significantly improved compressive strength while at fixed binder content, increasing the water did not increase the strength. This implies that the presence of a binder has a greater influence on the briquette strength than water. Even though bran did not significantly affect the strength of RD briquettes, it is interesting to mention that bran slightly decreased the strength at 50 and 70% water while it slightly increased strength at 60% water (Figure 3.4).

For CSW, more interactions were found between the independent variables. The binder positively increased the strength, but not at 50% water or 10% bran. Increasing the water from 60 to 70% was not significant when no bran was present. It is interesting to note that the highest strength for CSW was also observed with 15% binder, 60% water and 0% bran. Bran did not improve the strength, even if mixing a second raw biomass was previously found to increase briquette strength (Bhattacharya et al., 1984; Kaliyan & Morey, 2009b).

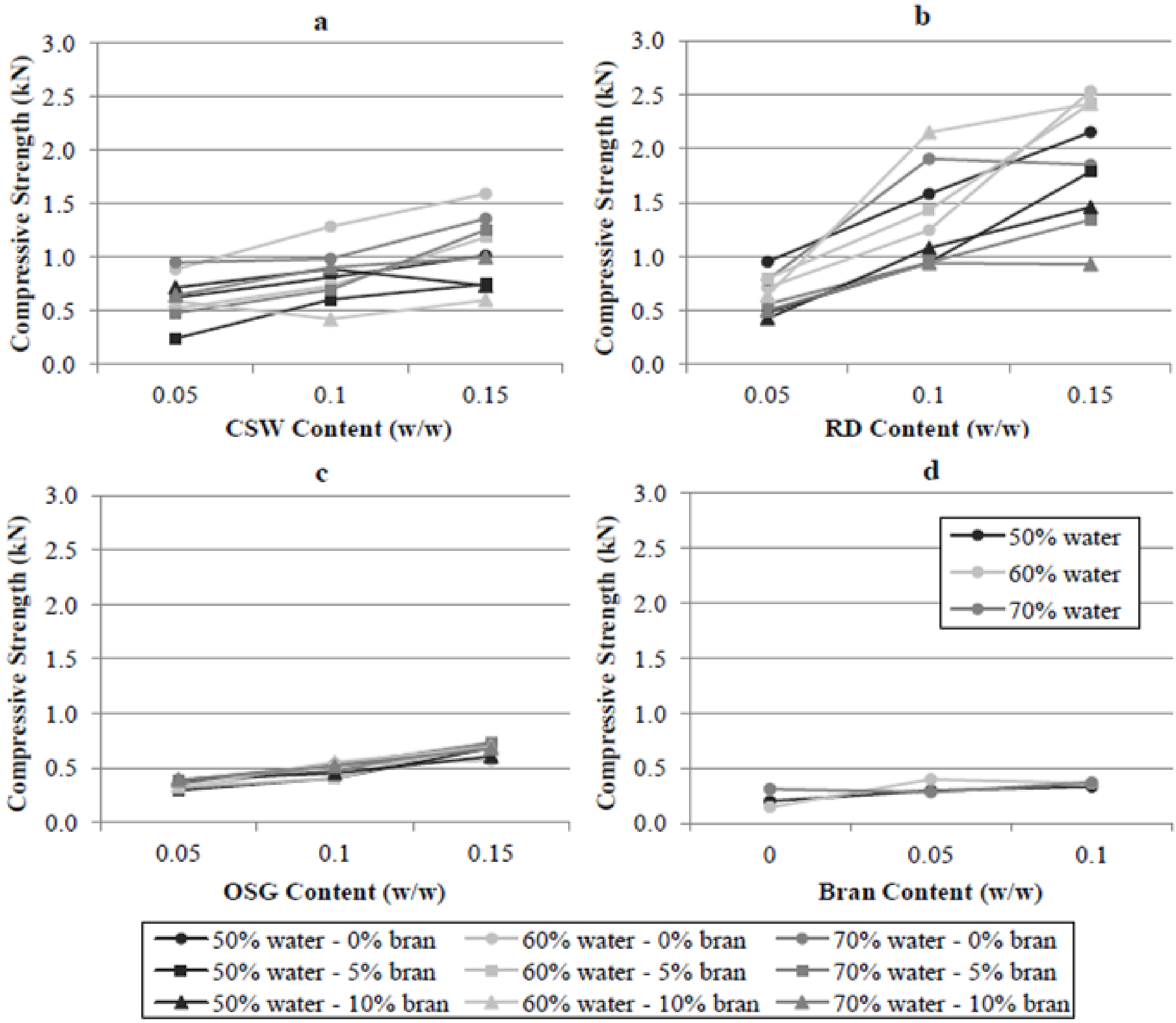


Figure 3.4 – Compressive strength (kN) of briquettes as a function of water, bran and binder content with (a) cassava starch wastewater (CSW), (b) rice dust (RD), (c) okra stem gum (OSG), and (d) control (0% binder). The same legend is used for graphs a, b and c.

The presence of bran could be more beneficial at high temperature densification. Chou et al. (2009a) reported that the strength of a rice straw briquette with 20% bran compressed at 90 °C was the same as the one of a briquette with 0% bran compressed at 110 °C. Finally, as observed with sawdust briquettes by Li and Liu (2000), it was noticed during the compression test that the RH briquettes were shortening (squeezing) before failure, which implies that the measured strength may be slightly higher than the actual briquette strength.

3.3.6 Correlations between Physical Properties

Correlations were observed between the response variables. The density seemed to have a positive effect on the durability (r = 0.73). Although some authors state that there is no correlation between durability and density (Obernberger & Thek, 2004; Temmerman et al., 2006), others mention that the density positively influences the durability (Singh & Kashyap, 1985; Sotannde et al., 2010). Kaliyan and Morey (2009b) concluded that the factors increasing the durability, density and strength may be the same without necessarily implying a positive correlation between them. Therefore, adding bran to increase the density would not necessarily improve durability. Relative correlations were detected between strength and durability (r = 0.55), and between strength and density (r = 0.54). According to Taulbee et al. (2009), increasing the density improves the strength. The effectiveness of inter-particular bonding may depend on the density, hence closer particles would bond strongly, leading to greater briquette strength (Kaliyan & Morey, 2009b; Mani et al., 2004b). Low correlations were noted between the moisture content durability (r = 0.16), compressive strength (r = – 0.12), and density (r = 0.17) as these only seem to be affected when the moisture is above a certain limit. Obernberger and Thek (2004) made a similar conclusion that moisture had no influence on durability when it remains within a certain range.

3.4 Conclusion

In conclusion, rice husk is a suitable biomass for low pressure densification to produce briquettes as an alternative cooking fuel. The briquettes presented adequate characteristics namely physical integrity (durability and compressive strength) as well as low moisture content (below 7.5%) and high calorific value (16.08 MJ kg^{-1} db). The RD was found to provide the highest compressive strength and durability, though CSW offered the highest density and similar durability to RD. The use of RD as a binder would be recommended first, but CSW may be suggested if it is readily available in a certain area instead of RD. It was found that a binder content of 10% may be sufficient, especially for briquette durability; however, 15% binder may be recommended if greater briquette strength is desired and if sufficient binder is available without increasing the cost of the briquettes. Water addition up to 60% was beneficial for the low pressure densification to improve homogenization of the binder through the biomass and inter-particulate bonding. Bran addition would not be recommended if the briquettes are made from the residues of a two-stage mill, i.e. when the bran and the rice husk are separated.

Further studies would be required to assess the overall life-cycle energy requirement of the low pressure densification system. If more time or energy is required for briquette preparation and production compared to fuelwood collection from the surrounding, the technology may be faced with low adoption rates compared to the immediate need to reduce fuelwood consumption. Overall, biomass briquettes, either from rice husk or other potential raw material, remain an interesting solution to provide an alternative fuel for rural Africa.

3.5 Acknowledgments

This study was made possible with the collaboration of Africa Rice and the financial support of the Canadian International Development Agency (CIDA) and the Natural Sciences and Engineering Research Council of Canada (NSERC).

Connecting Statement to Chapter 4

The reduction of fuel consumption in domestic cooking can be achieved by three different strategies: fuel substitution, tree planting and stove efficiency. Chapter 3 studied the production of densified rice husk briquettes as an alternative biomass fuels to wood. However, no matter the type of fuel burned, wood or alternative biomass fuels, it is imperative to improve the efficiency of the combustion to reduce the amount of fuel required to achieve a specific cooking task. Therefore, Chapter 4 looks into the development of improved cookstoves to increase the efficiency of cookstoves used for parboiling and cooking activities in rural communities of developed countries.

The chapter is drawn from an article submitted for publication in the journal *Energy for Sustainable Development*. The manuscript was co-authored by Audrey Yank, M.Sc. Candidate at McGill University, Dr. Michael Ngadi and Dr. Robert Kok, Supervisor, Co-supervisor, and Professors at McGill University, and Sali A. Ndindeng scientist at the Africa Rice Center. The format has been changed to be consistent with this thesis.

Chapter 4: Thermal and combustion efficiency of improved clay brick stoves for rural rice parboiling

4.1 Abstract

Up to three billion people in the world still use fuelwood in a 3-stone stove for cooking and for post-harvest processing on a daily basis. The 3-stone stove has low thermal efficiencies and burns more wood than what would normally be required. It also produces important amount of smoke from incomplete combustion resulting in various premature respiratory health diseases among stove users. The goal of this work was to study the performances of different stove designs for small-scale rice parboiling in rural areas. Four improved clay brick stoves were assessed using the Water Boiling Test method to assess their time to boil, energy efficiency, specific fuel consumption and emission factors (CO, CO_2, C_xH_y). The performances of the improved stoves were compared to the traditional 3-stone stove. The stoves were tested using wood and biomass briquettes. Tests were also conducted using a small electric fan to study the impact of forced air compared to natural draft on the combustion and thermal efficiencies of the stoves.

All the improved stoves with natural draft boiled water faster and burned less wood than the 3-stone stove. The boiling time was reduced by 31% at cold start and by 45% at hot start. The fuel use was reduced by 28% at both phases. The specific fuel consumption varied from 148.3 to 190.8 g L^{-1} and from 126.7 to 249.9 g L^{-1} at natural and forced draft, respectively. The overall thermal efficiency of the improved stoves varied between 19 and 25.1% in both conditions. The overall emission factors of CO of the 3-stone stove was 4.9 g MJ^{-1} and varied from 4.1 to 12.6 g MJ^{-1} and from 3.8 to 9.7 g MJ^{-1}, for the improved stoves with natural and forced draft, respectively. The improved stove presents an opportunity to reduce the fuelwood use and increase household livelihoods.

4.2 Introduction

Up to three billion people in developing countries cook daily using biomass (wood, charcoal, agricultural residues, dung) on a 3-stone fire (IEA, 2006; WHO, 2011). This basic system which consists of three rocks positioned in a triangle to support a pot over an open fire is used in domestic cooking but also in post-harvest processing of agricultural products. The 3-stone stove has been used for centuries though it does not efficiently transfer the thermal energy of combustion to the pot, thus burning more wood than what would normally be required. The consensus on the thermal efficiency of the 3-stone stove is usually around 10% (Alakali et al., 2011; Bhattacharya & Salam, 2002).

Rice parboiling is a post-harvest process common in West and Central Africa and basically consists of soaking, steaming and drying paddy before milling with the goal of improving milling yields (Ndindeng et al., 2014). About half of the world's rice is consumed parboiled and small scale parboiling is done using big cooking pots (~ 50 L or more), thus requiring a large amount of fuelwood. Wood represents up to 90 or 95% of the energy used in rural areas of developing countries (Adkins et al., 2010; Ezzati & Kammen, 2002; Perera & Sugathapala, 2002). However, wood resources are depleting faster than they are being replenished. In the early 1970s, alarming predictions on future fuelwood availability became a driver to develop improved cookstoves (ICs) (De Lepeleire et al., 1981; Prasad, 1981). The objective then was mostly to increase the thermal efficiency compared to the 3-stone stove to reduce fuel consumption, though the success of the first ICs implementation programs can be questioned (Ballard-Tremeer & Mathee, 2000; Perera & Sugathapala, 2002; Wallmo & Jacobson, 1998). ICs gained more popularity over time as they were associated to other socio-economic benefits such as reduced fire hazards, improved household livelihoods, improved kitchen hygiene, reduced cooking and fuelwood collection time, and reallocation of spare time (Alakali et al., 2011; Larson & Rosen, 2002).

Recently, ICs have received growing attention as they can reduce harmful emissions and subsequent respiratory health infections compared to the 3-stone stove. Particulate matters (PM), carbon monoxide (CO), hydrocarbons (C_xH_y) including methane (CH_4), polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs) and nitrogen oxides (NO_x) are amongst the main pollutants emitted during the incomplete combustion of biomass (Bhattacharya & Salam, 2002; Larson & Rosen, 2002). Indoor air pollution accounts for nearly two million premature deaths every year, mostly women and children under five years old (WHO, 2011). This equals to more than 3% of the global burden of disease (Gall et al., 2013). A number of health issues have been correlated to extended smoke exposure, especially for women who are traditionally associated with cooking and post-harvest processing. Women would be 50% more at risk of stillbirth during pregnancy (Smith et al., 2004), 2 to 4 times more likely to develop a chronic obstructive pulmonary disorder such as bronchitis (Larson & Rosen, 2002; WHO, 2011), and 2.7 more likely to develop tuberculosis (Smith et al., 2004). As for children, they are subjected to lower weight at birth (Boy et al., 2000) and are 2 to 3 times more likely to suffer from an acute respiratory infection (Larson & Rosen, 2002). Overall, 50% of pneumonia deaths are attributed to the inhalation of particulate matters (WHO, 2011).

Apart from ICs, interventions to reduce smoke exposure include increased ventilation, behavioural changes (cooking outside) and the use of non-biomass fuels (Larson & Rosen, 2002). Kerosene, natural gas and LPG do emit less smoke during combustion, though they generate more GHG emissions over their life-cycle (during their extraction and processing) (Afrane & Ntiamoah, 2012), and also remain expensive and without adequate distribution infrastructures in most rural areas. As for charcoal, the current production method actually increases wood consumption and GHG emissions since more wood is burned to produce charcoal than to cook directly with fuelwood (Afrane & Ntiamoah, 2012; Ezzati & Kammen, 2002). Therefore, interventions to improve the direct combustion of biomass in ICs remain an accessible and affordable strategy to reduce both air pollution and fuelwood use in rural areas of developing countries (Alakali et al., 2011; Ezzati & Kammen, 2002; Prasad et al., 1985).

One of the first ICs developed consisted of a variation of the 3-stone stove, the ‘u-shaped’ stove made from mud (Perera & Sugathapala, 2002). Since then, various ICs made of fired clay (Bhattacharya et al., 2002; Perera & Sugathapala, 2002; Venkataraman & Rao, 2001) or metal (Jetter & Kariher, 2009; Jetter et al., 2012; MacCarty et al., 2010), have been designed. Boy et al. (2000) studied a brick stove with multiple pot holes, but clay brick stoves remain under-investigated. Clay is inexpensive and available, and bricks are easy to make and transport. The heat resistance and the structural strength of clay bricks can also be increased if they are fired at high temperatures (700 to 1100°C) (Cultrone et al., 2004). The production of firebricks is already an established industry in West Africa (Alam & Starr, 2009) and stoves built with firebricks inside the combustion chamber have the potential to be more efficient, last longer and support heavier pots than regular mud stoves. Also, it does not require as much technical skills and specific equipment to build a clay brick stove compare to a metal stove, though a clay brick stove has to be built in-situ and cannot be move afterwards. Overall, clay brick stoves represent an incremental improvement, compared to the 3-stone or the basic ‘u-shaped’ mud stoves, to answer current environmental and health issues of cooking with fuelwood while remaining affordable, low-tech, and readily acceptable compared to metal stoves.

The objectives of this study were firstly to design and build four clay brick stoves to be used in small scale rice parboiling, secondly to assess the performance of the ICs compared to the 3-stone stove in terms of boiling time, efficiency, fuel consumption and emission factors, thirdly to assess the effect of design features (chimney, grate, fan), and finally to investigate the effect of biomass (wood and corncob, sawdust and rice husk briquettes) on emission factors.

4.2 Material & Methods

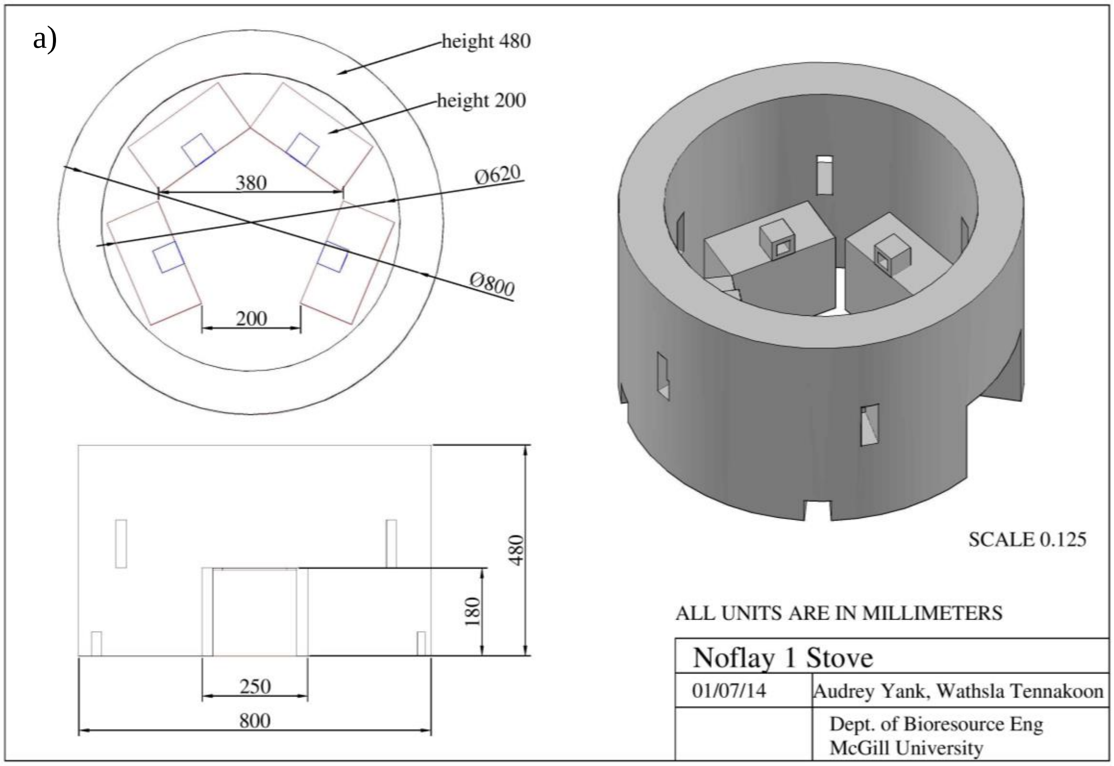
4.2.1 Stove Designs

The stoves were built for a standard spherical cast aluminum pot (~ 65 L, 55 cm diameter, size no. 25, purchased at a local market in Cotonou, Bénin) normally used for small scale rice parboiling. The 3-stone stove was tested as a basis of comparison and was made of three stacks of three bricks (total stack height of 16.5 cm) positioned triangularly around a 36 cm diameter circle. Two variations of the Africa Rice/McGill (AM) stoves were built, namely AM1 and AM2, which the designs were inspired by an IC built to fit a parboiling vessel at the Institute of Agricultural Research for Development (IRAD) (Yaoundé, Cameroun) in partnership with the Africa Rice Center. The AM1 was scaled up from the IC in Cameroun to fit the larger traditional cooking pot used in this study. The AM2 was built with secondary air holes at the top of the combustion chamber to test for potential improvement over the AM1 stove. The two AM stoves had a chimney (1 m) to move the flue gases away from the user and a grate in the combustion chamber to raise the fire bed (6.4 cm) from the bottom surface. The other stove design, called the "*Noflay*" parboiling stove, was scaled-up from an IC implemented for domestic household cooking. The smaller Noflay household cookstove was originally designed in partnership with the organisation REAP-Canada (Sainte-Anne-de-Bellevue, Canada) and implemented in The Gambia and Senegal. The word Noflay is a common expression understood across local dialects in The Gambia and Senegal as '*convenience*' or '*no problem*'. There were 2 variations of the Noflay parboiling stove design. The Noflay2 (NF2) had a grate that was added to the combustion chamber whereas Noflay1 (NF1) did not have the grate.

4.2.2 Stove Construction

Bricks (18.5 x 9 x 5.5 cm) and firebricks (23 x 11.4 x 6.4 cm) were purchased from Briques & Pierre Provinciales, Inc (Vaudreuil, QC) and Materiaux Refractaires Direct (St-Léonard, QC), respectively. The stoves were built on wheeled wooden platforms to be moved underneath the emission hood. The platforms were covered with heat insulation boards and a layer of thin firebricks (23 x 11.4 x 3.2 cm) to reduce fire hazards. For all stoves, a thin layer of refractory mortar was applied between the firebricks of the combustion chamber and about 2 cm of regular cement was used to bind the bricks of the outer wall. The stoves were left to dry for one week. A first fire was lit in the stoves before the experiments to ensure no more heat would be captured to dry the mortar or to condition the bricks.

The Noflay stoves (Figure 4.1) were built with a combustion chamber made of four stacks of firebricks disposed in a pentagon with two vertical gaps on the sides for primary air flow. One side of the pentagon was left open to insert the fuelwood. The stacks in the NF1 were three bricks high. The ones in the NF2 were four bricks high as a grate was inserted between the first and second row. Small stands rested on top of the stacks to elevate the pot from the edge of the combustion chamber for secondary air flow. A wall of regular bricks was positioned in a circular pattern around the combustion chamber to fit the pot with a gap of about 3.5 cm around the pot. The wall had three holes in the first bottom layer, located behind the stacks of firebricks. The configuration helped to preheat the primary air coming in the fire. Five holes were left in the outer wall, just above the top of the combustion chamber for secondary air inflow.



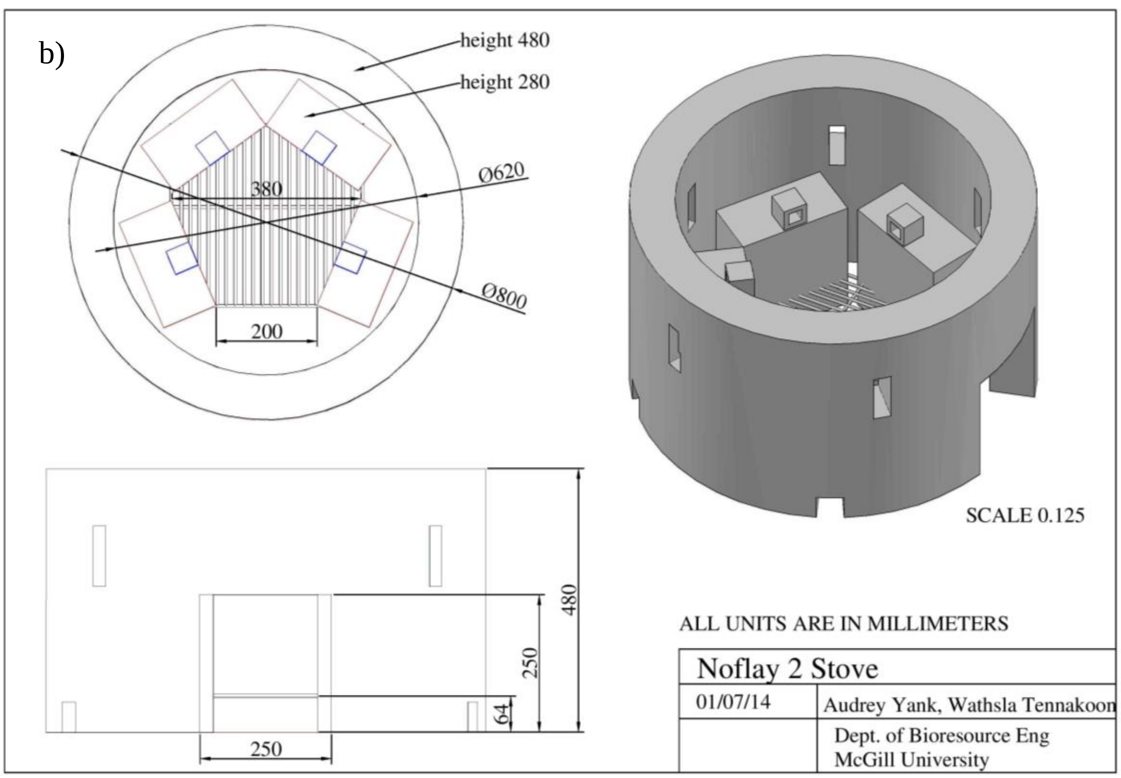


Figure 4.1 - Technical drawings of the a) Noflay 1 and b) Noflay 2 clay brick stoves

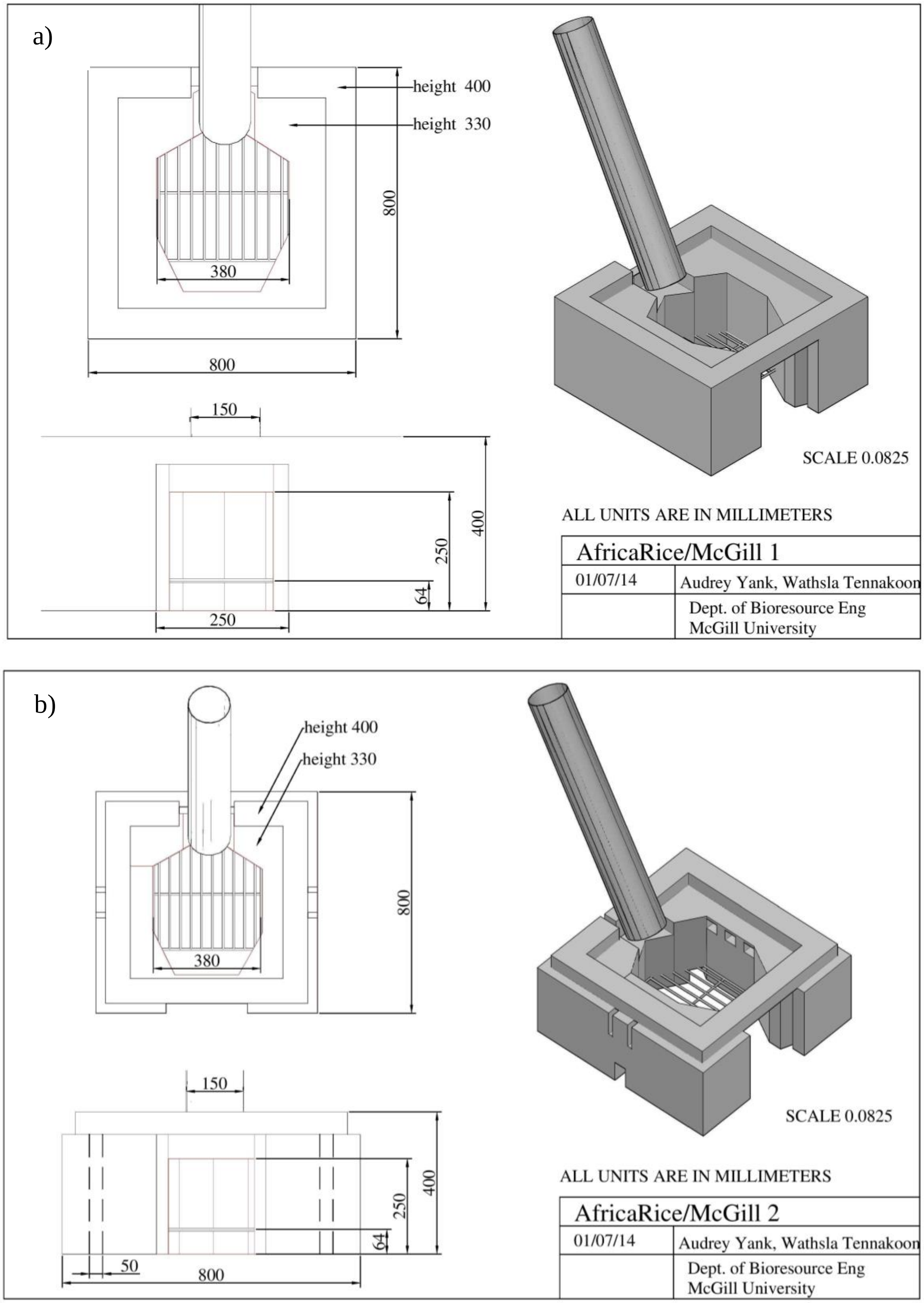


Figure 4.2 - Technical drawings of the a) AM1 and b) AM2 clay brick stoves

The AM stoves (Figure 4.2) had a combustion chamber in the shape of a heptagon (six sides of firebricks and one side for opening to feed the fuelwood). The combustion chamber was five bricks high and had a grate between the first and the second row as well. The combustion was enclosed (no stands to elevate the pot). The outer wall around the combustion chamber was made square and was built from regular bricks. The wall was higher than the combustion chamber by only one row of bricks, so the wall did not cover the side of the pot. The two AM stoves had a chimney inserted in the last row of firebricks in the combustion chamber. The AM2 differed from the AM1 as it had holes in the last row of firebricks for secondary air inflow. Those holes connected to the outside with holes in the outside wall as a space was left between the wall and the combustion chamber. The AM1 had an enclosed combustion chamber.

4.2.3 Thermal Efficiency Test

The water boiling test (WBT) Version 4.2.2 (ARC, 2013) was used to test the thermal efficiency and the fuel consumption of the stoves under laboratory conditions. The WBT investigates how efficiently heat is transferred to the pot by measuring the time and fuel required to boil water under controlled conditions. The WBT was preferred over the controlled cooking test (CCT), which assesses the performance of a stove during a specific cooking task, and over the kitchen performance test (KPT), which was developed for testing in communities. Though the WBT may not always reflect the actual performance of a stove in the field (Jetter et al., 2012), it facilitates the comparisons between stoves at a development stage while controlling for different design parameters (Bryden et al., 2005; Jetter & Kariher, 2009).

The WBT was conducted to study three different cooking scenarios namely two high-power phases (cold and hot start) and a low power phase. All phases were tested without the pot lid to test for the worst case scenario. In the high power cold start (CS) phase, 15 L of water was heated from room temperature to the local boiling point (98.7°C) on a cold stove (i.e. a stove used for the first time in a day). The high power hot start (HS) phase was conducted in the same way as CS except on a warm stove after the CS. In this phase, the pot was refilled with water at room temperature and brought to a boil. The HS served to identify differences in the performance of a stove when already warm compared to the cold condition (i.e. when a stove is used for the first time during a day), especially for high-mass stoves that may be used repeatedly during the day (Bailis et al., 2007). Lastly, the low power (LP) phase was conducted to simulate simmering conditions and took place immediately after the HS. During the LP, the water temperature was maintained as close as possible to 3°C below the boiling point for 45 min. A LP test was considered invalid if the water temperature dropped 6°C below the boiling point.

Wood was cut (60 x 5 x 2.5 cm) from air dried maple planks (JTM Sawmill, Vaudreuil, QC). A stack of little wood sticks (about 65 g) was used as kindling, with one stick partly soaked in kerosene for 5 s as a fire starter. The test started the moment a bigger piece of wood caught fire. The wood was fed radially inwards in the 3-stone stove according to traditional practices. At the beginning of each test, five or six pieces of wood were inserted in the same position through the front opening of the ICs. After, the wood was pushed slightly forward in a semi-continuous way during the high-power phases. The LP usually required two or three refuelling with one wood piece. During the WBT, the temperature of the water in the pot were recorded every 3 s using a data logger (Visual Hotmux V.3.1.0, DCC Corporation, US) connected to Type K thermocouple wires and a probe (chromium-nickel/aluminum-nickel alloy - Omega, Laval, QC) with the tip located 5 cm from the bottom of the pot. The time, water temperature, weight of wood and water were noted before and after each phase. The char was weighed (Setra, EL-

2000S, Acton, MA, USA) after the CS and LP. However, to avoid water temperature dropping 6°C below the boiling point, the weight of the char after the HS was not measured but assumed to be the same as CS (ARC, 2013). Pictures were taken during the WBT using an Infrared (IR) camera (FlirSystems, ThermoVision A20, Danderyd, Sweden) to identify areas of heat losses.

The soot was brushed from the underneath the pot after a full WBT to prevent the formation of a crust which could alter heat transfer (Prasad, 1981). The WBT was conducted in the most consistent manner considering the challenges of reproducing the same fire, a challenge previously reported (Ballard-Tremeer & Jawurek, 1996; Jetter & Kariher, 2009; Prasad, 1981). The firepower (Equation 4.1), defined as the ratio of fuel energy per unit of time, was used as an indicator of the consistency of the rate of fuelling by the operator between tests. The stoves were operated at firepower around 17 to 26 kW for CS and HS, and between 10 to 15 kW for the LP.

The data collected during the WBT were used to compute the performance parameters of the stove. The time to boil (Equation 4.2) was normalized to a starting water temperature of 25°C for ease of comparison between the tests (ARC, 2013; Bailis et al., 2007). The overall stove efficiency is a function of two internal efficiencies: thermal and combustion efficiency (Bhattacharya et al., 2002). The thermal efficiency, or heat transfer efficiency, refers to the fraction of the energy reaching the pot to heat and evaporate the water to the total energy released during combustion (Jetter et al., 2012). This ratio indicates how much energy is lost to the surrounding, through the stove body, pot surface, chimney, excess steam production and incomplete combustion of fuelwood (Prasad, 1981; VITA, 1985). Thermal efficiency (Equation 4.4) is a common performance parameter, though it is sometimes misleading as high steam produced from burning excess fuel yields high values of thermal efficiency with the current WBT calculations (Jetter & Kariher, 2009; MacCarty et al., 2010). This is the case especially for cooking during the simmering (LP), where excess steam can be interpreted as energy lost instead of energy used. Once the food reached boiling temperature, the energy required is mostly to maintain this temperature that will cook the food rather than increasing the energy input that will only generate unnecessary excess steam (VITA, 1985). However, parboiling requires steam and extra steam generation may not been interpreted as wasted energy. Therefore, the amount of fuel consumed becomes an important indicator of the capacity of a stove to efficiently use the combustion energy. The specific fuel consumption (SFC), corrected for a starting water temperature of 25°C (i.e. temperature rise of 75°C) (Equation 4.5), measures the mass of dry fuel burnt per unit of effective water boiled. The effective water boiled represents the water which remains in the pot at the end of the testing phase. The firepower, thermal efficiency and SFC were calculated as follow from the WBT protocol (ARC, 2013):

$$FP = \frac{f_c * h_f}{60 * \Delta t} \tag{4.1}$$

$$\Delta t_c = \Delta t * \frac{75}{(t_f - t_i)} \tag{4.2}$$

$$f_c = \frac{(M_i - M_f)h_f(1 - MC) - MC(C_p(\mathrm{T}_b - \mathrm{T}_a) + h_{fg}) - M_c h_c}{h_f} \tag{4.3}$$

$$TE = \frac{M_w C_p (t_f - t_i) + M_{evp} h_{fg}}{f_c * h_f} * 100\,\% \tag{4.4}$$

$$SFC = \frac{f_c}{1000 * M_e} * \frac{75}{(t_f - t_i)} \tag{4.5}$$

Where, FP = firepower (kW); h_f = lower heating value (LHV) of fuel (kJ kg^{-1}); Δt = time to boil (min); Δt_c = temperature corrected time to boil (min); T_f = final water temperature (°C); T_i = initial water temperature (°C); f_c= equivalent dry fuel consumed (kg); M_i = initial mass of fuel weighted before the start of a test (kg); M_f = mass of fuel unburned at the end of a test (kg); MC = moisture content of the fuel (w/w); C_p = specific heat capacity of water (4.186 kJ kg^{-1} °C^{-1}); T_b = boiling point (°C); T_a = ambient temperature (°C); h_{fg} = heat of vaporisation of water (2 260 kJ kg^{-1} °C^{-1}); M_c = mass of char (kg); h_c = LHV of char (kJ kg^{-1}); TE = thermal efficiency (%); M_w = initial mass of water (kg); M_{evp} = mass of water evaporated (kg); SFC = specific fuel consumption (g L^{-1}), and M_e = effective mass of water boiled (kg).

4.2.3 Combustion Efficiency Test

The concentration of the flue gas was monitored continuously and direct measurements were recorded every 15 s. The gas analyser (M700, Enerac TM, Holbrook, NY, USA) included a non-dispersive infrared sensor to monitor CO and CO_2, an electro-chemical sensor for O_2, and a flame ionization detector for C_xH_y. The particulate matters were not monitored because CO has been reported to serve as a proxy for the emission of particulate matters (McCracken & Smith, 1998; Roden et al., 2009). For the AM stoves, the probe was inserted axially at the end of the chimney (Roden et al., 2009) at a distance of 1.5 m from the fire bed. The chimney had a diameter of 15 cm. For the other stoves, the probe was inserted in the center of a 15 cm diameter pipe fixed above a 1 x 1 m stainless steel hood hanging about 1.5 m over the fire bed (Roden et al., 2009). A suction blower at the end of the pipe drew the exhaust into the hood at a velocity of 0.3 m s^{-1}, measured with a digital anemometer (Reed, LM-8000, NY, USA). Typical air velocity in a closed room is estimated as about 0.25 m s^{-1} (Ballard-Tremeer & Jawurek, 1996). Parboiling usually takes place outside, but an extraction rate of 0.3 m s^{-1} was chosen to minimize the escape of flue gas from the bottom of the hood while avoiding to influence the flame from excess draft (Ballard-Tremeer & Jawurek, 1996; Bhattacharya et al., 2002). The gas monitoring started after the fire was ignited and ended when the water reached the boiling point.

The combustion efficiency, $CO_2/[CO_2+CO+C_xH_y]$ on a molar basis (Jetter et al., 2012), refers to the quality of the combustion. It measures the fraction of carbon emitted as CO_2, other products being a result of incomplete combustion (Smith et al., 2000). The combustion efficiency is a proxy to estimate true combustion efficiency, i.e the ratio of energy produced by combustion to the energy contained in the fuel (Jetter et al., 2012; Johnson et al., 2009). The emission factors were determined from the total mass of pollutant emitted per task. The emission rate (g min^{-1}) equals the mass divided by the time. The emission factor was also normalized by the mass of equivalent dry fuel burned (Equation 4.6) or by useful energy delivered to the pot (Equation 4.7). The useful energy consists of the energy that reaches the pot as opposed to the total energy going into the system by taking into consideration the thermal efficiency. The emission factors were calculated from the equations reported by Zhang et al. (2000) and Battacharya & Salam (2002):

$$EF_f = M_T / f_c \qquad (4.6)$$

$$EF_e = EF_f / (h_f * TE) * 1000 \qquad (4.7)$$

Where EF_f = emission factor in terms of equivalent dry fuel burned in (g kg^{-1}); M_T = total mass of one pollutant emitted (g) ; f_c = equivalent dry fuel consumed (kg); EF_e = emission factor in terms of useful energy delivered to the pot (g MJ^{-1}); h_f = lower heating value (LHV) of fuel (kJ kg^{-1}), and TE = thermal efficiency (%).

The total mass of a pollutant emitted during a test was calculated using the following equations described by Cooper and Alley (2007):

$$M_T = \sum\left(\frac{C_{pollutant} * 15}{10^6} * \rho_{air} * \dot{V}_{dry} * \frac{MW_{pollutant}}{MW_{air}}\right) \qquad (4.8)$$

$$\dot{V}_{dry} = \dot{V} * \left(\frac{273.15}{273.15 + T_s}\right) * (1 - H_2O_{vap}) \qquad (4.9)$$

Where $C_{pollutant}$ = concentration of pollutant (ppm, measured every 15 s); ρ_{air} = density of air at standard condition (1 294 g m^{-3}); $\dot{V}_{dry}$ = dry volumetric flow rate adjusted for standard temperature (m^3 s^{-1}); MW = molecular weight (g mol^{-1}); $\dot{V}$ = volumetric flow rate (m^3 15 s^{-1}) determined by multiplying the area of the pipe and the exhaust velocity; T_s = stack temperature at time of measurement (K); H_2O_{vap} = fraction of water vapor in the flue gas (%). The water vapor in the flue gas was determined by stoichiometry and set to 0.12. The molecular weight of the C_xH_y was taken as 28.97 g/mol as the detection probe was calibrated for propane.

4.2.5 Fuel Characterisation

The moisture content of the fuels was determined after drying for 24 h in an oven (Fisher Scientific 750F, USA) at 104 ºC based on the ASABE Standard S358.2 (2006b). A bomb calorimeter (Parr Oxygen Bomb 1341EB, Calorimeter Thermometer 6772, IL, USA**)** was used to measure the higher heating value (HHV) according to the ASTM standard D5865-11a (2010a). The ultimate analysis of the fuels was derived from the proximate analysis (Parikh et al., 2007) which was determined by thermogravimetry (TGA) using a constant heating rate of 20°C min^{-1} (Q500 V4.7A, TA Instruments, USA) following the ASTM standard E1131-08 (2010b). Wood was used for the WBT to test the performance parameters of the stoves. The biomass briquettes used to compare emission factors, were sawdust with and without a hole in the center, corncob densified at 107 N, 129 N and 149 N, corncob mixed with sawdust (25:75) and rice husk.

4.2.6 Experimental Design

The WBT was performed following a complete randomized design with three independent variables namely the type of stove, the WBT phase and the type of air supply (either natural draft or forced draft with a fan with air flow rate of about 0.05 m^3 s^{-1} added to the side of the combustion chamber). Each test was replicated at least three times. The statistical analysis were conducted on SAS version 9.3 using a significance value of $p<0.05$.

4.3 Results and Discussion

4.3.1 Specific Fuel Consumption

Table 4.1 – Proximate and ultimate analysis of the wood and biomass briquettes

Proximate Analysis	Wood	Corncob (107 N)	Corncob (129 N)	Corncob (149 N)	Sawdust[c]	Rice Husk	25% Corncob 75% Sawdust
Moisture (%)[a]	9.67	6.74	7.14	7.35	5.76	5.49	6.89
Ash (%)[a]	0.98	3.54	3.81	4.06	1.36	17.06	4.09
Volatile matter (%)[b]	71.05	62.73	62.31	63.78	72.69	54.91	63.40
Fixed carbon (%)[b]	28.02	33.73	33.01	32.05	25.93	30.00	27.51
HHV (MJ kg^{-1})	19.22	17.29	17.34	17.37	19.12	16.01	18.82

Ultimate Analysis	Wood	Corncob[d]	Sawdust[c]	Rice Husk	25% Corncob 75% Sawdust
Carbon (%)	50.17	47.87	48.13	43.18	46.64
Hydrogen (%)	5.86	5.35	5.74	4.84	5.40
Oxygen (%)	42.34	37.85	41.52	34.31	38.82

* Results are the mean of three values. [a.] Expressed on a wet basis. [b.] Expressed on a dry basis. [c.] The values are the average values for the two types of sawdust briquettes (with and without a hole in the middle). [d.] The ultimate analysis was the same for the three corncob briquettes densified at different pressure.

All the ICs burned significantly less wood compared to the 3-stone stove, at all stages of the WBT with natural air (Figure 4.3a). At CS, the ICs saved on average 27.7% wood to boil 15 L of water (65.2 g L^{-1}) with no significant difference between the ICs, the equivalent of almost 1 kg of wood saved (978 g) compared to the 3-stone stove to boil 15 L. During HS, the NF1 and the two AM stoves achieved fuel savings of 19.4% (40.0 g L^{-1}) compared to the 3-stone stoves. The SFC of the NF2 was significantly lower by saving 28% wood (57.4 g L^{-1}) compared to the 3-stone stove. The difference in the SFC between the CS and HS was not as high as what was expected for high-mass stoves. At LP, more fuelwood was required than during the high-power phases, which was also noted by Adkins et al. (2010). However, the ICs still saved 17.8% wood at LP compared to the 3-stone stove (except for the AM2 that used significantly less fuelwood with 22.7% savings). The SFC of the LP can be misleading as it would be more sensitive to the behaviour of the operator than during the high-power phases, though SFC during LP would correlate better to the actual SFC in field conditions (Bailis et al., 2007). Also, the grate in the NF2 was found to bend under the heat of the fire after a few tests only, which prevented the wood pieces to remain straight and stable on the bent grate. The durability and the practical aspect of the grate could be questioned with regular stove use.

The impact of a forced draft on the SFC is illustrated in Figure 4.3b. The forced draft significantly improved the SFC of the Noflays at CS compared to the 3-stone stove (46 and 36%, for the NF1 and NF2, respectively), though the reduction relative to the natural draft condition was not significant for the NF2 at all three phases. This could be explained by the grate in the which already allowed for greater air circulation and reduced SFC at natural draft (Adkins et al., 2010). For the AM stoves, the forced draft significantly increased the SFC compared to the natural draft condition at CS and HS. This increase in fuel use can be attributed to the faster combustion rate because of high oxygen supply (from the draft induced both by the chimney and the fan). However, the forced draft improved (though not significantly) the SFC of the AM stoves at LP compared to the natural draft condition. The fan provided the necessary air to combust properly the wood. Otherwise the accumulation of char may have reduced the air supply. Compared to the 3-stone stove, the AM1 increased the SFC by 1% at HS and the AM2 increased SFC by 6% at CS. Alakali et al. (2011) also noticed increasing SFC with increasing air flow rates. At least, the SFC of the AM stoves at LP with forced draft was significantly lower than the 3-stone stove (26 and 23%, for the AM1 and AM2, respectively).

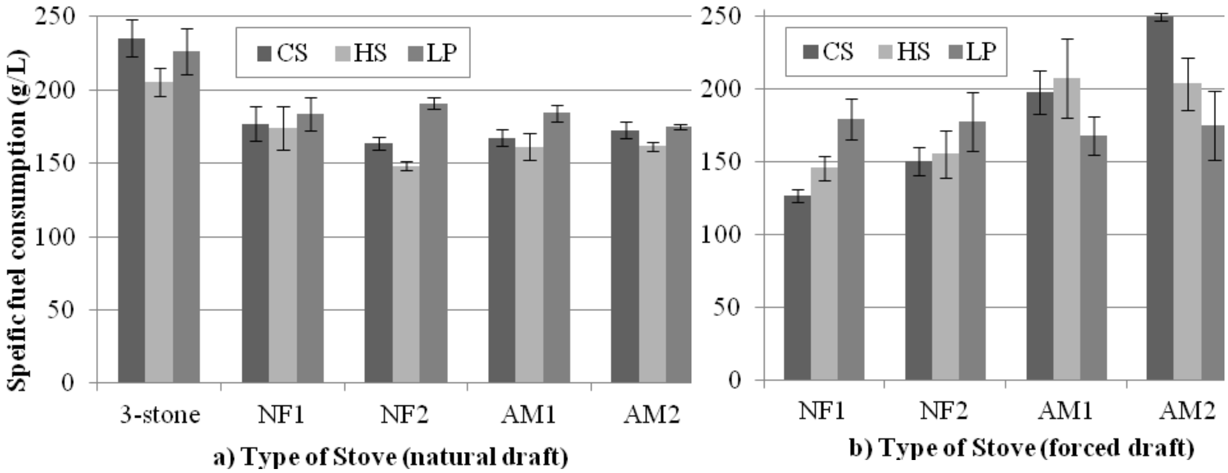


Figure 4.3 – Specific fuel consumption at each stage of the Water Boiling Test a) with natural and b) forced draft.The 3-stone stove was tested at natural draft.

Boy et al. (2000) measured fuel saving of 39% when a baffle was used in the improved *Plancha* stove, which is in the same range of the fuel saved with the Noflays with a fan. Otherwise, the first version of the *Plancha* (without baffle) did not save fuel relative to the 3-stone stove. A reduction of 40% in fuel use was noted by McCarty et al. (2010) for ICs with forced draft. Savings as high as 44 to 65% were achieved with the fired-clay *Patsari* stove in Mexico (Berrueta et al., 2008). Adkins et al. (2010) reported savings of 41% in the field, but of only 29% in the lab setting. Other studies have shown that some ICs actually increased the fuel consumption (Jetter & Kariher, 2009; McCracken & Smith, 1998; Wallmo & Jacobson, 1998).

4.3.2 Time to boil

During the CS, all the ICs boiled water in about 35 min as opposed to 51 min with the 3-stone stove, a 31% reduction in time (Figure 4.4). At HS, all the clay brick stoves performed even better than during the CS with an average boiling time of 12.5 min faster than the 3-stone stove. For high-mass stoves, the heat transfer to the pot is usually lower at CS conditions (i.e. when the stove is cold) (Boy et al., 2000). Studies previously reported that high-mass ICs had actually significantly increased the boiling time by up to 253% (Bailis et al., 2007). In the current study, the NF2 was the stove to boil water in the least amount of time (27.5 min) and was the only one to be significantly lower than the other ICs (average of 31.5 min). The NF2 probably had less heat loss to the bottom surface and greater natural airflow compared to the NF1 as the fire bed was elevated on a grate. Also, the ash falling through the grate most likely preheated the air coming from underneath. The AM stoves also had a grate, but Noflays had fewer firebricks to heat up in the combustion chamber (12 instead of 24 for the AM stoves). Similarly, Ayoub and Brunet (1996) reported boiling 30 L of water in a community stove (50 L pot and similar firepower of about 20 kW) in 35 min at HS conditions.

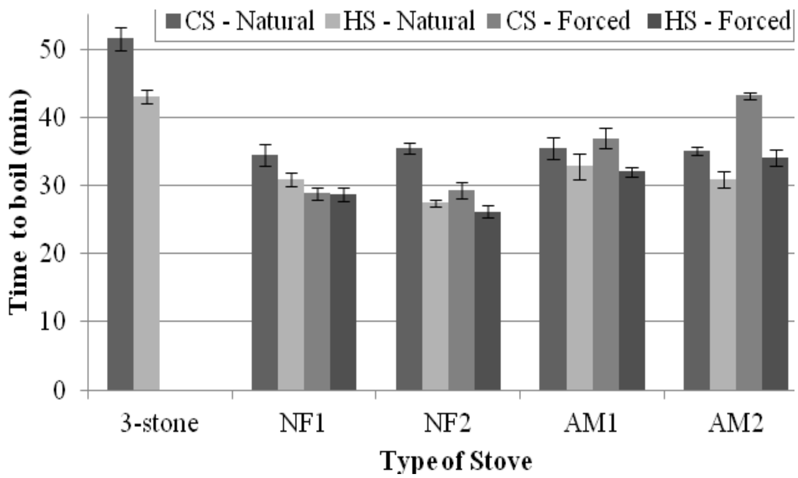


Figure 4.4 - The time to boil 15 L of water during cold start (CS) or hot start (HS) under natural or forced air draft using the different types of stoves.

The 3-stone stove was 15% faster at HS than at CS, though it did not have a stove body to capture heat like a clay brick stove. This reduction in time was probably caused by heat stored in bricks of the bottom surface. Bailis et al. (2007) observed a similar time reduction for a 3-stone stove between the two WBT stages. For the ICs, the time saving between the two stages could be linked mostly to the heat accumulated in the stove body, as the bottom surface exposed to the fire was small compared to area of stove body.

The Noflays performed better in terms of time to boil than the AM stoves with the presence of a fan (forced draft). During the HS, the NF2 was significantly faster by completing a boil in 26 min. At CS, the forced draft increased the boiling time of the AM stoves compared to the natural draft condition (though not significantly for AM1). Both had a chimney which probably already induced a greater natural draft in the combustion chamber, up to a point where the forced draft blew the heat away in the chimney, reduced heat transfer to the pot and increased the boiling time. The heat escaping by the chimney was observed using the IR camera (Figure 4.5). Alakali et al. (2011) observed a cooking time almost twice as fast by increasing the volumetric air flow rate from 0.09 to 0.16 m^3 s^{-1}. Time to complete a cooking task may not be instinctively considered an important performance parameter by stove designers, but it is often amongst the most important factors of acceptability and adoption (Adkins et al., 2010).

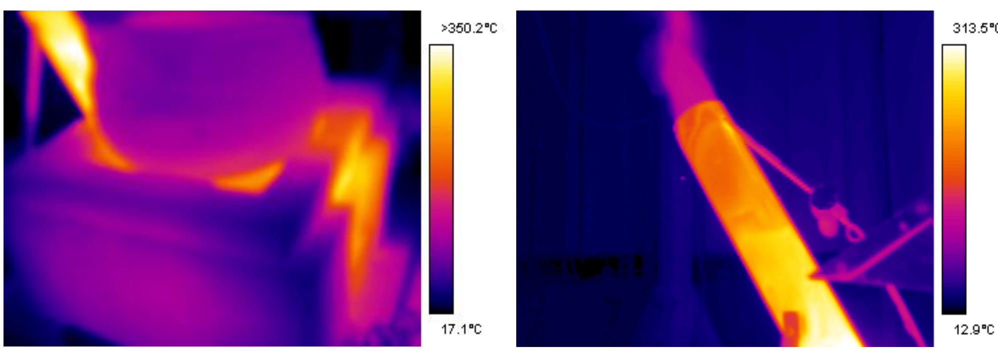


Figure 4.5 – Heat losses from the stove body and chimney.

4.3.3 Thermal Efficiency

At natural draft (Figure 4.6a), the thermal efficiency varied between 17 and 20.7% at CS, 19.1 and 23.2% at HS, and 21.6 and 25.6% at LP. The highest thermal efficiency (25.5%) was observed during LP with the NF1. At CS, the AM1 had the highest efficiency of 20.7% (slightly above the NF1 19.5%), a significant increase of 13% compared to the 3-stone stove (18%). The AM1 also performed best amongst the clay brick stoves at HS with a thermal efficiency 22.8%

higher than the 3 -stone stove. However, the AM1 was the only clay brick stove to show no improvement at LP. The LP is the phase that probably simulates best the condition in which the improved parboiling stoves in the current study would be used as rice parboiling takes place with continuous feeding of fuel to generate steam for a series of batches of 25 to 35 min each as opposed to bringing water from room temperature to a boil at the beginning of each batch.

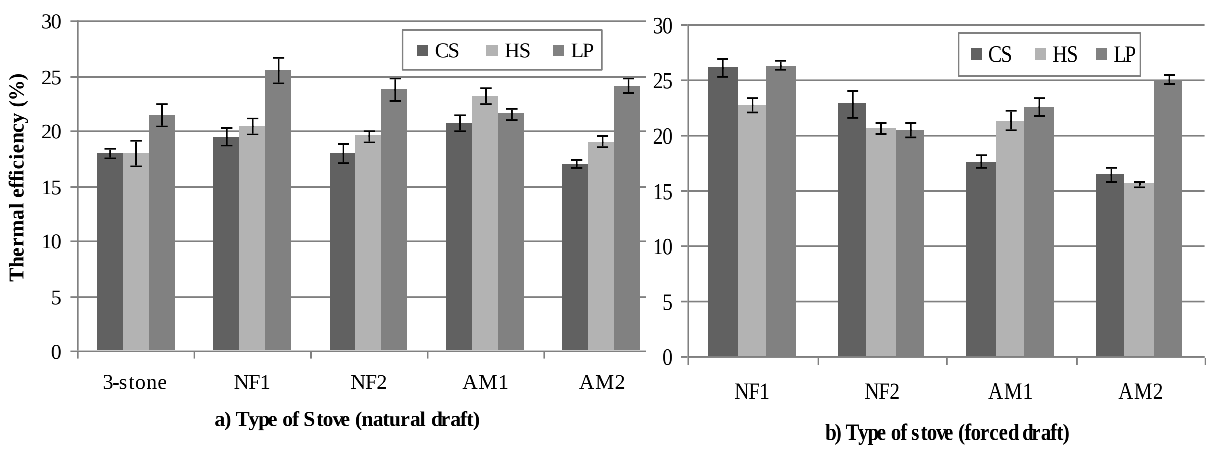


Figure 4.6 – The thermal efficiency in percentage (%) at all stages of the Water Boiling Test a) with natural draft and b) forced draft. The 3-stone stove was not tested with a fan.

Looking at the overall thermal efficiency (average of all stages of the WBT) at natural draft, the AM1 and NF1 had the same value of 21.8%, which was considered only a marginal increase compared to the thermal efficiency of the 3-stone stove (19.1%). At CS, the AM2 had a thermal efficiency of 17.0% (which was 5.9% below the 3-stone stove). It would be interesting to investigate further if the AM2 was properly sized for the pot. An underpowered stove tend to produce more water vapour during the high-power phase while an overpowered stove would do the same at low-power (Jetter & Kariher, 2009). The thermal efficiency would have maybe increased if the combustion chamber was wider or if a smaller pot had been used instead. The thermal efficiency of a stove would decrease when used with a pot larger than what it has been designed for (Wallmo & Jacobson, 1998).

The thermal efficiency measured for the 3-stone stove was higher than expected. A lower average thermal efficiency of 12.4% was reported for 11 different traditional stoves for pots of diameters 16 to 30 cm (Bhattacharya et al., 2002), half or more the size of the pot used in this study. Berrueta et al. (2008) reported a wider range of overall thermal efficiency (5 to 17%) for the 3-stone stove. The higher thermal efficiency measured here for the 3-stone stove could be link to the large fire required to heat a 55 cm diameter pot. Adkins et al. (2010) observed that the heat transfer and SFC improved along with an increase in the scale of cooking.

The two AM stoves showed greater improvement between the CS and HS relative to the NF stoves (Figure 4.6a), with the higher number of warm firebricks in the combustion contributing to preheat the air at HS. The difference in thermal efficiency between the two phases was not significant for the NF1, though it was for the NF2. The grate may explain the lower thermal efficiency at CS for the NF2 by letting more cold air in the fire. However, the thermal efficiency of the Noflays was not significantly different from one another at the two high-power phases. On the other hand, the thermal efficiency was significantly different between the two AM stoves at each phase. The secondary holes in the AM2 seemed to negatively affect the heat transfer at CS and HS, compared to the AM1, with the opposite trend at LP. Precautions should be taken when interpreting the thermal efficiency results. High thermal efficiency may simply arise when more heat is generated, i.e. when more wood is burned. The thermal efficiency should not be the only metric to conclude on stove performance. Bailis et al. (2007) showed how there was a significant increase in thermal efficiency at LP, though the IC significantly consumed more fuelwood than the 3-stone stove.

The effect of a forced draft depended on the stove design (Figure 4.6b). The overall thermal efficiency of the NF stoves increased to reach 25.1 and 21.3%, respectively, while the overall thermal efficiency of the AM stoves decreased to 21.8 and 20.1%, respectively, with presence of a fan. The greatest improvement in overall thermal efficiency over natural draft was observed with the NF1 (3.3%). At CS, the forced air significantly increased the thermal efficiency of the Noflays, by 34.4 and 27.7%, respectively, and significantly reduced by 15% the thermal efficiency of the AM1. The forced air also reduced the thermal efficiency of the AM2, but not significantly (3.2%). Alakali et al. (2011) noticed an improvement of 17.5% in heat utilized when the air flow rate was increased from 0.13 to 0.16 $m^3 s^{-1}$. The reduction in thermal efficiency of 15% for the AM1 at CS was probably caused by the combined effect of the fan and the chimney which did not provide enough residence time in the combustion chamber for effective heat transfer (MacCarty et al., 2010). Wood combustion is efficient when there is enough air, but not too much (Alakali et al., 2011; Kituyi et al., 2001).

The greater increase in thermal efficiency for the Noflays at CS relative to the natural draft condition may have been a result of the pot shield in the design. A shield (sometimes called skirt) favors contact between the side of the pot and the hot flue gases, allowing for convective heat transfer (Akter & Hossain, 2001). The forced draft may have increased the contact of the hot flue gas with the pot, which made a greater contribution to improve the thermal efficiency at CS. Lucky and Hossain (2001) observed an increase in thermal efficiency of 6.4% by the addition of a shield to an IC. McCarty et al. (2010) mentioned how the 60 L stove with a shield was particularly efficient with the big pot having a larger surface area in contact with the hot flue gases. Finally, the forced air did not significantly affect the thermal efficiency of the clay brick stoves at HS and at LP, except for the AM2 at HS (-17.7%) and for the NF2 at LP (-14%).

The results with the natural draft can be compared with the overall thermal efficiency reported for other ICs, namely 9.5 to 25% (Bhattacharya et al., 2002), 20 to 24% (Ballard-

Tremeer & Jawurek, 1996), and 11.6 to 24.3% (Bailis et al., 2007). A thermal efficiency up to 30% was measured for the *Patsari* clay stove at LP, though the same stove had a thermal efficiency of only 7% at CS (Berrueta et al., 2008). Thermal efficiencies higher than 30% (up to 53%) were reported with some ICs built from metal (wood gasifiers, rocket stoves) or using liquid fuels (Akter & Hossain, 2001; Jetter et al., 2012). Boy et al. (2000) measured a thermal efficiency of only 12.4% for the improved version of the *Plancha* (with baffle) though it saved 39% in fuelwood. However, thermal efficiency should not be the only indicator of performance.

Prasad et al. (1985) considered stoves as non-steady-state systems with their thermal efficiency being better represented in correlations with the firepower rather than using single values (Figure 4.7). Thus, the thermal efficiency would vary depending at which firepower it is operated, as noticed with the difference in thermal efficiency between the high-power and low-power phase of the WBT (Figure 4.6), where the thermal efficiency tended to be higher at LP.

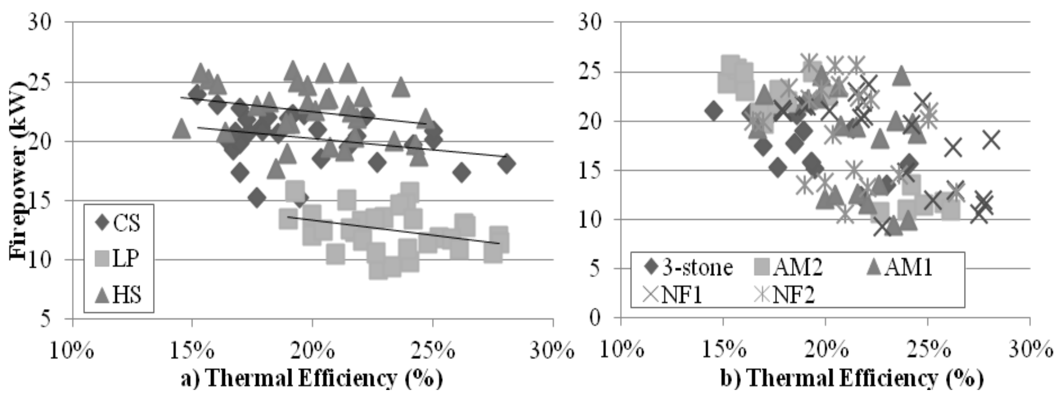


Figure 4.7 – Correlation between the firepower and the thermal efficiency of the stoves in function of a) the different phase of the Water Boiling Test and b) the type of stove.

4.3.4 Stove Emission Factors

The emission factor of CO ranged between 3.0 and 22.9 g MJ^{-1} at natural draft condition and between 2.8 and 17.0 g MJ^{-1} at forced draft condition (Figure 4.8). The Noflays emitted the least amount of CO, but with no statistical difference compared to the 3-stone stove or between the two NF stoves. At CS, the emission factors of the two AM stoves were significantly higher than the 3-stone stove. The production of CO is usually higher at lower temperatures (MacCarty et al., 2010) and the AM stoves had more bricks, therefore took longer to heat up at CS. There was no significant difference between the CS and HS for all stoves, except for the AM2. On the other hand, all the emissions at LP were higher than during the high-power phases, especially for the AM stoves, which increased by as much as 156 and 117%, respectively. The LP lasted longer than the CS and HS which led to the accumulation of char in the fuel bed and to the reduction of oxygen, i.e. lack of primary air (Ballard-Tremeer & Jawurek, 1996). As well, CO forms mostly when the air to fuel ratio is fuel rich and with smoldering fires as opposed to fires with vivid flame (MacCarty et al., 2010; Roden et al., 2009). The secondary air holes in the combustion chamber of the AM2 reduced the CO emission by introducing secondary air, especially during the LP. The difference between the two AM stoves was not significant at CS and HS.

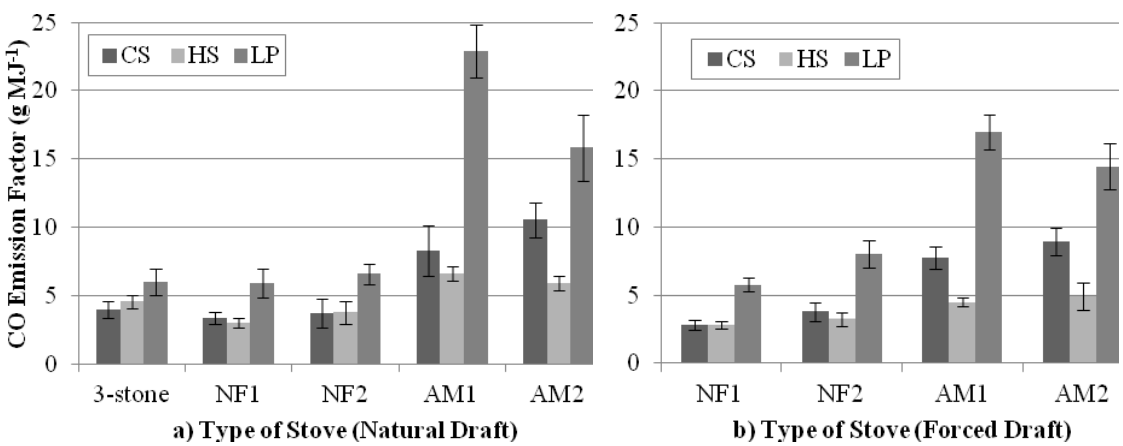


Figure 4.8 – Emission factors of carbon monoxide in terms of mass emitted per energy delivered to the pot for each stage of the Water boiling test at a) natural draft and b) forced draft. The 3-stone stove was not tested with a fan.

The forced draft did not affect the emission factors of CO in the NF stoves and reduced the production of CO in the AM stoves. The fan provided oxygen in the more enclosed combustion chamber of the AM stoves, which could explain why the forced draft did not affect the CO emission in the NF stoves. Future tests could assess if both the CO emission and SFC could be further reduced with a higher volumetric air flow rate, especially for the Noflays especially for the Noflays (as the SFC of the AM stoves increased with forced air – Figure 4.3).

Table 4.2 – Overall emission factors of CO, CO_2, and C_xH_y

Stove	Air	g $task^{-1}$			g min^{-1}			g kg^{-1}			g MJ^{-1}		
		CO	CO_2	C_xH_y	CO	CO_2	C_xH_y	CO	CO_2	C_xH_y	CO	CO_2	C_xH_y
3-stone	Natural	43.4	1551.2	2.430	0.94	33.3	0.052	16.7	581.2	1.779	4.9	165.3	0.262
NF1	Natural	33.3	1924.2	1.287	0.90	53.4	0.035	17.0	947.0	0.673	4.1	232.9	0.163
NF2	Natural	40.0	2243.8	1.164	1.11	64.9	0.034	19.0	1058.9	0.547	4.7	262.5	0.138
AM1	Natural	96.6	3690.7	2.041	2.41	97.3	0.054	47.3	1738.0	0.975	12.6	459.2	0.262
AM2	Natural	80.4	2764.3	1.341	2.12	77.0	0.036	40.4	1264.4	0.623	10.8	346.7	0.169
NF1	Forced	33.8	1948.0	0.637	0.99	59.4	0.019	18.5	1045.5	0.356	3.8	217.3	0.072
NF2	Forced	39.1	2037.3	0.807	1.13	61.9	0.024	20.2	1019.9	0.402	5.0	249.5	0.098
AM1	Forced	74.2	3223.5	1.755	1.89	84.7	0.046	38.5	1525.7	0.899	9.7	395.5	0.227
AM2	Forced	84.5	2288.9	1.330	2.00	55.6	0.031	37.5	936.3	0.566	9.4	251.3	0.142

The overall emission factors (average of all stages of the WBT) expressed in terms of different units are presented in Table 4.2. The emission factors had different absolute values when normalized for different units, but they kept similar relative values as when expressed in g MJ^{-1} (Figure 4.8). The emission factors of CO normalized per fuel burned varied from 11.9 to 84.6 g kg^{-1} at natural draft conditions and between 12.6 and 69.4 g kg^{-1} at forced draft conditions. These results are somewhat higher than the values reported in other studies (9 to 29 g kg^{-1} (Venkataraman & Rao, 2001) and 11.1 to 19 g kg^{-1} (Zhang et al., 2000)) but remain within the same range measured in other studies (19 to 136 g kg^{-1} (Ballard-Tremeer & Mathee, 2000) and 20 to 217 g kg^{-1} (Roden et al., 2006)). McCarty et al. (2010) suggested a benchmark of 20 g of CO emitted to boil 5 L with an IC. An IC is expected to perform better than the 3-stone stove when the benchmark is attained. In Table 4.2, the total mass emitted by the 3-stone stove (43.4 g $task^{-1}$) could be taken as the benchmark to boil 15 L of water. Then, the two Noflays meet this benchmark, both at forced and natural draft.

The total mass of pollutant emitted per parboiling task relates to the exposure of the stove users. For health reasons, the WHO has set an exposure limit of 25 ppm for a one-hour average (WHO, 2006). Yet, the results in Table 4.2 should be used for stove development and design purposes and not to estimate the air pollution levels or direct human exposure which should be based on field data (ARC, 2013; MacCarty et al., 2010). From Table 4.2, the 3-stone stove had the highest emission factor of C_xH_y, which demonstrates the incomplete combustion. However, the 3-stone stove did not have the highest emission factor of CO, which can be a result of excess air available in the combustion zone (Kituyi et al., 2001). The emission rate (mass of pollutant per unit of time, g min^{-1}) provides information on the reduction in emissions. For example, the NF1 with forced draft emitted less total CO during the WBT, but the emission rate was actually higher than the 3-stone stove (0.99 g min^{-1} compared to 0.94 g min^{-1}) because the WBT boiled water in less time in the NF1 with forced draft compared to the 3-stone stove.

A doubt may arise about the higher values of the emission factors of the AM stoves. Possible dilution of the flue gas may have occurred when the measurements were taken from the hood as opposed to the tip of the chimney. This was probably the case, as the CO_2 concentration measured in the chimney was higher than the concentration of CO_2 measured in the hood (Table 2). Therefore, the results from the combustion efficiency can solve the dilution discrepancy. Measured as a ratio of the pollutants, the combustion efficiency is independent of the absolute value of the mass of pollutant measured and solves the dilution discrepancy. Figure 4.9 presents an overall comparison of the combustion and thermal efficiency. The AM2 stoves (natural and forced draft) had a combustion and thermal efficiency in the same range as the 3-stone stove. The NF1 with forced draft stood out with the highest thermal efficiency, though with the same range of combustion efficiency as the NF1 and NF2 at natural draft. The results were recorded in laboratory conditions. It would have been interesting to investigate how the stove performed in windy conditions, which is often the case for parboiling taking place outdoors. The combustion chamber offers wind protection compared to the 3-stone stove which strongly disadvantaged in windy conditions. Efficient combustion is a result of proper combination of oxygen supply, high enough temperature and residence time for the reaction to take place.

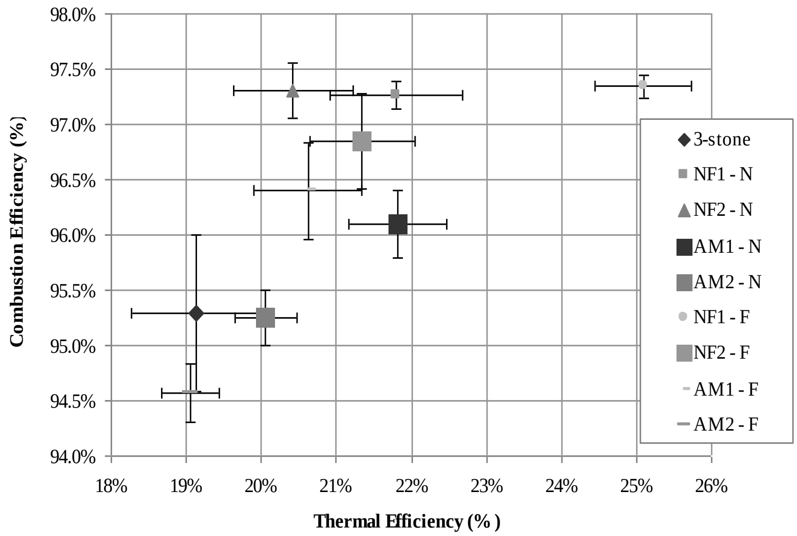


Figure 4.9 – Thermal and combustion efficiency with natural draft (N) and forced draft (F), the combustion efficiency being the molar ratio of CO_2 to the sum of all emission products.

The thermal and combustion efficiency should be considered together. These two factors are affected differently by stove design. The thermal efficiency is often improved to the expense of combustion efficiency (Ballard-Tremeer & Mathee, 2000; Zhang et al., 2000). Large flames create high air entrainment and increase heat transfer, but reduce at the same time the temperature of combustion, leaving to more carbon particle unburned (Kituyi et al., 2001). Reducing the distance between the pot and the flame is another measure that increases thermal efficiency, but cuts on secondary air necessary to improve the quality of combustion (Edwards et al., 2007). A case was reported where the thermal efficiency was improved by 1.4% while increasing by a factor of five the emission factor of CO (Ballard-Tremeer & Jawurek, 1996).

4.3.5 Biomass Fuel Emission Factors

All the biomass briquettes provided enough energy to successfully complete WBT. The emission factors of the biomass fuels are presented in Table 4.3. The mass of pollutant per amount of fuel burned allows comparing between the biomass (Figure 4.10). The corncob briquettes compressed at 107 N had the lowest CO emission factor. It is interesting to note that the rice husk briquettes had an emission factor in g kg^{-1} in the low average, while having the highest total emission load during a WBT. The density of the rice husk briquette is lower than wood, which may have allowed for more oxygen in the fuel bed. Also, rice husk has a lower energy content compared to other fuels (Table 4.1). Therefore, a higher number of rice husk briquettes were required to complete the WBT, which explains the higher total mass emitted and emission factor in terms of useful energy.

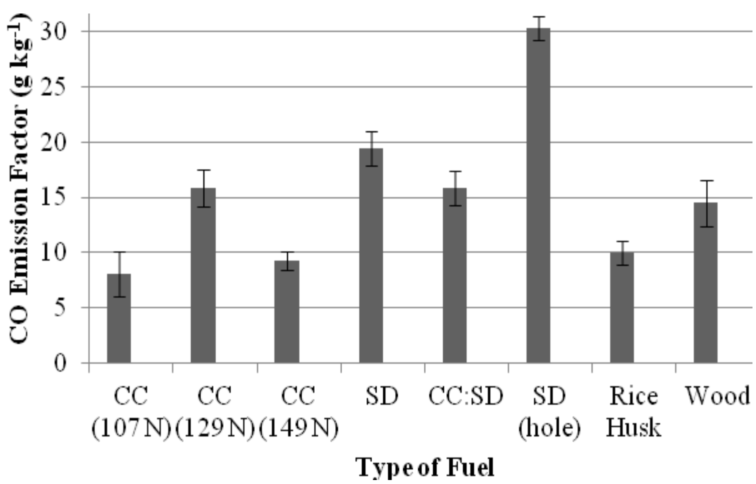


Figure 4.10 – The emission factors of carbon monoxide expressed in terms of mass emitted per equivalent dry fuel burned (g kg^{-1}) for each type of fuel.

The sawdust briquette without a hole in the middle had a higher emission rate and total amount of pollutant emitted (both CO and C_xH_y) per task than the sawdust briquettes with no hole. The hole provided more air into the fuel bed during combustion. However, the emission factor in terms of fuel burned was particularly high for sawdust briquettes with a hole. Referring to the proposed benchmark of 20 g of CO emitted to boil 5 L of water (MacCarty et al., 2010), the briquettes made of sawdust with no hole, of a blend of sawdust and corncob, and of rice husk would not meet the emission standards. The force used for densification did not affect the emissions in a linear way. The corncob briquette compressed under a force of 149 N did not emit significantly more CO than the ones compressed at 107 N.

The briquettes made with corncob and rice husk had a faster burning rate and required frequent refuelling from the stove user. The ash content of those two agricultural residues was also higher than wood (Table 4.1), especially for rice husk, leading to the fast accumulation of ash in the combustion chamber. All the space underneath the grate in the NF2 was filled with ash at the end of the WBT when using rice husk briquettes. The agricultural residues would not be very practical in a stove without a grate from a user point of view.

Table 4.3 – Emission factors of the different biomass briquettes

	g min^{-1}			g task^{-1}			g kg^{-1}			g MJ^{-1}		
Biomass	**CO**	**CO_2**	**C_xH_y**	**CO**	**CO_2**	**C_xH_y**	**CO**	**CO_2**	**C_xH_y**	**CO**	**CO_2**	**C_xH_y**
Corncob (107 N)	0.57	65.6	0.061	10.2	1167.2	1.11	8.1	923.9	0.87	3.04E-03	0.347	3.28E-04
Corncob (129 N)	0.99	67.4	0.081	17.4	1176.8	1.41	15.9	1072.8	1.29	5.32E-03	0.360	4.34E-04
Corncob (149 N)	0.62	52.2	0.059	15.7	1316.0	1.44	9.3	780.2	0.87	3.73E-03	0.314	3.42E-04
Sawdust	0.98	50.3	0.052	20.9	1071.2	1.11	19.4	994.4	1.03	5.99E-03	0.306	3.17E-04
Corncob Sawdust[a]	1.07	62.8	0.111	20.2	1188.8	2.09	15.8	925.4	1.64	5.48E-03	0.326	5.71E-04
Sawdust (with holes)[b]	0.95	59.9	0.008	19.1	1197.3	0.15	30.3	1880.3	0.25	6.13E-03	0.386	4.92E-05
Rice Husk	0.94	69.7	0.010	21.1	1541.4	0.22	10.0	736.4	0.11	7.36E-03	0.535	7.67E-05

* The emission factors were determined by conducting the WBT with 5 L of water using the NF2 stove with natural draft condition. a. The blend of corbncob and sawdust was in proportion of 25:75 and b. the sawdust briquettes had a hole in the center.

4.4 Conclusion

In conclusion, four different clay brick stoves were built and tested for the applications in small-scale parboiling in rural communities. Clay brick stoves have the potential to reduce the fuel consumption as well as harmful emissions. The Noflay stoves, especially the NF1, took less time to boil, used less fuel and had a better heat transfer efficiency, and lowered pollutant emissions altogether compared to the 3-stone stove. The NF1 was the simplest of the clay brick stoves. This simple stove design without too technical features was found to appropriately provide a first-hand alternative to address the current challenges of the 3-stone stove. Adding a fan was found to further improve the performance of the NF1. The grate in the NF2 improved the performance compared to the 3-stone stove, but not significantly compared to the same stove with no grate (NF1). The NF2 mostly just allowed boiling water faster. However, a grate would be recommended when biomass briquettes are to be burned. The simultaneous addition of a chimney and a fan would not be recommended. The chimney in the AM stoves improved the thermal efficiency compared to the 3-stone stove, but only at natural conditions. The AM stoves performed better than the 3-stone stove in terms of fuel consumption and heat transfer, but not as much as the NF stoves. The combustion efficiency of the AM1 stove improved compared to the 3-stone stove, but the AM2 had lower combustion efficiency than the 3-stone stove. The usefulness of a chimney can be questioned as it may only provide a measure to remove smoke away from the stove users. Cooking outdoors may also provide the same benefit without the cost and challenge of material acquirement. Social-economical factors should always be considered for the acceptability of ICs by end users before implementation.

4.5 Acknowledgments

This study was made possible with the collaboration of the Africa Rice Center and the financial support of the Canadian International Development Agency (CIDA) and the Natural Sciences and Engineering Research Council of Canada (NSERC). Special thanks to Roger Samson from Reap-Canada for his support to accomplish this research work.

Connecting Statement to Chapter 5

A technology that is designed to be energy efficient used less energy by definition than a conventional equivalent technology. This description considers generally the energy requirement during the time of use of this technology by the end users. However, the actual energy requirement of a technology should also include the energy that was used to build, manufacture, and transport this technology. A new sustainability approach consists of evaluating a product over its entire life cycle. Chapter 4 studied new cookstoves designed to improve the energy efficiency of domestic cooking. Therefore, Chapter 5 evaluates the cookstoves over their life cycle to assess the actual energy and environmental impact of those new products outside of the utilisation phase.

The chapter is drawn from the report *Life cycle analysis of improved clay brick stoves* that was submitted for the course *BREE 608: Special Problems in Bioresource Engineering* in April 2014. The report was written by Audrey Yank, M.Sc. Candidate at McGill University, and supervised by Dr. Michael Ngadi, Supervisor and Professor and McGill University. The format has been changed to be consistent with this thesis.

Chapter 5: Life cycle analysis of improved clay brick stoves

5.1 Abstract

The Life Cycle Analysis or Assessment (LCA) is a sustainability tool developed to provide a framework to evaluate the environmental consequences of a product or process over its life cycle. The LCA methodology, as defined by the International Standard Organization (ISO), consists of four phases: objective and scope definition, inventory analysis, impact assessment, and interpretation. Common environmental impacts studied are air and water pollution, resource and energy consumption, and human toxicity. The description, history and methodology of LCAs are provided along with a literature review studies conducted on fuels and cookstoves.

An LCA was conducted on three small scale rice parboiling stoves, the traditional 3-stone stove and two improved clay brick stoves, the Noflay and the AM (Africa Rice/McGill) stove. The environmental impacts associated with the stove construction and parboiling were assessed. It was found that the energy required to build the Noflay and AM stove could be recovered in 6.78 and 10.15 days, respectively, if at least one parboiling is achieved per day. The two improved stoves reduced the wood consumption and the emission of hydrocarbons compared to the 3-stone stove. The Noflay performed better than the 3-stone stove in all impact categories though it did not save as much wood as the AM stove. However, the AM stove significantly increased the emission of CO. Finally, parboiling was the main source of emissions, brick firing required the most energy input and brick production had the highest material input.

5.2 Introduction

The current market is submerged with similar products, often leaving consumers puzzled at time of purchase. The decisions of consumers used to be mostly based on the cost and the quality of an item. Nowadays, a growing awareness about the environment has brought new factors to take into consideration in consumption habits. There is also increasing awareness in the industry. Businesses concerned about natural resource depletion and ecosystem degradation want to assess the current or potential impacts of their activities to reduce the cost of resource extraction, meet new environmental standards and adopt new management systems. This relates to sustainability which ensures good quality of life over a prolonged time period. The commonly accepted definition of sustainable development is one that “meets the needs of the present without compromising the ability of future generations to meet their own needs" (UN, 1987).

A number of sustainability assessment tools, such as GHG inventories, environmental audits, environmental performance evaluations, risk assessments or impact assessments, have been developed for comparisons based on environmental criteria, (UNEP, 2009; WRI/WBCSD, 2011). The Life Cycle Analysis or Assessment (LCA) is another tool gaining popularity that was developed to provide a framework to evaluate the environmental consequences of a specific product/process (UNEP, 2009). The idea is to provide an analysis over of the life span of a product, from cradle-to-grave, and bring this more ‘holistic’ approach into a consistent and structured framework of decision-making process (Guinée & Heijungs, 2005). On the short term, the large scale economic force will not be overcome by a desire to protect the environment. Therefore, the LCA fundamentally implies that the environmental protection needs to take place within the economic system itself and chooses the final choice as the opportunity for indirect environmental changes along the whole network upstream (Guinée & Heijungs, 2005).

5.3 Life Cycle Analysis

5.3.1 Definition and Types of LCAs

An LCA is defined by the International Standard Organization (ISO) (2006b) as the “technique that aims at addressing the environmental aspects of a product and their potential environmental impacts throughout that product’s life cycle”. Life-cycle itself is defined by the

US Environmental Protection Agency (EPA) (2006) as the “major activities in the course of the product’s life-span from its manufacture, use, and maintenance, to its final disposal, including the raw material acquisition required to manufacture the product”. Conducting an LCA moves away from the traditional focus on the production site or manufacturing process, and considers other steps involved that do not necessarily take place at this specific site or during this process. For instance, driving an electric car reduces the ecological footprint while driving but the impact of manufacture has to be considered. Also, making a lighter car from aluminum reduces gas consumption, but the production of aluminum actually requires more energy than steel (Guinée & Heijungs, 2005). An LCA provides information to systematically evaluate the cumulative environmental impacts over a life-cycle, and better understand and address these impacts. The impacts often considered include raw material extraction, GHG emissions, energy, waste production, hazardous release, water and air pollution, and land use (Guinée & Heijungs, 2005).

Apart from the usual environmental perspective provided by the LCA, other types of analysis have been developed. First, the Social-LCA (S-LCA) looks at the social impacts of a product to actively support the stakeholders improving the social and socio-economic conditions of a production and consumption system. Secondly, the Life Cycle Costing (LCC) conducts the analysis from an economic standpoint and compiles the financial costs associated with each stages over the life-cycle (UNEP, 2009). Thirdly, the application of sustainability principles in businesses has led to the Life Cycle Management (LCM). This integrated approach considers the three pillars of sustainability (social, environmental and economic) and the technical aspects of a service, product or organization (EPA, 2006). Finally, the environmental LCA is sometimes identified as E-LCA, though in the present paper it will be referred to as LCA.

5.3.2 Historical Background

The initial idea to account for the total energy used in a process came from the concern of the availability of energy and raw material supplies (EPA, 2006). Harold Smith first reported calculations on the total energy requirements to produce chemical intermediates at the World Energy Conference in 1963 (EPA, 2006). After, the first LCA was done for Coca-Cola Inc. in 1969, by the Midwest Research Institute, to determine which beverage container manufacturing required less material and energy input, and released less chemicals to the environment (EPA, 2006). Originally, LCAs were mostly from an energy point of view, especially during the energy crisis in 1970s when the price of oil was a driver to reduce energy consumption. In the 1980s, the environmental concern also included hazardous wastes (Svoboda, 1995) with the emergence of regulations related to air pollution and waste production (UNEP, 2009). As a result, the life-cycle approach was incorporated in risk assessment methods to develop environmental protection standards (Svoboda, 1995). Deeper sustainable thinking also came from the Earth summit in Rio de Janeiro in 1992 with the adoption of the Agenda 21 which highlights the importance to "develop criteria and methodologies for the assessment of environmental impacts and resource requirements throughout the full life cycle of products and processes" (UNEP, 2009). The use of LCA spread in the 1990s with the development of standard procedures. A first initiative to provide coherent science-based guidelines at the international level came from the Society of Environmental Toxicology and Chemistry (SETAC) in 1989 (Guinée & Heijungs, 2005). The first official standard was developed in 1994 by ISO, supported by SETAC, which harmonized the different terminologies in use. A series of standards (ISO 14040-43) were produced in 1997-98 (revised in 2006) to outline the LCA principles and framework. The UNEP further globalized the LCA in 1996 with the release a user-friendly guide.

5.3.3 Uses and Limitations

The LCA is a flexible tool. An LCA can assist to (EPA, 2006; ISO, 2006b; McManus, 2005):

- Assess environmental trade-offs
- Identify opportunities to improve the environmental aspect at various point in a life-cycle
- Help gain better acceptance from stakeholders (community, consumer, government, etc)
- Quantify the total inventory of releases (pollutants to the air, water and soil) and inputs (energy, material and resource consumption)
- Identify the life-cycle stages that contributes the most or the least to this total amount
- Assess potential impacts (health and ecological) of the releases and inputs
- Compare the impacts between two or more similar products or processes
- Identify the impacts of a specific product or process
- Identify the impacts to a specific environmental area of concern
- Recognize the shift of the environmental impacts from one life-cycle stage to another
- Interpret results to guide decision-making processes in industry, organizations or government (strategic plans, priority settings, design, etc)
- Select relevant indicators of environmental performance and measurement techniques
- Provide market opportunities (environmental claim, ecolabel, environmental product)
- Improve profitability by using environmental management

The LCA provided new perspectives and benefits to all stakeholders (producers, consumers, and environment). However, some limitations exist and should be well understood for the LCA to be used and conducted adequately. The main limitations (ISO, 2006b; McManus, 2005) relate to the flexible nature of LCA:

- The basis of the assumptions made in the analysis process (system boundary setting, methodologies and impact categories) may be subjective
- The source of data collected may vary for two independent studies analysing the same product and lead to different results (apparently similar LCAs may be incomparable)
- The quality and quantity of the data collected is not always sufficient or relevant for a comprehensive analysis
- The lack of spatial and temporal dimensions in the data collection introduces uncertainty (e.g. pollutants are assumed to be released in the water without indicating in which water body and under a total time-integrated release rather than regarding time distribution)
- The results based on a larger scale issue (global, regional) may not be applicable or may not well represent a local issue or condition
- The overall process is lengthy and can be expensive

5.4 Methodology

5.4.1 Key Methodology Features

According to the ISO standard 14040 (2006a), general guidelines are provided to conduct an LCA though no unique method exists. This flexibility requires adapting, within the framework, to the specific applications of the study and requirements of the end users. The depth of the analysis, the time and geographic context, and the level of details may vary depending on the scope defined. Therefore, transparency is essential at each step to validate the results. The goal and scope, assumptions, data quality, methodologies and output should be defined while the choice and source of the data should be communicated to increase the credibility. This allows end readers to understand why the study was conducted in a certain way. Some specifics are also required when it consists of a comparative study to make sure the comparison is made on the same basis (e.g. comparing the same distance travelled for different means of transportation).

The assumptions and resulting conclusions usually depend on the application. Results can be used internally within a company or organization to provide a general picture, which allows a higher number of assumptions. On the other hand, results can be communicated externally to influence other parties (for grants, regulating bodies, consumers, etc). Then, the results have a greater impact, so a lesser amount of assumptions and a greater depth in the details and analysis would be expected. The ISO standard (2006a) also mentions how confidentially and property matters should be considered in the way an LCA is conducted and the results are communicated. Specific requirements are defined as well when a study is meant to be disclosed to the public.

The flexibility of an LCA is to include new scientific findings and technologies. The methodology is also iterative, meaning that it is usual to adjust the LCA along new incoming information. The goal usually remains the same, but the scope initially defined at the beginning of the process could become irrelevant with a new data acquisition and can be modified before to continue further in the study. Finally, the results of an LCA are interpreted according to the context in which the study is being conducted as the LCA is not able to express the complexity of a system in a single number. Therefore, the analysis should be conducted depending on the goal, the number of stages over the life-cycle and environmental impacts assessed.

5.4.2 Phases of an LCA

5.4.2.1 Objective and Scope

The most important step is to set the direction of a study so that meaningful results are obtained. According to the ISO standard 14041 (2001), “the goal [...] shall unambiguously state the intended application, the reasons for carrying out the study and [...] to whom the results are intended to be communicated”. The scope defines and describes the product to be studied (functional unit), the steps included in the LCA (unit processes), and establishes the context and limit, i.e. system boundaries, in which the assessment will be done (Figure 5.2) (EPA, 2006). The functional unit quantifies the use of a product or service. The function of a cup is to hold coffee. The functional unit could be defined as holding 150 ml of hot coffee. Transporting people is the function for a bus, moving 30 people over 15 km would be the functional unit (Bage, 2014).

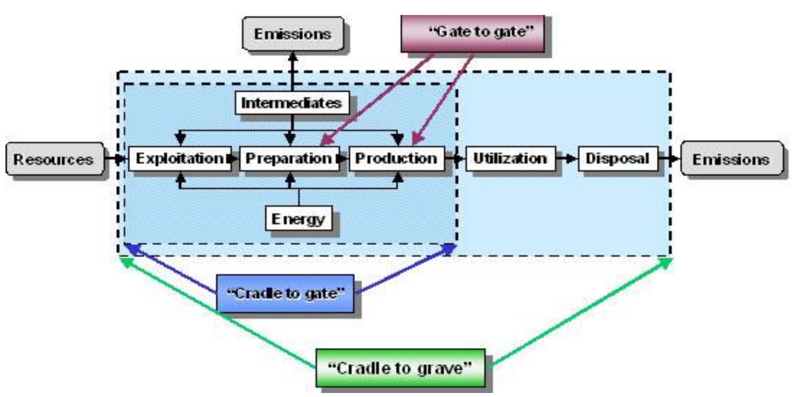


Figure 5.1 – Flowchart of a process illustrating different system boundaries (WSA, 2012)

5.4.2.2 Inventory Analysis

The information on the Life Cycle Inventory (LCI) and following phases were obtained from the current standards (ISO, 2006a;2006b). The LCI is the lengthiest phase. It quantifies inputs (resources, material, energy, etc) and outputs (emissions, environmental releases, waste, etc) for each step of a process. Data is collected from literature, database and/or field testing according to the requirements defined in the scope (depth, time and geographic limit, sources, etc). Assumptions are formulated when data are missing. Limitations that were not expected at first could be identified later during the data collection, leading to an iteration process of the scope definition. The data requirements can be modified according to availability.

Once the data is collected, the inventory calculations quantify the elementary flows, i.e. the inputs and outputs from and to the environment. Producing paper for coffee mugs requires wood pulp and energy (elementary flow inputs) and releases CO_2 and wastes (elementary flow outputs). The inventory can include multiple unit process. The unit processes in bus transportation could be oil refining and the travel (Figure 5.2). Refining requires crude oil and releases GHG (elemental flows). An intermediate flow is a product exchanged between the unit processes. Here, the diesel is an intermediate flow resulting from the refining and required for the travel. The reference flow measures the final outcome of the unit processes to fulfill the functional unit. Here it would be equal to 750 people * km (moving 30 people over 15 km). Then, the elemental flows have to be adjusted with a scaling factor to meet the reference flow. If 160 L of crude oil generates 35 L of diesel and 10 kg of CO_2, those quantities have to be scaled to the actual amount of diesel needed to achieve the reference flow (Figure 5.2). Finally, the inventory process is completed by aggregating together the outputs from each step, i.e. adding the CO_2 emitted during the refining and during the travel.

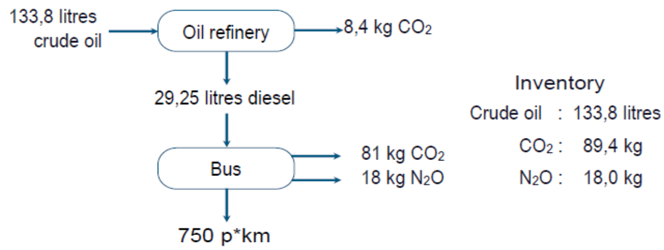


Figure 5.2 – Example of diagram with elementary flows (horizontal arrows), and intermediate and reference flows (vertical arrows) leading to the life-cycle inventory (Bage, 2014).

5.4.2.3 Impact Assessment and Interpretation

The Life Cycle Impact Assessment (LCIA) phase translates the inventory of the flows into environmental impacts. Categories and mid-point categories are selected depending on the inventory and each LCI results are classified into one of the impact category. After, the impacts are characterized by calculating the magnitude of the contribution of the LCI results in the category. For example, not all GHG gases contribute equally to climate change (global warming potential). Further analysis can take place by normalizing, weighting or grouping.

Finally, the results are interpreted in agreement with the goal and scope. The reliability of the final results should be evaluated by looking at how they are affected by uncertainties. Such evaluation includes completeness, sensitivity and consistency checks. The interpretation phase also provides conclusions, recommendations and areas of potential improvement. Overall, the four different phases of the LCA can be synthesis as follow (Figure 5.3)

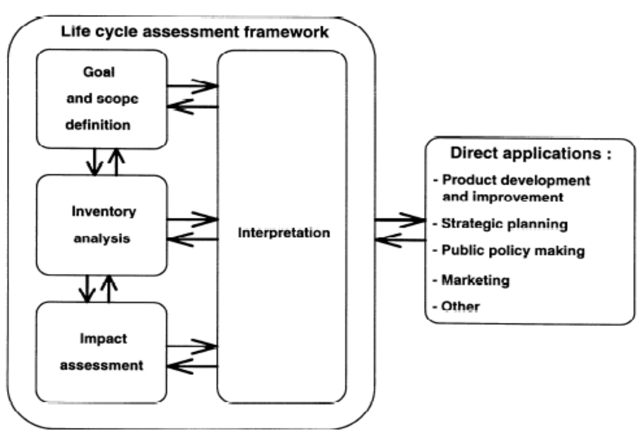


Figure 5.3 – The LCA framework and phases. The arrows show the iterative nature (ISO, 2006a)

5.5 Literature Review of LCA applications to Cookstoves

A number of studies have been conducted on stoves and fuels, with a few targeting cookstoves specifically. The LCA were based on different geographic locations and socio-economical contexts (developing or developed countries). Most studies compared the energy efficiency, environmental impact and/or costs of different fuels and combustion processes. The common pollutants and environmental impacts reported are presented in Table 5.1.

Table 5.1 – Substances released and impacts assessed in LCAs on stoves and cooking fuels

Substances		Impact Category	
CO	$CO_{2\ eq.}$	Acidification potential (AP)	Terrestrial ecotoxicity potential (TETP)
CH_4	Solid wastes	Water eutrophication potential (EP)	Financial Cost
NOx	Particulate matter (PM)	Freshwater aquatic ecotoxicity potential (FAETP)	Land use
SO_2	Heavy metals	Global warming potential (GWP)	Radioactivity
N_2O	Volatile organic compound (VOC)	Human toxicity potential (HTP) (carcinogenic/non-carcinogenic)	Social factors (Noise, space, gender, culture, accidents, time budget, etc)
NH_3	Polycyclic aromatic hydrocarbons (PAH)	Photochemical ozone creation potential (POCP)	Energy (used and/or lost)
NO_2	Hydrocarbons (C_xH_y)	Resource extraction	

5.5.1 LCA of Heating Stoves

Solli et al. (2009) conducted a comparative LCA of wood heating stoves in Norway to estimate the benefits of a new stove model compared to an old one, on a basis of air pollution, GWP and costs. The emission factors (per kg of gas emitted, kg of wood or kg of gas burned , kWh of heat delivered) of the main pollutant were calculated and showed a reduction in environmental impact of 28 to 80% with the new technology. It was found that the major step contributing to the GWP was the combustion in the stove (64%) and not the transportation.

5.5.2 LCA and LCC of Cooking Stoves and Fuels

Different cooking methods using a range of energy sources are found in households in Sweden, namely microwave ovens, gas/LPG stoves, electric ovens/stoves, and wood stoves. Jungbluth (1997) evaluated the environmental impact of the appliances while accounting for the energy efficiency. Wood and electric stoves were the most efficient at 70% followed by the gas stove at 58%. For comparison purposes, the study compiled data for the 3-stone and kerosene stoves in developing countries. The unit processes studied were the fuel supply and distribution, the stove production, and the combustion. The study concluded that less impact was associated with gas or electricity, though the source of electricity was not specified. The 3-stone stove had a high impact on HTP (emissions released during combustion), but scored well on the other impacts since no manufacturing and transportation is required.

Jungbluth et al. (1997) conducted a study in India, to assess the environmental impact of LPG and kerosene. They looked at the energy required, the material input (water, steel, cement and chemicals), the water pollution, air pollution, GWP and waste produced. They also included land used and the costs associated with both fuels. It was noticed that transportation was responsible for the greatest share of the environmental impacts. The study concludes that LPG presented more advantages, especially a higher efficiency and less emissions of air pollutant.

Similarly, Singh and Gundimeda (2014) concluded that LPG was preferable in India over other fuels (wood, electricity, kerosene, biogas, dung, crop residues and charcoal). They assessed the life cycle energy efficiency (LCEE), but not the environmental impact. They considered the efficiency over the life-cycle (extraction, refining, bottling, transportation, combustion, labor required, cooking). Singh and Gundimeda (2014) found that combustion was responsible for the greatest energy losses. Higher LCEE was measured for commercial fuels (from 45% for LPG to 14.7% for coal) than the biomass fuels (11.9 to 7.5%). Dung had the lowest value (7.5%) and biogas was identified as a promising fuel with an LCEE equivalent to LPG (43.3%).

The LCA of charcoal, biogas and LPG as cooking fuels in Ghana has been conducted by Afrane and Ntiamoah (2011). The results favored biogas which had no impact in five of the seven categories and only contributed significantly to acidification. LPG had the best score for GWP but the study found that LPG scored poorly in most of the impact categories, unlike in previous studies (Jungbluth et al., 1997; Singh & Gundimeda, 2014). The difference in the results can originate from disparity in the assumptions or from the context (Ghana vs. India). The shares of transportation, production and cooking were different for each fuel. For biogas, the main contribution was during cooking while there was no transportation. For charcoal, the production process contributed the most in each impact category, while for LPG, the production and the transportation where main contributors in different categories (e.g. transportation accounted for almost 100% of the GWP, while production accounted for 100% of the HTP).

An LCC of firewood, charcoal, kerosene, liquefied petroleum gas, hydro-electricity and biogas was also conducted by the same authors (Afrane & Ntiamoah, 2012). Electricity, firewood and biogas were not leading contributors in any impact category. Kerosene and LPG were the fuels with the highest amount of releases in five of the seven categories, while charcoal was the highest in the two others (GWP and POCP). However, these results considered the overall release and not the amount released in each steps of the life-cycle. When the results were isolated for the cooking process, a much greater impact was attributed to firewood and charcoal.

Lu and Zhang (2010) compared the LCC and LCA of 13 different biomass transformation systems to produce energy from corn residues China (gasification, anaerobic digestion, co-firing, direct combustion, liquefaction, biogas, etc). The main environmental effect considered was GWP. Other air pollutants were reported though not categorized into impact categories. The authors also conducted a sensitivity analysis by varying by 10% certain factors associated with the crop growth (carbon fixation, crop removal rate, crop yield), the technology (energy conversion rate, operational cost, capital cost) and the political context (feedstock price, subsidy). Currently, co-firing was identified as the best choice for the near future. Household biogas scored second if profit making and commercial operation are not the objectives. Biogas has a good net energy output and was identified here as well to reduce the GWP. Finally, liquefaction was the least attractive technology both in financial and carbon reduction terms.

An LCA was conducted on rice parboiling methods (parboiling vessel, small-boiler, medium-boiler and non-parboiled rice) in Bangladesh (Roy et al., 2009). Roy et al. studied the energy and resource requirements, the environmental releases (GHG, air pollutants and water pollutants) and solid wastes (ash). The smallest impact inventory was for the medium-boiler, but the non-parboiled rice had to lowest impact overall as it does not require as much energy and water input. The rice soaking was the step contributing the most to the water pollution.

5.5.3 Software, Database and Models

Software, database or models can facilitate the inventory calculation of more complex systems, but the choice of support remains subjective since there is no widely agreed method to model the inventory data into environmental impact (ISO, 2006a). Over 30 main software or databases exist (Levin, 2013). The majority are not open source, except for Open LCA, and GEMIS, and each of them are usually intended for a specific field such as plastic or material manufacturing (APME, ECO-it), the built environment (Athena), capital investments (BLCC), transportation (GREET), policy/ management (WISARD), etc. A number of software is also dedicated to the energy sector. The variety of models provides useful support but highlights how easy one can get lost in the analysis. It is important to well define the scope, to understand the assumptions behind each software and to be transparent in reporting the assumptions used.

Solli et al. (2009) used a hybrid approach for the LCC that combined the usual reference flows of LCAs with a input-output price model called Leontief which represents the financial interdependencies between the background economy and the main supply chain of the regional economy (Raa, 2010). The same hybrid approach combining the inputs-outputs of the financial sectors with the environmental input-outputs at the process level was used by Lu and Zhang (2010). This model analyzed the interdependencies between the national economy and the industries to assess the LCC of the energy production systems.

In his first study, Jungbluth (1997) used the ECOINVENT database and the Eco-indicator 95+ software (earlier version of the SimaPro used by Singh and Gundimeda (2014) in their LCAA). The software models the environmental releases into carbon and water footprint categories and is also used for environmental performance monitoring, environmental product declarations, eco-design, environmental reporting and to determine key performance indicators. In his second study, Jungbluth et al. (1997) used the open source software Temis 2.0 (Total Emissions Model for Integrated Systems) and reported the stages and indicators investigated in a matrix. TEMIS is mostly for energy, material, and transport systems with a database for fossil fuels, renewable energies, electricity and heat generation, raw materials, and transports.

Afrane & Niamoah (2011; 2012) used altogether the literature, field measurements and databases (Gabi 4, for product development and sustainable manufacture) for their data collection. In the first study (2011), the analysis was carried using ISO standards and the inventory results were classified into the environmental impact categories using the Gabi 4 software. In the second study (2012), an LCC combined to a standard LCA the Environmental Product Strategy (EPS) approach (Steen, 1999) was used to classify negative environmental impacts as ‘threats’ and positive impacts as ‘safeguards’. Then, the analysis was monetised to assess the willingness to pay to restore a degraded safeguard. The financial impact was calculated by summing purchasing costs, replacement fees and annual fuel consumption.

In an E-LCA and LCC of 13 energy production systems, Lu and Zhang (2010) used a novel hybrid approach, the national EIO-LCA (Economic Input-Output Life Cycle Assessment) which "considers the environmental effects throughout the economy that result from a change in output for a particular industry". Finally, Roy et al. (2009) conducted an LCA using data from the literature and their own experiments. They followed the SETAC and ISO standards and conducted manual calculations and analysis as they did not report using any software.

5.6 LCA of Improved Clay Brick Stoves

5.6.1 Goal and Scope

The goals of this LCA was first to determine the environmental impacts of the 3-stone stove and compare it to two improved stoves (ICs) designed for small scale rice parboiling in rural areas (Figure 5.4) and secondly to assess the net energy balance of each stove before implementation, i.e. to determine if the energy required to build the stove can be recovered by the energy saved by parboiling with an IC. The target audiences were the project partner, Africa Rice involved in the implementation of ICs, and the end users (women in charge of rice parboiling). This LCA was also conducted to identify areas to improve the environmental performance of ICs and to guide future research work on stove development.

Figure 5.4 – Biomass stoves, a) the 3-stone stove, b) the Noflay and c) the AM stove.

5.6.1.1 Scope Definition

The LCA was carried in the context of West Africa. The product studied was the stove (two ICs and the 3-stone stove). The function of the stove was to boil water for rice parboiling (steam generation) and the functional unit was one stove boiling 15 L of water. The steps of the life cycle included in the product system were: material extraction, brick production (drying and firing), stove construction, stove use (parboiling), and waste production (ash) (Figure 5.6).

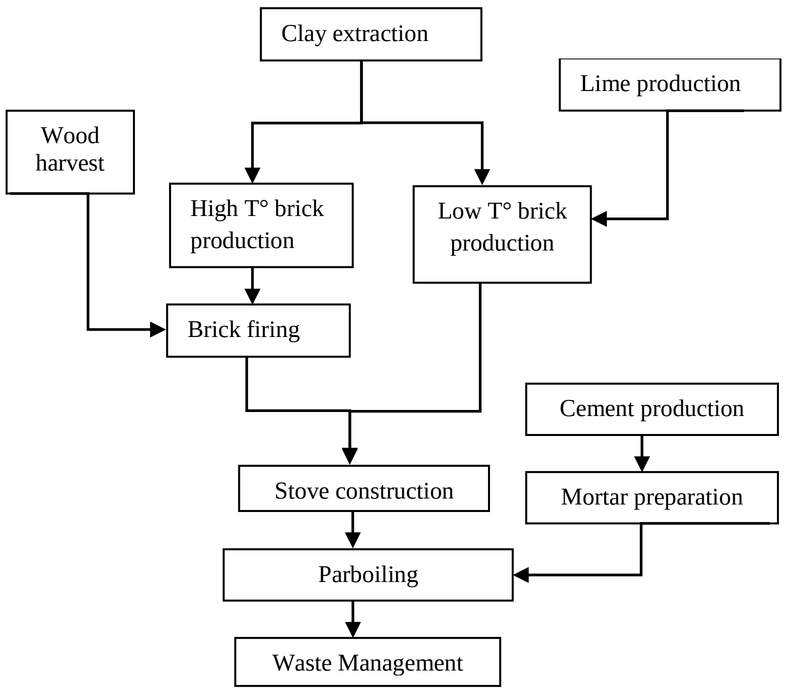


Figure 5.6 – Flow diagram of the product system of the ICs

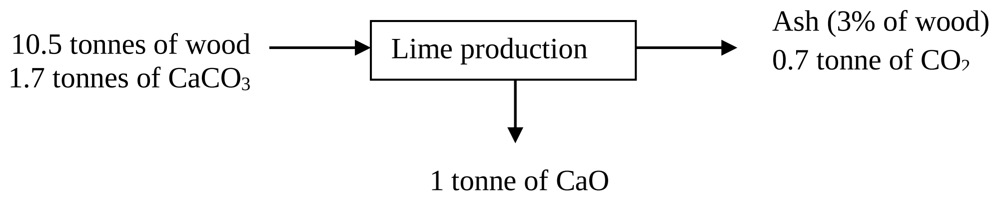
The stove disposal and brick drying were not considered because they were the same for all stoves. Drying consists of leaving the bricks in the shade and disposal would usually consist of moving the broken bricks with a cart or by hand to the backyard. The impact of leaving bricks to disintegrate was assumed minimal as they are mostly made of clay. Transportation was omitted (clay from collection site, bricks to stove construction site, cement bag to construction site, wood transportation) as it mostly takes place using wheelbarrows, donkey carts or horse carts. The transportation taking place with a vehicle was to move the cement bags from the factory to the market and was considered negligible considering the small amount required for one stove (~ 5 kg). The same functional unit was used for all stoves because of the comparative nature of the LCA. The system boundaries for the 3-stone stove differed from the ICs as no processes are required prior to the construction which only consists of three stands (here, assumed to be made of three stacks of three clay bricks each).

The data was collected for the West-African geographical location with no restriction in terms of timeframe since no technology that would have significantly changed recently was used. The parboiling data (energy, fuel consumption, emission) were collected during experimental work. The emission of CH_4 and PM were not measured because of instrumental apparatus limitations. Data for the stove construction was collected from field work conducted in Gambia and Senegal with the REAP-Canada and from literature. The literature for West-Africa was limited, so studies from other developing countries (Sudan, China, India) were used. The environmental impacts of interest were the emissions of CO_2, CO and CxHy, the energy requirements (wood consumption) and the extraction of raw material to build the stove.

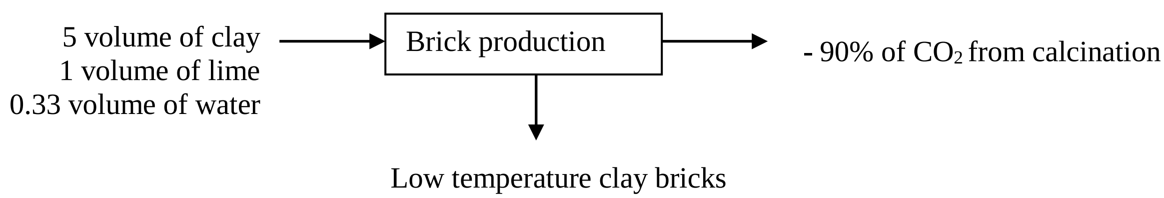
5.6.2 Inventory Analysis

Clay extraction: The clay is collected by hand with shovels from the river bank and transported with carts where bricks are made. The energy going into this process is from human and animal labor which was not considered in this study. No environmental outputs resulted from the clay extraction. If clay was collected at a large scale, bank erosion could be a concern. For now, the clay is collected in different locations every rainy season for the sediments to replenish.

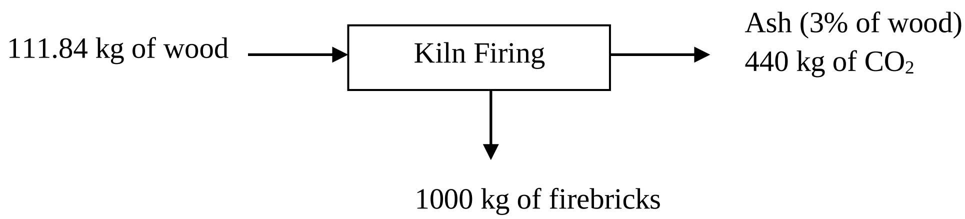
Lime production: Lime is produced from seashells, a by-product of the seafood industry. The shells are a source of calcium carbonate ($CaCO_3$) which is fired to make lime (CaO). The calcination requires 0.03 MJ of energy (Tzilivakis et al., 2005) and releases 0.7 kg of GHG (Ip & Miller, 2012) per kg of CaO. Lime is used in the mortar and in the low temperature bricks to increase the strength. An efficiency of 10% for calcination in an open fire (worst case scenario) and an energy content of wood of 19 MJ kg^{-1} were used.



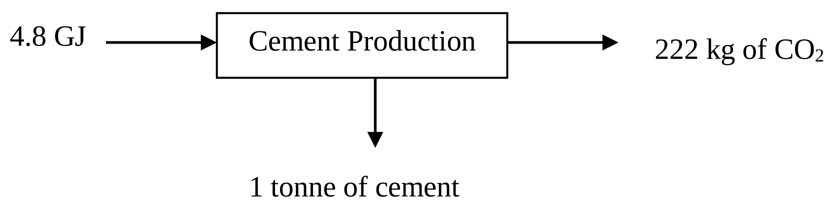
Low temperature brick production: The lime and clay are mixed using a 1:5 ratio. Water is added and the mixture is covered with a tarp to rest for five days before to make bricks (by hands using molds). The bricks are left to dry before being stored or transported. When water is mixed with lime, the CaO forms hydrated lime ($Ca(OH)_2$ and up to 90% of the CO_2 released during calcination can be recaptured as it binds to the $Ca(OH)_2$ (Ip & Miller, 2012). Time is associated with the hand production of bricks, but the social factors were not considered in this LCA.



Production and firing of firebricks: The firebricks, made from clay only, are used inside the combustion chamber were they are exposed to the flames as they resist high temperatures and have greater strength. After the green bricks are shaped, they are left to dry for at least five days under a tarp (to avoid cracking from rapid water evaporation). After, they are fired usually in a kiln to increase efficiency. The energy and material required to build a kiln were not considered. Firing can also take place without a permanent assembly (clamp kiln) and kilns are often used to fire other products (pottery), thus reducing to a minimum the impact of the construction of the kiln in the life cycle of a stove. Typically, the energy requirement of firing is 0.85 MJ (Erbe et al., 2011) with 0.44 kg of CO_2 emitted per kg of brick (Alam & Starr, 2009). The energy needed depends on the efficiency of the kiln (40 to 90% (Maithel et al., 1999)). In this study, an efficiency of 40% for a small batch kiln with a chimney and with no fan was assumed.

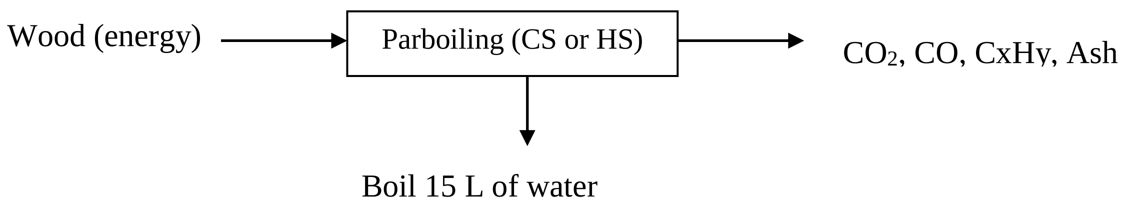


Cement Production: A small amount of cement was used in the mortar to increase the strength of the stove. On average, 222 kg of CO_2 is produced per tonne of cement and 4.8 GJ of energy is required to produce one tonne of cement (Worrell et al., 2001).



Stove Construction: The firebricks, low temperature bricks and mortar are used to build the ICs. The stoves were sized for a spherical cast aluminum pot (~ 65 L). The AM stove required 80 low temperature bricks and 24 firebricks. The Noflay stove required the same number of low temperature bricks and 12 firebricks. The number of bricks and the amount of mortar to build one stove were used as scaling factors to adjust the elementary flows of each process. A layer of mortar of 2 cm is usually applied between the bricks. The mortar consists of one part of cement for one part of lime and two parts of sub-soil collected below the top layer (15 to 20 cm) of sandy soil. The impact associated with the building equipment (shovels, trowels, wheelbarrows) was neglected. Table 5.2 presents the LCA inventory for the construction of the stoves.

The amount of wood required to boil 15 L of water depends on the efficiency of the stove. The flue gas contains pollutants such as CO_2, CO and CxHy, and ash is left as a waste product. The data (wood, efficiency, emissions) was collected from experiments conducted on the stoves. The data has been categorized for two situations, one being when the first parboiling of the day takes place, i.e when the stove is cold (at CS), and the other when a second batch of rice is parboiled, i.e. when the stove is warm and has already absorb heat from the fire (at HS). Table 5.3 provides the number associated with the impact inventory of parboiling.



5.6.3 Impact Inventory

Table 5.2 – LCA inventory of environmental flows involved in the stove construction

Stove	Total energy (MJ)	Wood (kg)	Lime (kg)	Water (L)	Clay (kg)	Cement (kg)	Sub-soil (kg)	CO_2[a] (kg)	Ash[a] (kg)
3-stone	n/a	n/a	n/a	1.24	16.38	n/a	n/a	n/a	n/a
Noflay	112.89	4.78	19.30	20.56	185.20	5.23	10.47	7.79	0.144
AM	197.04	9.21	19.30	26.50	224.80	10.47	5.23	13.07	0.276

a) The CO_2 and ash are environmental output flows while all other categories are input flows.

Table 5.3 – LCA inventory of environmental flows involved with parboiling

CS Parboiling (boiling 15 L of water from a cold stove)					
Stove	Wood (kg)	CO2 (kg)	CO (kg)	CxHy (kg)	Ash (kg)
3-stone	3.53	2472.36	52.99	5.90	0.201
Noflay	2.65	2572.13	36.06	1.74	0.199
AM	2.51	6432.42	147.84	4.35	0.147
HS Parboiling (boiling 15 L of water from a hot stove)					
Stove	Wood (kg)	CO2 (kg)	CO (kg)	CxHy (kg)	Ash (kg)
3-stone	3.08	1927.83	59.09	5.81	0.201
Noflay	2.61	2727.87	51.55	3.59	0.199
AM	2.42	4994.31	101.78	1.94	0.147

5.6.3 Impact Assessment

The LCA inventory was divided in five impact categories, namely human toxicity potential (CO, CxHy), climate change/GHG (CO_2), resources (raw material: clay, water, lime, and cement), energy (wood) and waste produced (ash). The energy was computed from the amount of wood required and using the energy content (19.0 MJ kg^{-1}). Ash was the only waste product listed. It could also be included in the HTP if it is not managed properly. When ash is not collected, the fine particles disperse in the air and can be inhaled. Table 5.4 presents the results for one full day of parboiling, assuming five batches (one CS and four HS).

Table 5.4 – LCA inventory for one full day of parboiling operation

Stove Type	Wood (kg)	CO2 (kg)	CO (kg)	CxHy (kg)	Ash (kg)
3-stone	15.87	10183.67	289.36	29.15	1.00
Noflay	13.10	13483.62	242.26	16.08	1.00
AM Stove	12.19	26409.64	554.96	12.09	0.73

The amount of wood saved by parboiling with the Noflay and AM stove compared to the 3-stone stove was 0.88 kg and 1.02 kg, respectively, per CS. After one full day of operation, the stoves would save 2.77 and 3.68 kg of wood each. Then, it would take 2.14 days of full day of operation to save the energy that was spent to build the Noflay and 2.82 days for the AM stove. If the stoves are only used once a day (CS only), the energy would be recovered in 6.78 and 10.15 days for the Noflay and AM stove, respectively.

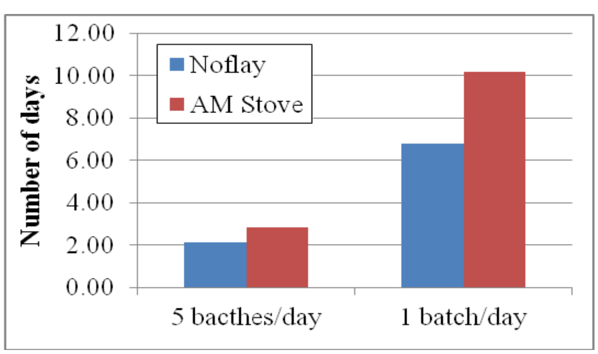


Figure 5.8 – Number of days of parboiling to recover the energy used for stove construction

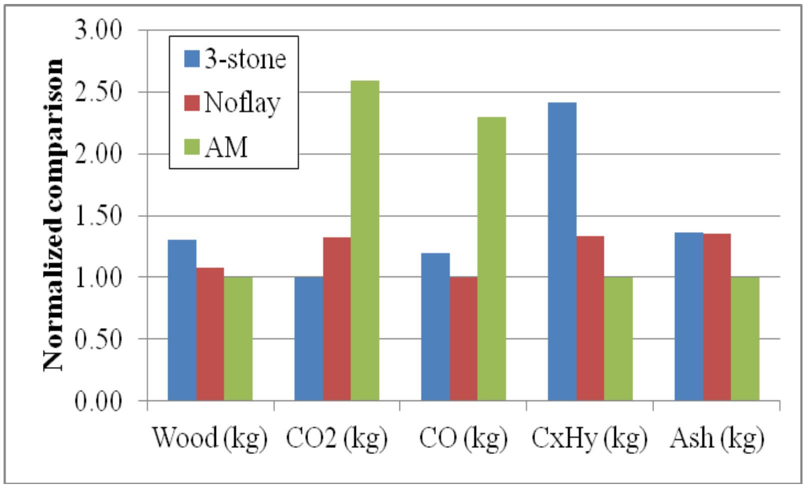


Figure 5.9 – The normalized environmental impact of parboiling

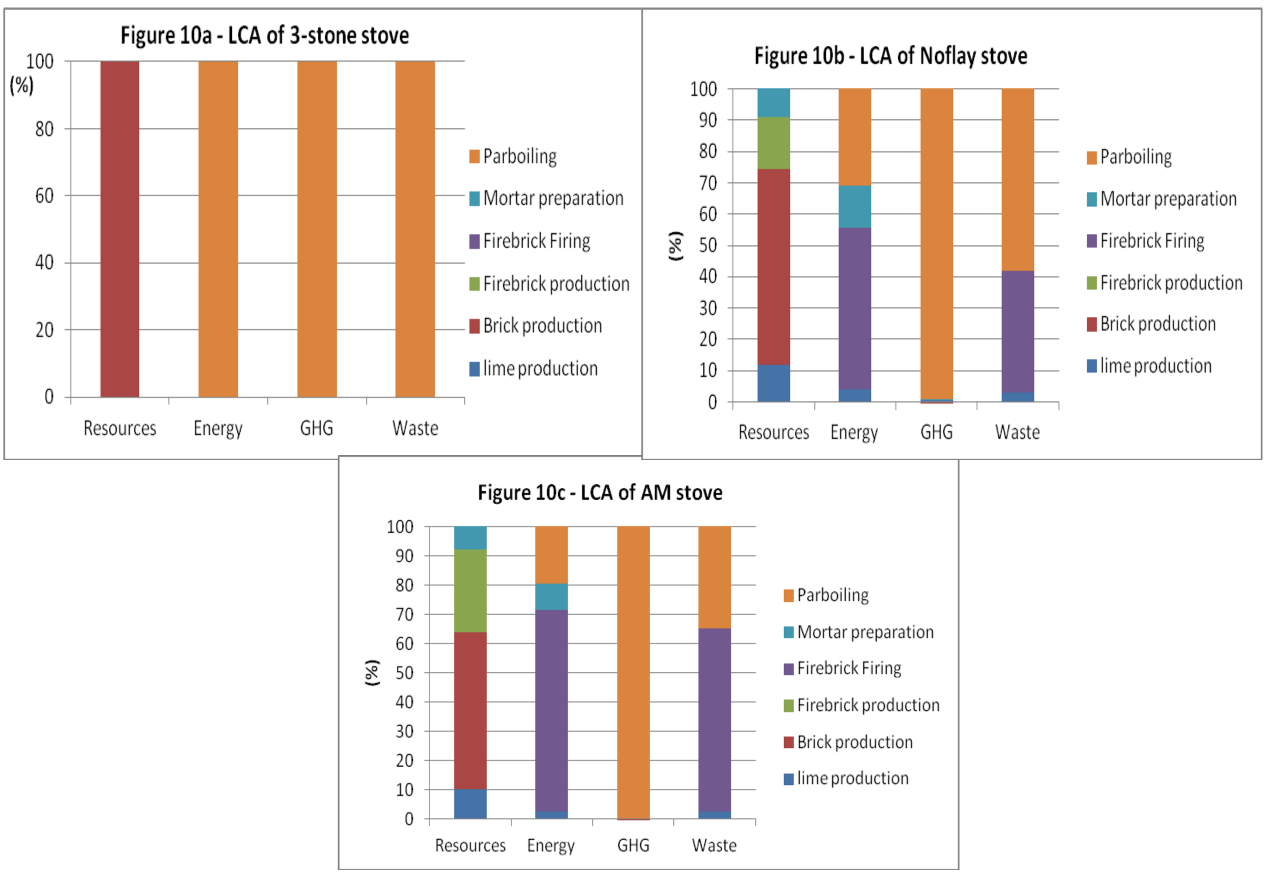


Figure 5.10 – The contribution (%) of each construction step to the impact categories

5.6.4 Interpretation

Figure 5.9 compares the normalized impact of parboiling. The 3-stone stove used more wood and produced by far the greatest amount of CxHy. The AM stove used less wood and produced less ash and CxHy, but was by far the worst in terms of CO and CO_2 emissions. A question was raised concerning the sampling method and if some flue gas escaped from the hood during the sampling during testing of the Noflay and the 3-stone stove. However, this hypothesis would have shown higher CxHy emissions for the AM stove as well. The Noflay performed better than the 3-stone stove in all impact categories except for the CO_2 emission, which indicates higher combustion efficiency. An opposition exists between climate change and human health. CO_2 is not directly considered toxic to the human health, therefore, a stove that produces more CO_2 will be considered 'cleaner' because it emits less products of incomplete combustion. Then, a stove that has a high impact on climate change will have a lower impact on human health. However, the wood saving reduces deforestation which reduces climate change. The climate change mitigation from the reduction in deforestation was not calculated in this LCA.

Figure 5.10 presents how much each unit process contributes to an impact category in terms of percentages. The HTP was not presented in Figure 5.10 because data contributing to that category was collected only for the parboiling process. Toxic compounds are also released during brick firing and limestone calcination, but no data was found in the literature on the emissions of those products harmful to human health (only data on the release of CO_2 was found for brick firing and calcination). The process with the highest raw resource requirement was brick production for all stoves. Similarly, the greatest source of CO_2 came from combustion during parboiling. A significant amount of energy was required for the firing of firebricks. It would be recommended to increase the energy efficiency of the kiln to fire the bricks to reduce the energy required in building the ICs. Also, a kiln should be used to calcinate the $Ca(CO_3)$ instead of using an open fire to reduce further the energy consumption.

Overall, the construction of the 3-stone stove required no energy and almost no resources. However, an IC reduced the amount of wood used for parboiling. Both ICs required energy to be built, but this energy was recovered after less than two weeks of stove use (Figure 5.8). The AM stove saved more wood, but emitted more gases (CO_2 and CO) than the Noflay. Therefore, a decision on the implementation of a stove should be made depending on the context and the objectives of the local partners, i.e. reducing wood deforestation or improving respiratory health.

This LCA provided a good assessment on the energy and resource requirements, though it could have been more complete by including more data on other GHGs than CO_2 (CH_4 for example) and other air pollutants often included in LCAs (Table 5.1). This would allow a better assessment of the GWP and the HTP of the stoves. The LCC analysis could also have been performed to assess the economic impacts and drawbacks of the different stove design. A deeper analysis could include the time and labor requirements as well as the energy going into the current animal transportation system (animal feed). The LCA should be revised if motorized transportation is eventually used. This would affect the GHG emission and the number of days of parboiling required to recover the energy spent to build the ICs.

5.7 Conclusion

In conclusion, the LCA was a good tool to provide insight on the environmental impacts of the stoves over their life-cycle and on potential priority actions to address those impacts. The Noflay stove was found to address simultaneously the wood consumption and health issue compared to the 3-stone stove, though it could be recommended that the AM stove be first implemented to quickly reduce wood consumption, but only along with appropriate air ventilation or measures to reduce the exposure of stove users to smoke.

The LCA is one of many tools to provide sustainability measures though it doesn’t provide all available solutions. While the LCA focused on the details involved in the different steps to manufacture the stoves, it is essential not to forget the system’s bigger picture to find other potential solutions. In this case, sustainable forest management, three planting, or land management strategies could be other interesting parallel solutions to reduce wood scarcity along with making changes in the stove construction. Finally, an LCA provides information from the environmental perspective, but other factors also need to be considered in decision-making, such as social, cultural and economic factors. Overall, a sustainable decision is one that integrates the three main pillars of sustainability, the environment, the society and the economy.

Chapter 6: General Conclusion

More than ever before, current environmental challenges are bringing sustainable development and energy efficiency at the center stage of a number of fields. Those two key elements are now increasingly agreed as essential paths to reduce the human impact on the environment while they are also driving forces in the development of new technologies. Innovative hands-on alternatives are now required to address quickly some of the pressing global issues. Biomass energy is one of those opportunities which can act simultaneously over a wide spectrum of concerns. While it allows to move away from fossil fuel, to reduce deforestation and to positively mitigate climate change as a low-carbon fuel, sustainable and efficient production and combustion of biomass energy can reduce energy scarcity, increase household livelihoods, and address some current health issues associated with inefficient domestic combustion.

The general objectives of this research were to explore the densification of rice husk into biomass briquettes as an alternative fuel and the use of improved stoves for more efficient energy production in cooking and post-harvest processing. A review of the current literature provided an overview of biomass and biomass energy, as well as the parameters involved in densification (available technologies, properties of raw biomass, pre-treatments of biomass, densification technologies, and compression and bonding mechanisms), and in biomass combustion in improved cookstoves (basic combustion principles, stove designs, and health issues).

Low pressure densification of rice husk for direct combustion was selected as it is a low-tech and readily applicable to provide an alternative fuel to local populations in the rural areas of developing countries, but also especially to alleviate the management of high volumes of rice husk produced as an agricultural waste product. The experiments performed with a 4.2 MPa double-lever hand press were to identify a formulation that allowed compressing the rice husk into a solid fuel. Rice dust added in concentration of 10% to the raw rice husk (one-stage milling) was identified as a promising binding agent along with up to 60% water addition.

Improved cookstoves were investigated to assess the potential in reducing the impacts associated with direct combustion of solid fuels. The experiments were conducted using four models of clay brick stoves and one traditional 3-stone stove. The time to boil 15 L of water was reduced by 31% at cold start and by 45% at hot start and the fuel use was reduced by 28% at both phases compared to the 3-stone stove. The lowest specific fuel consumption (126.7 g L^{-1}) and CO emission factor (3.8 g MJ^{-1}) was measured at forced draft with a stove with no chimney. The overall thermal efficiency of the improved cookstoves varied between 19 and 25.1%.

The overall environmental impact of implementing a clay brick stove for rice parboiling was further assessed using the life-cycle analysis approach. The source of pollution and energy requirements associated throughout the main steps, starting from clay collection, to stove construction and use during parboiling. It was found that the energy required to build two different models (Noflay and AM stove) could be recovered in 6.78 and 10.15 days, respectively, if at least one parboiling process is completed per day. Parboiling was the step responsible for the main source of atmospheric emissions, brick firing required the greatest amount of energy input and the production of bricks necessitated the highest material input.

Considering that the rice husk briquettes presented physical integrity and that improved cookstoves significantly reduced the time to boil and the fuel consumption, direct combustion of densified biomass is a promising alternative in domestic cooking and small scale post-harvest processes in developing countries. This work achieved the first steps in determining some key parameters in the formulation of rice husk mixture for low pressure densification in the form of briquettes while contributing to the general knowledge on biomass combustion in clay brick stoves. Future research following the work accomplish could include optimizing the densification parameters and the determination of quality standards for low pressure rice husk briquettes. The research on densification could also expand to other biomass waste product. As for the combustion aspect, future work could look with more depth the influence of control parameters of combustion in clay brick cookstoves such as the volumetric inflow of forced air, the cross-sectional area of natural air inlets, the excess air ratio, the control of combustion with the addition of a baffle in the chimney and a door, and the size of the combustion chamber relative to the desired power output. Studies could also be conducted in the field with end users to investigate actual performance and exposure to pollutants.

Biomass energy is one of the appealing solutions to current energy and environmental challenges, though the implementation of any new technology must be thoroughly thought through. A new technology carries a number of other implications outside the technical need it fulfills and those implications have not always been taken into considerations at time of implementation. Research has the amazing ability to constantly develop new ideas, but the benefits can only be fully appreciated if an innovation is implemented sustainably. Therefore, wide adoption of biomass energy needs to meet simultaneously the three main pillars of sustainable development to avoid future negative side effects. From the environmental perspective, biomass energy is interesting if it is generated from by-products considered as waste and reduces the net amount of CO_2 released in the atmosphere since there are some serious environmental and conservation issues associated with large scale energy production from biomass collected in natural forests and rich ecosystems that provide valuable environmental services. Biomass energy also needs to be economically viable on the short and long term, both for the manufacturers but also for the end users. And finally, the implementation must be in agreement with the local cultural and social context, especially in developing countries. Those aspects cannot be left aside by developers and designers which are often exterior to the context where the new technology will be implemented.

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