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Low Grade to High Grade Energy Conversion: An Approach to Harness Waste Heat

by

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Abstract

Pyro-metallurgical industries are among the largest producers of large quantities of low grade waste heat which they vent, for the most part, to the environment. It is estimated that 30-45% of the total waste heat is released to the atmosphere through the exhaust gas streams. Currently, there is no economical approach to harness this waste heat. However the world's energy crisis as well as environmental concerns makes the recovery of the waste heat a desirable approach.

In this research a new approach to harness waste heat from pyro-metallurgical production processes is proposed. This is achieved by introducing an innovative combined heat and power cycle, which we have termed the heat pipe cycle. This cycle uses the science of heat pipes and couples it with a piston-cylinder configuration heat engine. The heat pipe cycle comprises 3 distinct interacting units for recycling waste heat. The first unit captures and concentrates waste heat using heat pipe technology. The second unit converts some of the concentrated heat to mechanical work which can then be readily converted to electricity. This unit is based on the classical piston/cylinder engine arrangement that is widely used by consumers to power systems with compressed air, for example. The third unit of the process dissipates the heat that the engine cannot convert to high grade energy. A prototype unit for capturing and concentrating low grade waste heat and converting it to mechanical work and ultimately to electricity has been designed, built and installed in the lab. Experiments have shown that it can capture and convert 1 kW of low grade energy from a 'warm' gas stream. The entire system we have developed is referred to by the acronym the 3C's (i.e. Capture, Concentrate and Convert).

With this approach one can achieve the two following benefits: 1) reduction in the carbon footprint – by improving the overall energy efficiency of a process, and 2) production of electricity at an economically viable cost.

Résumé

Les industries métallurgiques pyrotechniques sont parmi les plus grands producteurs de grandes quantités de chaleur résiduelle de faible qualité dont ils évacuent, pour la plupart, à l'environnement. On estime que 30 à 45 % de la chaleur totale de déchets est libéré dans l'atmosphère par les courants de gaz d'échappement. Actuellement, il n'existe aucune approche économique de harnais à la chaleur résiduelle. Cependant les crises énergétiques de la planète ainsi que les préoccupations environnementales font de la récupération de la chaleur résiduelle une approche souhaitable.

Dans cette recherche, une nouvelle approche pour exploiter la chaleur résiduelle des processus de production pyro-métallurgique est proposée. Ce résultat est obtenu par l'introduction d'un cycle de chaleur et d'électricité combinée innovante, que nous avons appelé le cycle de caloduc. Ce programme utilise la science des caloducs couplé avec un moteur thermique de configuration à piston et cylindre. Le cycle de caloduc comprend trois unités distinctes qui interagissent pour recycler la chaleur résiduelle. La première unité capte et concentre la chaleur résiduelle en utilisant la technologie de caloduc. La deuxième unité convertit une partie de la chaleur concentrée à un travail mécanique qui peut alors être facilement convertie en électricité. Cet appareil est basé sur l'agencement de moteur piston/cylindre classique qui est largement utilisé par les consommateurs pour des systèmes d'alimentation en air comprimé, par exemple. La troisième unité du processus dissipe la chaleur que le moteur ne peut convertir en énergie de haute qualité. Une unité de prototype pour capturer et concentrer la chaleur résiduelle de bas grade et de le convertir en travail mécanique et, finalement, à l'électricité a été conçu, construit et installé dans le laboratoire. Des expériences ont montré qu'il peut capturer et convertir 1 kW d'énergie à faible teneur d'un courant de gaz chaud. L'ensemble du système que nous avons développé est nommé par du 3C (c.-à-d.- Capturer, Concentrer et Convertir).

Avec cette approche, on peut atteindre les deux avantages suivants : 1) la réduction de l'empreinte carbone - en améliorant l'efficacité énergétique globale d'un processus , et 2) la production de l'électricité à un coût économiquement acceptable.

Acknowledgements

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Nomenclature

1.1 Symbol	Description	Units
A	area	m^2
D	hydraulic diameter	m
E	energy	J
g	gravitational acceleration	m/s^2
h	enthalpy	J
I	turbulence intensity	
J	diffusion flux	$kg/m^2 \cdot s$
L	length	m
k	thermal conductivity	$W/m \cdot {}^oC$
m	mass	kg
$\dot{m}$	mass flow rate	kg/s
N	RPM	
P	pressure	Pa
Q	heat load	W
Q″	heat flux	W/m^2
r	radius	m
Re	Reynolds number	
S	Entropy	J/K
S_{energy}	energy source term	$W/m^3 \cdot s$
S_{mass}	mass source term	$kg/m^3 \cdot s$
$S_{momentum}$	momentum source term	N/m^3
T	temperature	${}^oC$ or K
t	time	s
V	volume	m^3
$\dot{V}$	volumetric flow rate	m^3/s
v	velocity	m/s

W	Work	J
x	mass fraction of species	m

1.2 Greek Characters — Units

γ	heat capacity ratio	
η	efficiency	
ρ	density	kg/m^3

1.3 Subscripts

CO_2e	*CO_2 Equivalent*
eff	effective
H	high
L	low
m	*mean*
misc	miscellaneous
ref	reference
Th	Thermal

Superscripts	**Description**	**Units**
•	rate	1/s

1.4 Operators — Units

∇	Gradient operator	1/m
$\nabla .$	Divergence operator	1/m

Chapter 1 Introduction

Low Grade Energy Conversion– An Overview

For decades, scientists have been exploring and developing new energy production methods from various sources of energy. In some cases these developments are profiting from natural renewable energy sources, like hydro, wind and solar, in other cases, the researches are in line with governmental policies regarding reducing greenhouse gas emissions and energy consumption. In many cases, energy shortage situations along with environmental impacts demand the development of energy recycling measures, which simply means using the excess low grade energy from current processes to produce higher grade energy for the same process. Governments are acknowledging the importance of developing advanced technologies for low grade energy recovery and the focus is now on the most economically viable approaches.

Heat cycles like the Rankine cycle, are considered as the most common and productive approaches in converting low grade energy; however, the greatest down side of the Rankine cycle is at the energy conversion section, i.e. turbines. The steam entering the turbines should be superheated in order to reduce the possibility of damage to the blades. This implies that one needs to incorporate another energy consuming unit, the superheater, to produce superheated steam.

At McGill University an innovative heat cycle was considered. In this heat cycle a heat pipe and a heat engine are used. Because of its high thermal conductance the heat pipe can capture waste heat and concentrate it into steam through boiling. The steam is then directed to an external combustion heat engine to produce electricity.

The heat pipe cycle has the following characteristics:

- Employing the McGill heat pipe to extract energy from any stream of hot fluids. This unit is called "Energy Extraction Unit"
- "Energy Conversion Unit" consists of a double cylinder steam engine.
- Like any heat cycle, excess heat needs to be released to a sink, known as "Heat Dissipation Unit". This is achieved through the use of a heat exchanger.

Objectives

The purpose of the research presented in this thesis is the following:

- Employ Heat Pipe technology to capture and concentrate waste heat
- Convert the extracted heat to electricity as a valuable form of energy
- Evaluate the economic viability of this approach

Thesis Organization

Chapter 2 reviews the literature pertaining to this thesis and presents a summary of the current energy sources and shows how waste heat can be viewed as a renewable energy source.

Waste heat and waste heat recovery systems, i.e heat cycles are discussed in Chapter 3.

Chapter 4 describes our approach to create a heat cycle and the 3 essential components of a heat cycle, i.e Energy Extraction unit, Energy Conversion unit and Heat Dissipation unit, are reviewed in details.

The design and modeling of the heat pipe cycle are developed in Chapter 5.

Experimental procedure is described in Chapter 6.

Chapter 7 presents the results and discussions.

Chapter 8 summarizes the conclusions of this work.

Chapter 2 Literature Survey - Renewable Energy

Introduction

The problem of climate change caused by the use of fossil fuels is a known challenge to scientists and engineers. The composition change of the atmosphere, especially the concentrations of carbon dioxide (CO_2), laughing gas (di-nitrogen monoxide, N_20) and methane (CH_4), has been already well recognized. The depletion of fossil fuel resources and the catastrophic consequences of nuclear power generation call for renewable and safe resources of energy for both man and the environment.

Extensive researches in the production of energy from renewable sources and improvement in efficiency of the current technologies can help us to reverse this unfortunate trend.

The key concept for the 21st century is production of energy from renewable sources at a competitive cost with fossil fuels. The sun, wind, water and biomass were the first to be explored. Hydroelectric plants with their dams and reservoirs are the most common source of renewable energy and it has been in use since the 19th century thanks to the second industrial revolution. The growing number of wind power plants, solar collectors and photovoltaic installations clearly shows that there has been substantial progress in those areas. Geothermal heat is now attracting more industries as it is almost available everywhere.

The greatest advantages of using renewable energy are that they don't deplete and also they contribute to a green environment. On the other hand the disadvantage of using these resources is that the energy available from the renewable sources are much less concentrated than that provided by fossil fuels and nuclear energy making them less attractive for large scale industrial uses.

This Chapter briefly reviews the major technologies which are already in use for production of energy.

Energy Consumption in Canada

Canada is a rich country in energy sources: oil, natural gas, nuclear and hydroelectric are just a few examples of energy resources in Canada. Figure 2-1 shows the total primary energy consumption in Canada by type.

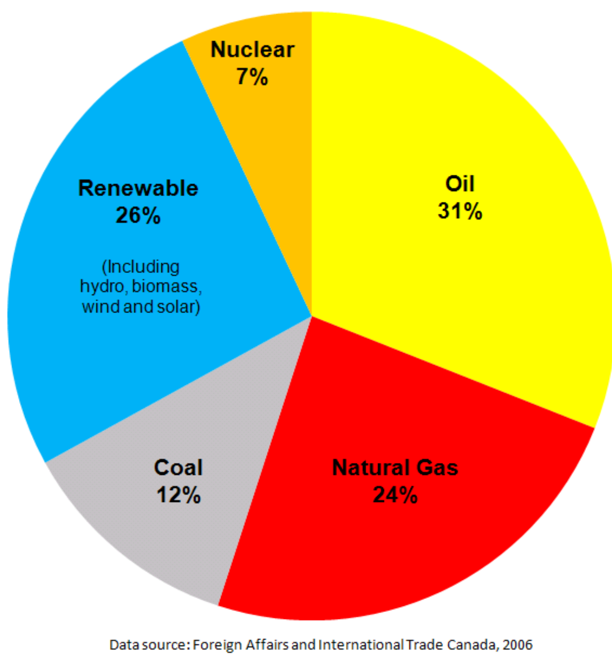


Figure 2-1 - Total energy consumption by type for year 2006 [4]

Figure 2-2 on the other hand, shows the total energy consumption by sectors in Canada. It can clearly be acknowledged that the industrial section is the largest consumer of energy considering this chart does not include mining (including oil and gas extraction), forestry and construction.

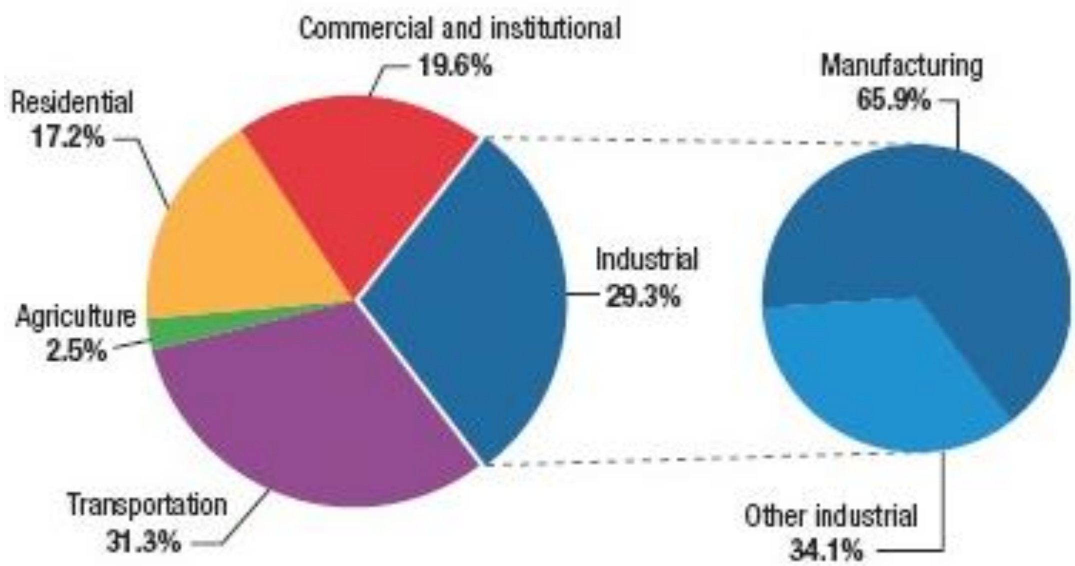


Figure 2-2 - Canada's secondary energy consumption by sector for year 2009 [2]

According to Natural resources Canada survey [2] there are 21 subsectors within the Manufacturing sector but only the following 4 subsectors accounted for 76 percent of all energy consumption of the sector in 2009: Paper Manufacturing, Primary Metal Manufacturing, Petroleum and Coal Product Manufacturing and Chemical Manufacturing.

Renewable Energy Sources in Canada

Renewable energy sources in Canada include but are not limited to wind, water, combustible renewals and waste, solar, hydrokinetic and geothermal. Figure 2-3 shows the total Renewable Energy Capacity by Resource Type, Including and Excluding Large Hydro in Canada.

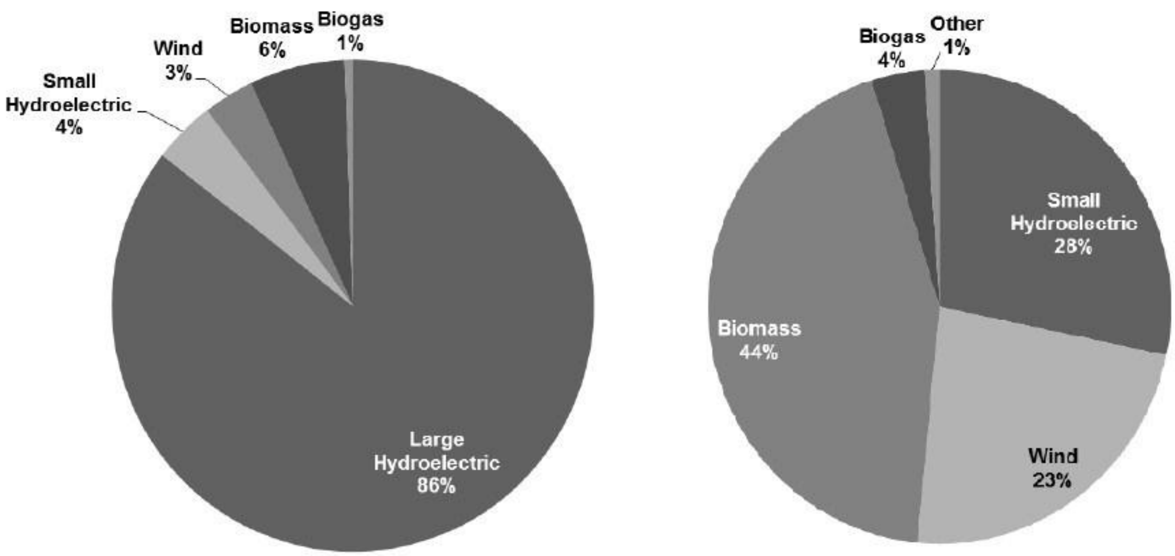


Figure 2-3 - Total Renewable Energy Capacity by Resource Type, Including and Excluding large hydro [5]

There are various methods to convert the renewable energies to a valuable form of energy. Below is a brief description of the renewable energy sources and their current status in Canada.

Water or Hydroelectric Power

Water is one of the oldest renewable energy sources and is the only renewable energy source which contributes on a large scale to the world's supply for electricity generation. About 18% of the power generated worldwide comes from hydroelectric plants. [8] Simply speaking hydro power is based on converting the potential and kinetic energy of water into electricity by directing the water steam into a turbine that is connected to a generator. The greatest advantages of water power are the availability, long operating lifetimes of the water power plants and the efficiency of water turbines. About 90% of the kinetic energy of the flowing water can be converted into electricity.

Canada’s hydroelectric resource provides 60% of Canada’s electricity and it accounts for 90% of the total renewable energy resources.

Most studies show that the life-cycle emission of CO_2e (CO_2 equivalent) is small for conventional hydropower plants. It varies between 11 and 230 gCO_2e/kWh depending on the size of the plant. This is due to the emission of CO_2 and CH_4 which arises from the flooding a large portion of biomass when the plant is constructed.

Wind Power

Wind is the second most important renewable energy source. As the name is self-explanatory, wind power is the kinetic energy of wind that is captured through turbines and is converted into electricity directly. “Modern wind power plants, whose rotors operate on the aerodynamic principle, achieve efficiencies of up to 50%.”[8] A few negative aspects of using wind energy can be summarized as creating noise pollution, disturbance of animal life, especially the birds, blighting of the landscape and most importantly not continuously available.

Canada has the potential to generate at least 20% of its power from the wind by 2025.[6] Currently wind farms in Canada have a capacity of 4,963MW – enough to power over 1 million homes or the equivalent to about 3 % of Canada’s total electricity demand. [7]

Between the renewable sources of energy, wind is among the lowest life cycle emitter of greenhouse gases with emission between 2-29 gCO2e/kWh. For the wind farms with higher electricity generation capacity, the greenhouse gas emissions are higher.

Hydrokinetic

This group of renewable energy consists of the following subgroups.

Tidal

This type of energy is employing tidal water flows to turn turbines and generate electricity. Energy production of tidal in Canada is minimal. Nova Scotia has the only tidal power plant in Canada.

Wave

This group is using the kinetic energy of ocean, waves / currents, to generate electricity.

Combustible Renewables and Waste Power

This group of renewable source by itself includes several categories from which energy is extracted in different ways. The greenhouse gas emission for this group varies between 15 and 52 gCO_2e/kWh. Currently in Canada this group accounts for 7% of renewable energy sources.

Biomass Energy

Combustion of non-fossil, organic matter produces heat, electricity, or both. The primary source of biomass energy in Canada is the pulp and paper products industry.

Biogas Energy

Anaerobic degradation of biomass produces methane and carbon dioxide that can be used to produce electricity through the combustion of these gases. It is generally generated from organic waste products in agricultural operations.

Municipal Solid Waste (MSW)

It consists of combustible organic matter such as paper, leather, natural rubber products and more. In Canada millions of tonnes of MSW are produced annually but only a fraction of them is recycled for heat or electricity production.

Liquid Biofuels Energy

Chemical transformation of biomass into a liquid fuel produces biofuels such as biodiesel and ethanol. Biofuels are available all the time and can be consumed in power plants like any other fuel. They are mainly used in transportation.

Waste Heat Energy

It is produced in most processes (Figure 2-4) and depending on the quality of the heat it can be used for generating electricity, heating or both. This source of energy is discussed more in Chapter 3.

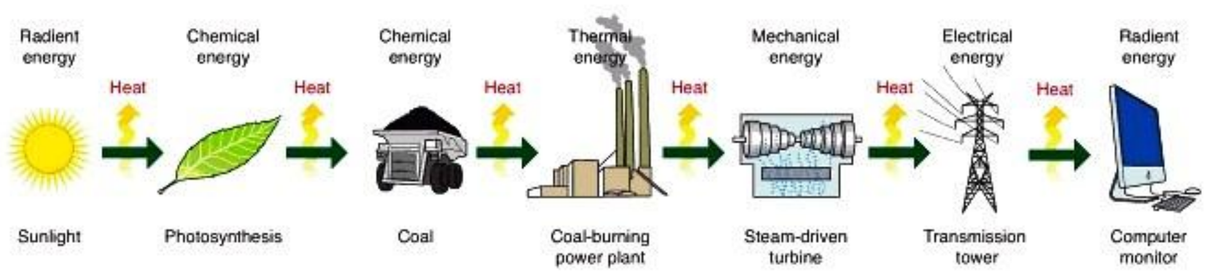


Figure 2-4 - Different forms of energy [8]

Solar Power

Solar energy is an excellent renewable energy. The use of solar power can be divided into the following three categories. The greenhouse gas emission for this group varies between 21 and 71 gCO_2e/kWh. Currently in Canada this group accounts for only 1% of renewable energy sources.

Solar Thermal

Direct heating of air and/or water is the most common use of solar energy. The terms of active or passive may be used for solar heating but also for all the renewable energy databases which refer to active solar heating which involves collecting solar energy and storing or distributing it.

Solar Photovoltaic

Photovoltaic conversion is the most instantaneous use of solar energy. This employs a sophisticated technology of solar photovoltaic (PV) cells. By direct application of sunlight to a semiconductor electricity is generated. Economically speaking, due to the high power generating costs, its role in energy production is still low. However, the market for photovoltaic devices shows growth.

Solar Thermal Electric

In this technology the solar energy is converted to heat by means of parabolic mirrors or lenses and stored in a medium that can later be directed into turbines (via steam generation) to produce electricity.

Geothermal Energy

Geothermal energy is the least developed renewable energy resource. The source of this energy is the hot water from the depth of the earth or the heat of hot, dry rock strata that can be extracted by hydraulic stimulation i.e. water injection. Electric power is produced at temperatures over 120℃. [8] The energy of the steam formed from heat in the earth's crust can be used to generate heat or electricity. In Canada energy production from geothermal is negligibly small. The cost for creating a geothermal plant is high as the energy source should be extracted from kilometers below the surface of the land [10], [11]. The greenhouse gas emission for this group varies between 1 and 740 gCO_2e/kWh.

Renewable energy resources offer a continuous supply of energy as they don't diminish through use and they certainly will lead the energy technology of the 21st century.

In 2009 the total energy and electricity production in Canada from renewable sources was estimated between 10.1% and 62% respectively. 90% of these productions were dominated by hydroelectricity and 7% by Combustible Renewables and Waste and 3% with wind, solar, tidal. [5]

Increases in financial incentives, including tax breaks and subsidies, as well as decrease in the regulatory burden for providers of renewable energy by the government, would encourage the trend towards green energy.

Chapter 3 Low Grade Energy- Waste Heat

Introduction

The sources of energy are divided into two main categories: High grade and Low grade. The difference between these two types of energy is in their conversion to other types of energy. High grade energy sources can be converted to other forms of energy easily with high efficiency while the low grade energy conversion is subject to the second law of thermodynamics.[12] Between different forms of low grade energy, the focus of this paper is on heat or thermal energy.

Thermal energy that can be used to produce electricity has various sources. These sources can be categorized into two groups: 1) non-renewable and 2) renewable energy sources which the latter is referred to energy sources that are continuously available. However, regardless of the source of the thermal energy there are common technologies that can be used to convert thermal energy to a valuable form of energy.

Waste Heat

Waste heat is the energy of waste hot streams of fluids that is released to the environment. It is the heat rejected from processes with high enough temperature compared to the temperature of the ambient to allow economically feasible energy conversion. [13] Three main characteristics of waste heat dictate the viability of waste heat recovery:

1. Heat quantity
2. Heat quality
3. Chemical Composition of waste heat stream

Quantity of Waste Heat

The quantity of waste heat is the amount of energy of the waste heat stream and is a function of temperature and the mass flow rate of the waste stream:

$$\dot{E} = \dot{m}.h_{(T)}$$

Equation 3-1

Where $\dot{E}$ is the waste heat loss energy rate (J/s), $h_{(T)}$ is the waste stream specific enthalpy (J/s) as a function of temperature and $\dot{m}$ is the waste stream mass flow rate (Kg/s)[14] which can be calculated as:

$$\dot{m} = \rho.\dot{V}$$

Equation 3-2

Figure 3-1 shows the energy balance for a typical industrial process. For the system analyzed in this paper, the following assumptions were made: energy transfers are at steady state, exhaust gases are ideal gases at atmospheric pressure.

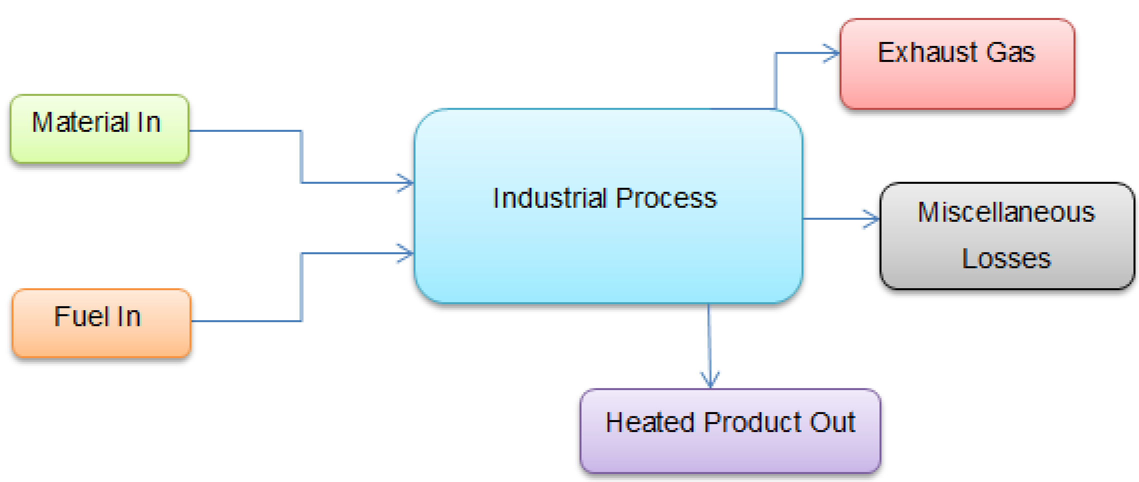


Figure 3-1 Energy balance for an industrial process

Conservation of energy dictates:

$$E_{In} = E_{Exhaust} + E_{Product} + E_{Misc}$$

Equation 3-3

The quantity of the exhaust gas waste heat loss, $E_{Exhaust}$ can be written as:

$$E_{Exhaust} = \left[\dot{m}h_{(T)}\right]_{Exhaust} = \dot{m}_{Exhaust}\sum_{i}(x_i h_{i(T)})_{Exhaust}$$

Equation 3-4

Where x_i is the mass fraction of the species contained in the exhaust gas, and $h_{i(T)}$ is the enthalpy of each species as a function of temperature. [14]

Based on the equations above, the energy content of exhaust gases is dependent on:

- Mass flow rate of the exhaust gas
- Exhaust gas chemical compositions
- Exhaust gas temperature
- Enthalpy ($h_{i(T)}$)of each species [14]

Table 3-1 summarizes an estimate of the quantity of waste heat produced by some of the most energy intensive industries in the U.S:

Table 3-1 Quantity of waste heat available for recovery [14]

Source	*Energy Consumption [GWh/yr]*	*Average Exhaust Temperature [°C]*	*Waste Heat [25°C] Ref [GWh/yr]*	*Waste Heat [150°C] Ref [GWh/yr]*	*Carnot Efficiency*	*Work Potential [GWh/yr]*
Aluminum Primary	***42.8***		***2.8***	***2.0***		***2.1***
Hall Heroult Cells	39.4	700	0.8	0.6	69%	0.5
Aluminum Secondary						
no Recovery	2.7	1,150	1.8	1.2	79%	1.4
with Recovery	0.6	538	0.2	0.1	63%	0.1
Iron/Steel Making	**242.8**		**23.2**	**16.8**		**15.3**
Coke Oven	19.2					
Gas		980	4.6	4.1	76%	3.5
Waste Gas		200	3.3	2.9	37%	1.2
Blast Furnace	188.2					
Blast Furnace Gas		430	1.6		19%	0.3
Blast Stove Exhaust						
no Recovery	10.6	250	3.1	0.6	43%	1.3
with Recovery	10.0	130	0.9		26%	0.2
Basic Oxygen Furnace	14.6	1,700	7.9	7.6	85%	6.7
Electric Arc Furnace						
no Recovery	16.9	1,200	1.7	1.6	80%	1.3
with Recovery	3.9	204	0.1	0.0	38%	0.0
Glass Melting	**36.9**		**12.6**	**7.1**		**8.5**
Regenerative	15.9	427	4.4	1.9	57%	2.5
Recuperative	4.0	982	2.2	1.6	76%	1.7
OxyFuel	3.8	1,420	1.2	0.8	82%	1.0
Electric Boost	10.2	427	2.5	1.1	57%	1.4
Direct Melter	3.0	1,316	2.2	1.7	81%	1.8
Cement	***114.2***		***24.4***	***13.0***		***12.9***
Wet kiln	28.7	338	5.5	2.8	51%	2.8
Dry kiln	23.5	449	6.0	3.8	59%	3.5
Preheater(only)	19.9	338	4.1	2.1	51%	2.1
Precalciner	42.0	338	8.7	4.4	51%	4.5
Metal Casting	***21.9***		***9.6***	***7.0***		***7.2***
Aluminum						
Reverb Furnace	5.6	1,150	3.7	2.5	79%	2.9
Stack Melter	0.3	121	0.1		24%	
Iron Cupola						
no Recovery	13.7	900	5.7	4.5	75%	4.2
with Recovery	2.3	204	0.2	0.1	38%	0.1
Boilers	**342.8**		**100.5**			**121.4**
Conventional Fuels						
no Recovery	238.1	260	50.9	10.7	44%	22.4
with Recovery	714.4	150	115.6		30%	34.1
By product Fuels						
no Recovery	238.1	260	50.9	10.7	44%	22.4
with Recovery	714.4	177	125.4	7.9	34%	42.3
Ethylene Furnace	109.6	149	17.7		29%	5.2
Total	2,473.2		433.2	75.3		172.6

Quality of Waste Heat

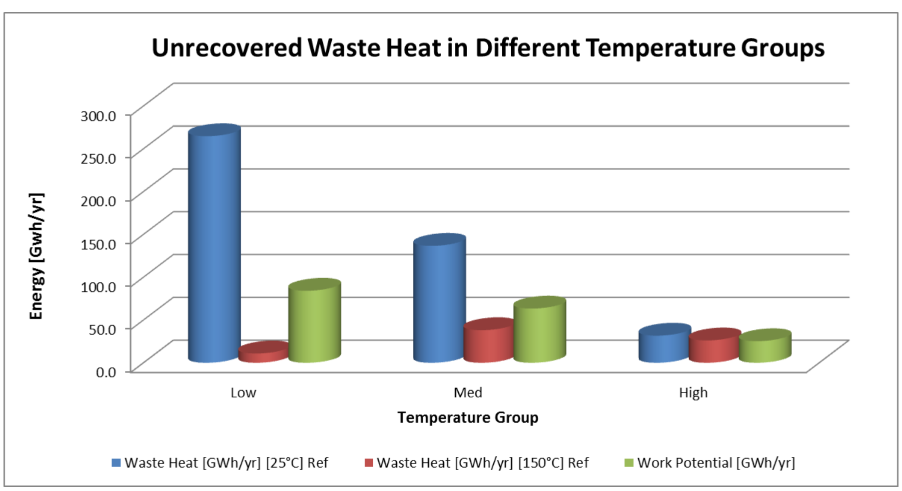
The quality of waste heat is directly related to the temperature of waste heat. From thermodynamics point of view the thermal energy's ability to convert to mechanical work is directly related to its temperature which is referred to as the quality of the thermal energy. The higher the temperature, the higher the quality of waste heat stream and it is more economically viable to recover it.

Figure 3-2 and Table 3-2 show the waste heat losses in different temperature categories:

Table 3-2 Unrecovered Waste Heat in Different Temperature Groups in U.S. [14]

Column1	*Temperature Range [°C]*	*Waste Heat [GWh/yr] [25°C] Ref*	*Waste Heat [GWh/yr] [150°C] Ref*	*Work Potential [GWh/yr]*
Low	<230	264.6	10.8	84.1
Medium	230-650	136.6	38.1	63.3
High	>650	31.7	26.1	25.2
Total		433.2	75	172.6

Figure 3-2 Unrecovered Waste Heat in Different Temperature Groups in U.S.[14]



As the temperature of the waste heat decreases, the challenges to recover this energy increase. Waste heat recovery is mainly driven by the economic benefits and at low temperatures the benefits are not as evident as the technology to recover the low grade temperature will:

- be more expensive to construct the technology
- require more primary energy to generate a unit of power
- require larger equipment and/or working fluid [16]

Chemical Composition of Waste Heat

The quality or quantity of the waste heat affects directly the recovery process while chemical compositions indirectly influence the process. The composition of the hot stream determines the material selection and equipment design as it directly impacts factors such as thermal conductivity and heat capacity. It is also an important factor for operational and maintenance cost. [14]

Waste Heat Recovery Technology

There are two general approaches to recover waste heat:

Direct Use:

In this method the lowest grade heat that is still clean enough to be used, is employed for space heating, providing hot water, pre-heating processes. The waste heat is used without any manipulations. A few common examples of direct use of waste heat are: heating storage rooms with the excess heat from the hot exhaust air, preheating materials before entering the production line, recycling waste heat to heat up water streams used in the processes or within different facilities. [37]

Direct Thermal Energy Conversion:

In this method thermal energy is directly converted to electricity. The current direct thermal energy conversion devices are:

- ***Thermo-electric converters - Peltier cell:*** The operation of these devices are based on the Seebeck effect. When two dissimilar materials are joined at one end and subjected to a temperature difference, a voltage is produced in the circuit. Heat energy is carried with electric current. [38]
- ***Thermionic converters:*** These devices are essentially similar to the thermo-electric converters with a fundamental change. The hot and cold junctions are in a vacuum chamber in order to eliminate convective heat transfer and relying solely on emission of electrons by heating to maintain the electric current.[39]

Heat Cycles:

In this method heat is converted to mechanical shaft work. There are two types of heat cycles:

1) Steam/Vapor power cycles
2) Air power cycles

The steam/vapor power cycles are the most applied technique for generating electricity from thermal energy. The working fluid used in a steam/vapor power cycle experiences phase change in each thermodynamic cycle in order to produce mechanical work. The air power cycle that is used in the waste recovery is limited to the Stirling cycle. The working fluid in an air power cycle remains in gaseous phase. The cycle relies on the expansion and compression of the gas to produce mechanical work. However, both these cycles consist of external combustion systems and therefore they are less polluting and less expensive in comparison to internal combustion systems. The other advantage of these cycles is that the input thermal energy can be from a variety of sources i.e. excess heat from the processes or from geothermal [39]. The well-known “Carnot cycle” is the theoretical version of the steam/ air power cycles.

Carnot Cycle

Proposed in 1824, the Carnot cycle is an ideal cycle with no engine that can work on its principal, yet its efficiency is considered as an indication of the maximum theoretical efficiency that a cycle can hypothetically reach.

The cycle consists of two reversible isothermal and two isentropic processes and it is valid for both steam/vapor cycles and air/gas cycles.[42],[87]

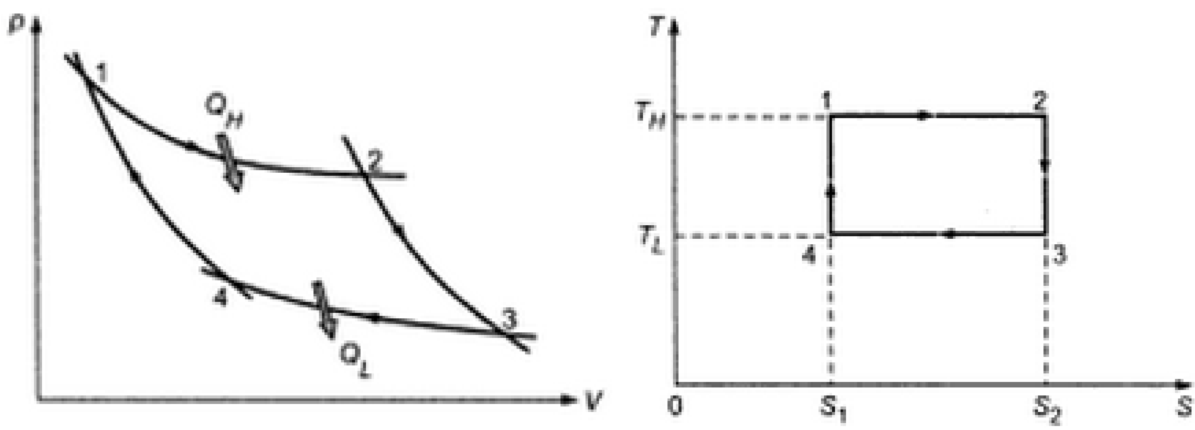


Figure 3-3 PV and TS diagram of Carnot cycle [87]

In the path 1→2 of Figure 3-3 the working fluid is heated to form wet steam/vapor. Thus heat addition is at constant temperature T_H and pressure P_1. The work done by the fluid is equal to the supplied heat:

$$Q_H = P_1 V_1 ln\frac{V_2}{V_1} = nRT_H ln\frac{V_2}{V_1}$$

Equation 3-5

During path 2→3 steam/vapor experiences an isentropic expansion to temperature T_L and pressure P_2 and the work done by the fluid can be expressed as:

$$= \frac{P_2V_2 - P_3V_3}{1-\gamma}$$

Equation 3-6

Path 3→4 is the heat rejection at constant pressure P_2 and temperature T_L. This is the state that the steam is exhausted.

$$Q_L = P_3V_3 ln\frac{V_3}{V_4} = nRT_L ln\frac{V_3}{V_4}$$

Equation 3-7

During path 4→1 the steam goes through isentropic compression until the steam returns to its original state of temperature T_H and pressure P_1 and the cycle is completed.

$$= \frac{P_4V_4 - P_1V_1}{1-\gamma}$$

Equation 3-8

The net work done by the cycle is equal to the heat extracted:

Net work done = Heat added – Heat rejected

$$= nR(T_H - T_L)$$

Equation 3-9

And the thermal efficiency of the Carnot cycle can be expressed as:

$$\eta_{Carnot} = 1 - \frac{T_L}{T_H}$$

Equation 3-10

Limitation of Carnot Cycle

Although the Carnot efficiency offers the highest thermal efficiency within a temperature limit, it is impossible to design a cycle and construct an engine with the Carnot efficiency. This is due to the assumptions made for the four processes:

1) All four processes are considered reversible, which in reality friction between the layers of the working fluids make it impossible.
2) The isothermal process requires extremely slow displacement of the piston while the adiabatic process requires fast displacement of piston in the same stroke. In practice variable motion of the piston in the same stroke is impossible.[39],[41]

There are other limitations with the Carnot cycle especially when a steam/vapor thermodynamic cycle is applied and therefore in practice the Carnot cycle has no application. However the heat cycles that are applied in industries are all a modified version of the Carnot cycle. The Rankine cycle, the Organic Rankine cycle, the Kalina cycle, the Stirling cycle and the modified Rankine cycle are a few examples.

In the next sections, the Rankine cycle and the Stirling cycle will be explained. Moreover, an alternative to the Rankine cycle, the "Heat Pipe Cycle", that is the main focus of this research will be introduced in the next chapter.

Rankine Cycle

The Rankine Cycle is the simplest and most used steam/vapor power cycle for generating electricity. There are four basic components for the Rankine cycle: the boiler, the turbine, the condenser and the pump. In most cases a 5th unit, the vapor superheater is added to increase the efficiency of the cycle and to minimize damage to the turbine. [40] In the boiler the working fluid, which is water, is transformed to vapor. The vapor goes through the superheater before it is directed to the turbine where mechanical work is produced. This work is transformed to electricity by a generator. In the condenser the working fluid condenses. Then a pump returns the condensate to the boiler and the next cycle begins. Figure 3-4 illustrates the simple Rankine cycle.

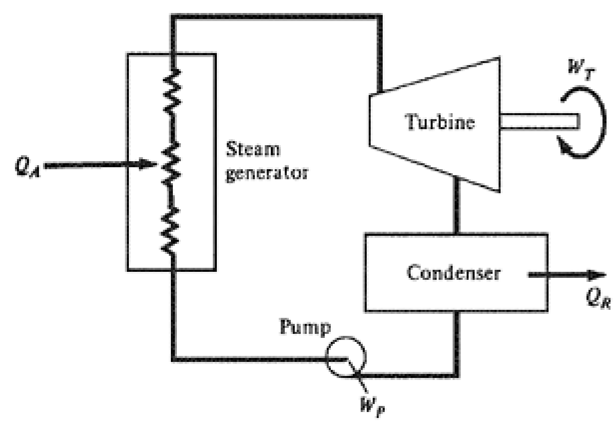


Figure 3-4 Simple Rankine Cycle [29]

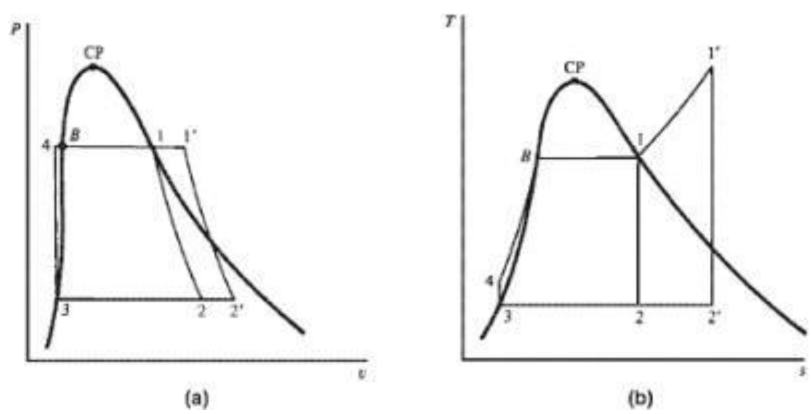


Figure 3-5 PV and TS Diagram for Rankine Cycle [40]

The above four processes of the Rankine cycle, as shown in Figure 3-5 (a) and (b), are:

In the path 1 → 2 isentropic expansion of the steam in turbine occurs.

During path 2→3 the isobaric and isothermal heat rejection in the condenser takes place.

Path 3 → 4 indicates the isentropic compression of the cycle. During this process the pump does external work on the condensate working fluid.

During path 4 →1 the isobaric heat addition from the high temperature source to the working fluid happens. Sensible heating, latent heating and super heating is all parts of this process.

The efficiency of Rankine cycle can be expressed as [39],[51]:

$$\eta_{Rankine} = \frac{Net\ Work\ Done}{Heat\ Supplied}$$

$$\eta_{Rankine} = \frac{h_1 - h_2}{h_1 - h_3} = 1 - \left[\frac{S_1 - S_3}{h_1 - h_3}\right].T_3$$

Equation 3-11

A significant advantage of the Rankine cycle is that the working fluid is water. Water is usually readily available and has acceptable qualities such as high latent heat of vaporization and specific heat, low viscosity and chemical stability to be considered as a suitable working fluid. Its favorable properties are suited for high heat fluxes, and its operating temperature range falls within those desired for many pyro-metallurgical applications. The inert nature of water also contributes to the safety aspect and low environmental impact of working fluid. [43],[50] If the working fluid is changed to an organic substance such as pentane, the cycle is named the Organic Rankine Cycle or ORC. The principal of operation of the ORC is the same as the Rankine cycle. The ORC is mostly used for medium to low grade waste heat recovery depending on the working fluid chosen in the cycle. [44] Many researches are conducted to determine the best working fluid to be used in the ORC. The choice of proper working fluid will ultimately benefit the process with high thermal efficiency as it affects the optimum utilization of the heat source. It also allows for using less expensive boilers and turbines. [53],[54] The characteristics of a suitable working fluid depending on the application can be summarized as [45,46,47,48,49,50]:

- Dry fluids or isentropic fluids: this aspect can be determined by the slope of vapor saturation curve. Dry fluids have zero or positive slope ($\frac{ds}{dT} \geq 0$)
- High density ratio of liquid to vapor phase and moderate critical temperature and pressure
- High latent heat of vaporization, specific heat, thermal conductivity, evaporating pressure and low viscosity, condensation pressure
- Safe with low environmental impact
- Abundant and low cost

The main disadvantage of the Rankine cycle is that the steam at throttle condition should be superheated to prevent condensation during expansion and consequently increase the risk of erosion of turbine blades.[52]

Because of the necessity of providing superheated steam for turbines which contradicts taking advantage of recovering the low grade thermal energy, the use of a heat engine cycle was considered in this research.

The heat engine cycles include the heat transfer equipment and work producing component, i.e. heat engine. A heat engine by definition is an engine that converts heat to mechanical work. The main characteristic of a heat engine is that a mass of working fluid undergoes a sequence of phase changes in a way that the P-V or T-S diagrams show closed paths. This working fluid should be chosen properly in order to achieve a realistic model of the heat engine. [15] The second law of thermodynamics states that the efficiency of a reversible engine is not dependent on the working fluid; hence any substances can be used as a working fluid in a heat engine. However the effect of different working fluids is on the power output (or power density). [60] To obtain a considerable amount of work, and therefore greater power, large changes of pressure and/or volume (ΔPV) is required. This requirement narrows the choices to liquid and/or gaseous phases of substances. Condensable fluids take advantage of the properties of both gaseous and liquid phases. Thus the use of condensable fluids is more desirable.

In this research different heat engine cycles were studied. The first approach was based on the Stirling cycle.

Stirling Cycle

Stirling cycle is the closest cycle to the Carnot cycle. The main element of this cycle is the Stirling engine. Since this cycle was considered for this research as the first option, Stirling engine is discussed in detail in the next sections.

Basic Principles

The principle of the Stirling engine is based on the tendency of a gas to expand or rise in pressure when heated.

In a Stirling engine, a fixed amount of gas is contained in a cylinder consisting of a high temperature and a low temperature zone (Figure 3-6). The displacer piston movement which is the result of pressure rise and fall in the cylinder shifts the gas between hot and cold regions; when a higher volume of the gas is in the hot region, the pressure rises and when the gas is transferred back to the cold space, the pressure falls.

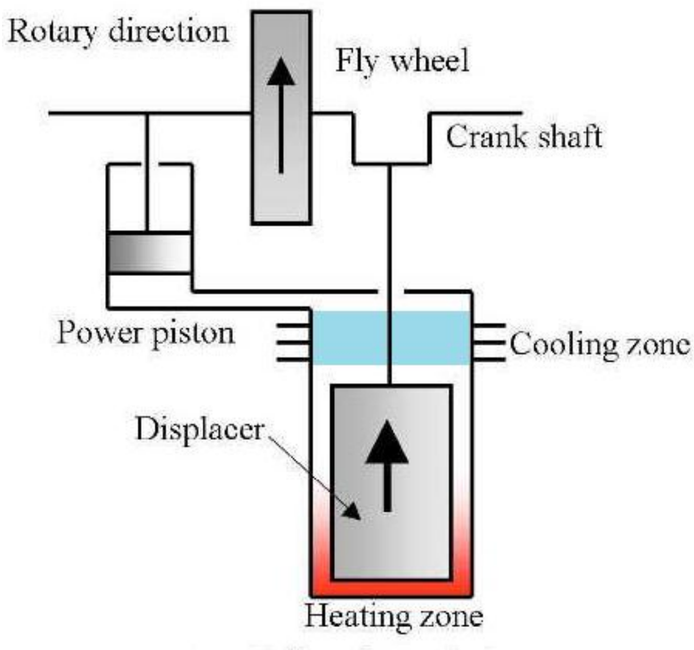


Figure 3-6- Stirling Engine Gamma Type [45]

Figure 3-7 and Figure 3-8 illustrate the Stirling engine cycle, and the PV diagram of the Ideal Stirling engine. The entire cycle consists of the following:

Step 1 -The displacer is situated at the cold end of its cylinder, and all of the gas is in contact with the heat source. The gas warms up, thus raising the pressure in preparation for the expansion stroke. This makes the power piston move upwards (path 1→ 2 in Figure 3-7 and Figure 3-8).

Step 2 - At position 2 the power piston is at its maximum height (the gas has its maximum volume) and is moving very slowly approximating the constant volume path 2→ 3 in Figure 3-7 and Figure 3-8.

Step 3 -The displacer moves into the hot region making the gas move to the cold region. Then the compression stroke takes place with all of the working gas in the cold region of the engine. Because all of the gas is in the cold region, it contracts (heat is removed from the gas) causing the power piston to slide down (path 3→4 in Figure 3-7 and Figure 3-8).

Step 4 -After the compression stroke, the power piston is at its minimum volume position. The displacer piston is moving upwards forcing the gas into the hot region. (path 4→ 1 in Figure 3-7 and Figure 3-8).

The above 4 steps are the complete cycle of the Stirling engine and the engine is returned to its initial state, ready for another cycle which it repeats indefinitely.

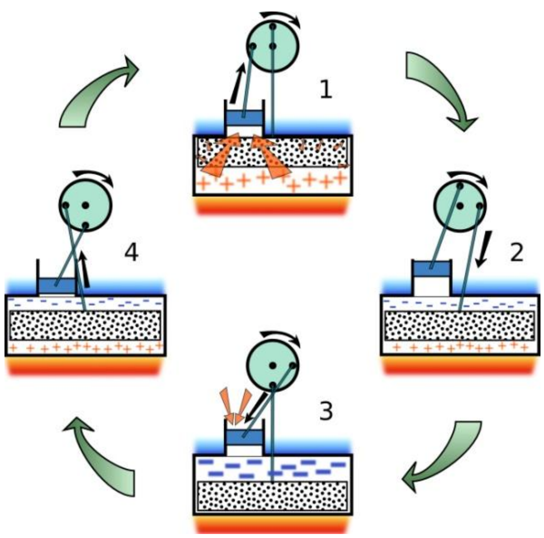


Figure 3-7- Stirling Engine Cycle [57]

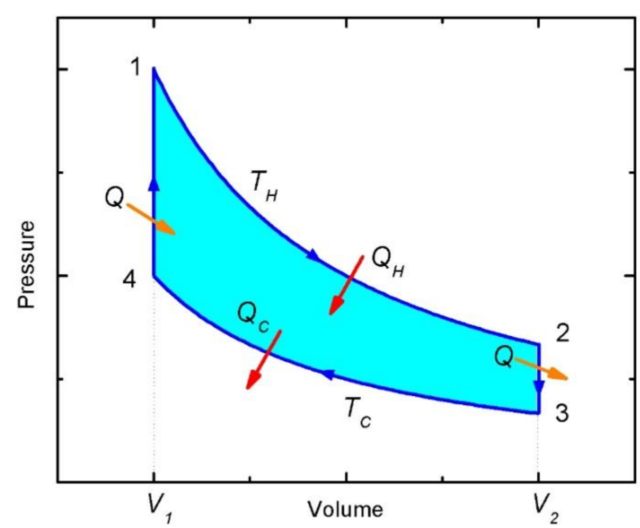


Figure 3-8- Ideal PV Diagram for Stirling Engine[57]

During the entire cycle the force on the power piston is less on its compressive stroke than its expansive movement. Thus the work done on the piston during the gas expansion is more than the work that has to be done to recompress the gas and the difference is the net amount of work achieved from the expansion and compression of the gas by the engine.

Stirling Engines in Practice

The above simplified version of Stirling engine is not used for most commercial purposes. The practical Stirling engines usually have the following differences:

First, they include a regenerator between the hot and cold regions of the system. Without a regenerator the displacer moves the hot gas directly from the hot region into the cold region where heat is extracted from the hot gas. This heat extracted is then rejected and lost. When the cooler gas is returned to the hot region, it would have to absorb more heat from the heat source in order to be reheated. Therefore, in each cycle there is an extra amount of heat that is both added and rejected which leads to a loss of efficiency. Since there is a temperature gradient through a regenerator it cause the gas to cool down by giving up heat to the metal of the regenerator while passing through it. It warms up in the subsequent cycle when the cooler gas is pushed down towards the hot region by picking up the heat that was deposited during expansion. This minimizes the amount of rejected heat before compression and also minimizes the supplied heat to the gas in the next cycle.

Although some simple Stirling engines have been built without regenerators, the Stirling brothers' original patent included a regenerator and with its help the Stirling engine's efficiency would approach the Carnot efficiency.

Second, for the real engine a high speed, typically in the order of 1000 rpm, is usually expected. In this case, because of the high speed, the gas inside the cylinder is not in thermal equilibrium with the cylinder walls, cylinder head, and piston crown. In fact there is not enough time for heat transfer thus the process is nearly adiabatic. It is common to attach an external heat source and cooler to the engine. These external heater and cooler devices are designed with a high surface area to add the necessary heat during the expansion and to collect the heat during the compression. It is evident that the difference between the heat added and rejected is the net amount of mechanical work available from the power piston.

Third, the piston movements in a real engine are simultaneously and almost sinusoidally. Figure 3-9 shows the PV diagram for a Stirling engine with the pistons moving sinusoidally with a 90° phase angle between them. The 90° phase difference is responsible for the position of the displacer at top or bottom dead center when the power piston is in the middle of its compression or expansion stroke respectively. This phase difference is essential for a real Stirling engine.

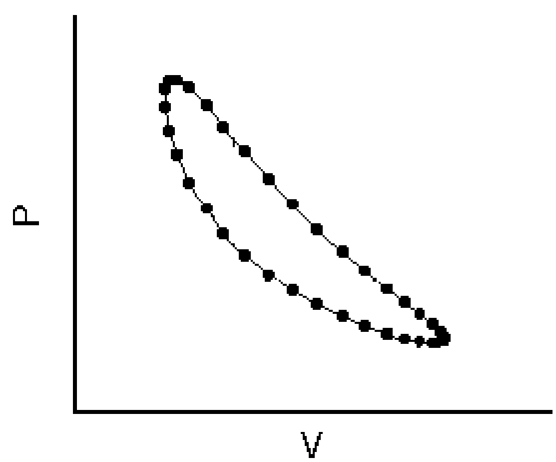


Figure 3-9- PV diagram of Stirling engine with sinusoidal piston [58]

Characteristics of The Stirling Engine

The following characteristics of the Stirling engine make it appropriate for certain applications:

External heating: This characteristic allows the use of a wide variety of heat sources. For example, one can operate a Stirling engine with fossil fuel combustion as well as solar heat, or heat stored in molten salts and more [56].

Preservation of working fluid: Since the working fluid is preserved inside the engine, the choice based on properties and effectiveness of the working fluid for each application is vast. A suitable working fluid can optimize the process by reducing flow losses and increasing heat transfer capability. Gases with low density and viscosity and high heat transfer properties like hydrogen or helium are excellent choices at the same time air with fair properties and low cost is an attractive working fluid.

Quiet engine: Contrary to internal combustion engines, the Stirling engine is quiet.

Opportunity to recycle the exhaust heat: With the Stirling engine there is the possibility of re-using the rejected heat at the cool region. This can be done by moving another Stirling engine coupled with the first one.

Efficiency: A Stirling cycle with the regenerative process is the most thermodynamically efficient since the cycle of this kind is considered isothermal which has the highest theoretical efficiency permitted by the laws of physics, the Carnot efficiency. [55] A real Stirling engine does not have the same efficiency but in the low power applications if the working fluid is chosen wisely combined with the opportunity to incorporate external heater and cooler, the Stirling engine can approach its theoretical efficiency more closely than other engines.

Less contaminations and emissions: The process in Stirling engine is well controlled thanks to external heat supply. Thus a well-designed Stirling system offers lower emissions and it can be easily adapted to various heat sources including fuels. The contamination and deterioration of the lubricants in the engine is suppressed by separation of working fluid from heat source.

It is apparent that the design of the Stirling engine and its operation involves complexity and difficulty:

Material selection: The continuous high temperature of the heat source and willingness of preservation of heat and dissipating less to the environment introduce materials selection complexity.

Average Pressure: After some time, the pressure of the hot and cold working fluid comes to equilibrium and takes its average value. However in order to have a large network, it is necessary to have large force difference between the compression and expansion stroke on the power piston which is achieved by large pressure changes in the cylinder.

External heat transfer complications: Effective heat transfer between the working fluid inside the engine and the heat source or coolant outside the engine is a great challenge as it requires the heat source to operate at high temperature for long periods of time. The efficiency of the engine is higher when the heat transfers to and from the engine is higher. However, there are limitations to the effective heat transfer.

Mathematical Calculations for Stirling Engine

Displacer Action

Before proceeding to the mathematical details valid for Stirling engine, one fact should be clear that the displacer piston does not do the work. Although pressure changes are encountered with the displacer movements, it is assumed that the pressure on the hot and the cold sides of the piston are the same. This will result in the balanced forces on the displacer and consequently no work can be done by the displacer piston.

Now let's consider the following:

V_e : The displacer piston Swap volume

T_e : Temperature of gas in the hot part of the cylinder

T_c : Temperature of gas in the cold part of the cylinder

V_m : The total gas volume in the engine

T_m : The effective average temperature (mean temperature)

P_m : The effective average pressure (mean pressure)

V_o : The power piston Swap volume

W_c : Net work available from the engine in 1 cycle

Below the first approximation of the pressure changes in the cylinder is described. In an ideal gas at a constant volume, pressure is proportional to the temperature; therefore the pressure changes between the hot and cold regions can be written as:

$$\frac{\Delta P}{P_m} = \frac{T_e - T_c}{T_m}$$

Equation 3-12

However, only a fraction of the gas is displaced. Thus:

$$\frac{\Delta P}{P_m} \approx \frac{V_e}{V_m} \times \frac{T_e - T_c}{T_m}$$

Equation 3-13

If the mean average temperature is considered as:

$$T_m = \frac{1}{2}(T_e + T_c)$$

Equation 3-14

Therefore the Equation 3-13 can be re-written as:

$$\Delta P \approx P_m \times \frac{V_e}{V_m} \times \frac{T_e - T_c}{\frac{1}{2}(T_e + T_c)}$$

Equation 3-15

Power Piston Action

The same argument for the displacer piston is valid for power piston. Power piston by itself cannot produce work. Let's consider a fixed displacer piston and a moving power piston. In this case the pressure changes on the power piston would be constant whether the piston is in compression or expansion stroke. In other word the pressure on the power piston during expansion would cancel out the one during compression and thus there would be no net energy achieved during expansion and compression and no work would be done. Scientifically speaking the pressure oscillation due to the power piston movements would be in phase with the displacer piston motions and that contribute to nothing over a complete cycle. [55]

Work Output

The net force on the power piston is responsible for the work done by the engine:

$$W_c = V_0 P_m \times \frac{V_e}{V_m} \times \frac{T_e - T_c}{\frac{1}{2}(T_e + T_c)}$$

Equation 3-16

The above work output is based on ideal engine and it does not include losses such as adiabatic losses, transient heat transfer losses, appendix gap losses, pressure drop losses and leakage losses. [55]

The efficiency of the Stirling cycle is calculated in the same way as the Carnot efficiency; however, this is only valid when a regenerator is used and the efficiency of the regenerator is 100%. In practice this is impossible and there would be at least 10 to 20% heat losses in the regenerators. Moreover the volume of the regenerator should be much higher than the engine's size.

After careful investigation and considering the above limitations, the idea of using Stirling engine for this research was rejected.

The idea of using a reciprocating engine and at the same time taking advantage of high latent heat of phase change, lead this research to consider the combined affects.

The work output of the Stirling engine is the result of the pressure change of the gaseous working fluid inside the cylinder of the Stirling engine which acts on the power piston. The extent of the pressure change depends on the gas inside the cylinder and the temperature gradient between the hot and cold surface. However, it is known that the saturated vapour pressure change of liquid over a limited temperature range is more than that of an ideal gas. Thus, low temperature engines will benefit more from a two phase working fluid compared to air alone. Practically the fluid is evaporating (or boiling) to its saturated vapour pressure on the hot surface of the engine and will condense when it reaches the cold surface of the engine. The extra power put into the system through evaporation and condensation increases the power output. The working fluid is both air and water/steam (in our case) and water is present in both liquid and gas states; therefore it is called two phase – two component engine. The literature has reported a 5% efficiency (or one-fourth of the Carnot efficiency) for a two phase two component engine but considering the mechanical and thermal losses of the real engines, the thermal efficiency of the two phase-two component engines are higher than the conventional Stirling engine. Since the heat transfer to a liquid is easier and more efficient than to a gas, the foot print of the engine will be reduced significantly. [55],[61]

This was followed by the "two-phase two component Stirling engine". That study led us to the Steam engine. Steam engine is the main component of "Modified Rankine cycle" or "Steam Engine cycle".

Modified Rankine Cycle-Steam Engine Cycle

This cycle is very similar to the Rankine cycle with the energy conversion unit being different. In the Rankine cycle the expansion of steam is occurring in a turbine while in modified Rankine cycle the expansion of steam is inside the cylinder of a steam engine. Figure 3-10 shows the PV and TS diagram of a modified Rankine cycle. It is important to note that the engine does not operate in the shaded areas of the P-V or T-S diagram i.e., point 2′. The fact is the length of the stroke would be too large at this point while the gained work is very small and does not even overcome the friction between the reciprocating parts. Thus the adiabatic expansion is completed at a point '2' which is known as "Release Pressure". At this point at constant volume a sudden pressure drop occurs. This event results in shortening of the stroke length and consequently it requires a smaller cylinder engine.

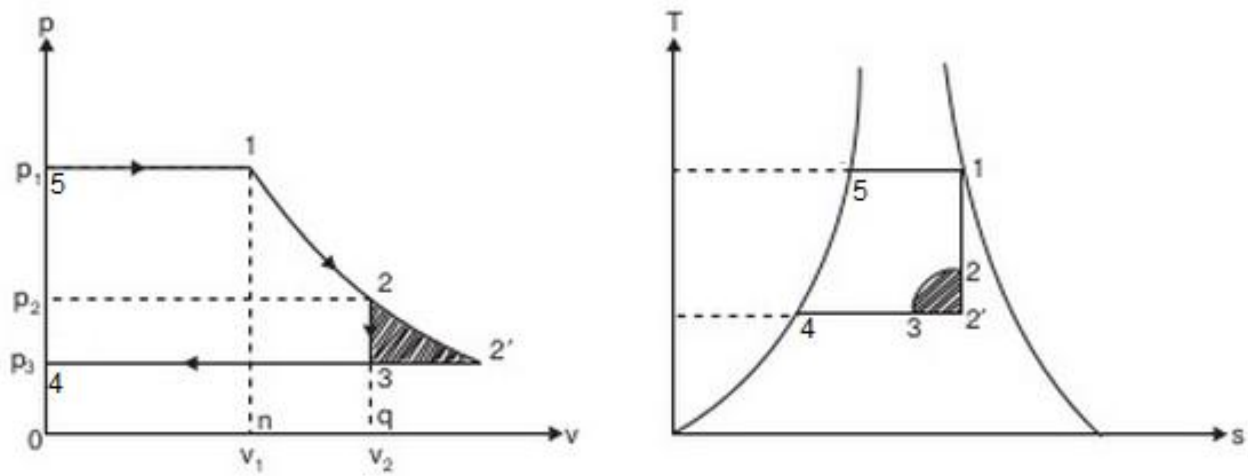


Figure 3-10 PV and TS Diagram for Modified Rankine cycle

During path 1→ 2 high pressure steam enters into the cylinder of the engine. Comparable to the Rankine cycle, this is an isentropic expansion too.

Path 2→ 3 is the release of steam in the cylinder at constant volume.

Path 3→ 4 is the exhaust of steam from the cylinder into condenser. Net work done is the area of 1-2-3-4-5.

$$\eta_{Modified\ Rankine\ Cycle} = \frac{(h_1 - h_2) + (P_2 - P_3)V_2}{\left(h_1 - h_{f3}\right)}$$

Equation 3-17

Steam Engine

The industrial revolution was closely linked with steam power. Steam engines were used to generate mechanical work. Eventually the mechanical shaft work was converted to electricity. In recent years, steam power has gained attention once more for the combined heat and power (CHP) applications that current technologies are either not appropriate or have a large footprint.

Steam engines are classified as external combustion heat engines that can transform any type of heat to mechanical work. As the name is self-explanatory, the steam engine employs the power of steam. Steam, with the advantage of phase change, is used mainly for energy storage and energy release through its phase change phenomena without change of temperature. This aspect is especially useful in the development of power cycles.

The first steam engine was a piston cylinder configuration, but today over 75% of steam engines are using turbines to create power. [62]

The steam engine admits a specific amount of steam and allows it to expand to drive a piston in a cylinder. At relatively low pressures a large torque can be achieved from a small steam engine.

The Mike Brown [86] engine is of this kind that does not require high RPM. Steam engines have a simple design that makes it easy to fabricate and have long operating life.

As it can be seen in Figure 3-11, in a steam engine steam enters the cylinder and moves the piston. A cut off valve moves forward to impede the flow of steam into the cylinder.

At this point steam expands and causes the piston to continue moving until the end of the stroke is reached. In a double cylinder engine the same sequence of events occurs with 180^0 delay.[78]

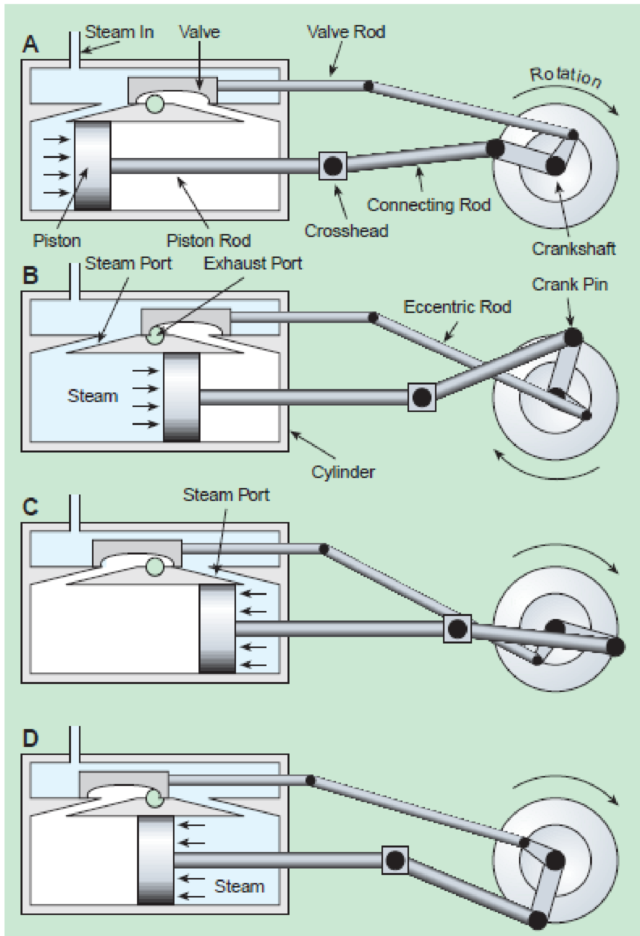


Figure 3-11 Steam engine's operation [78]

Figure 3-12 shows the PV diagram of the steam engine. In this diagram:

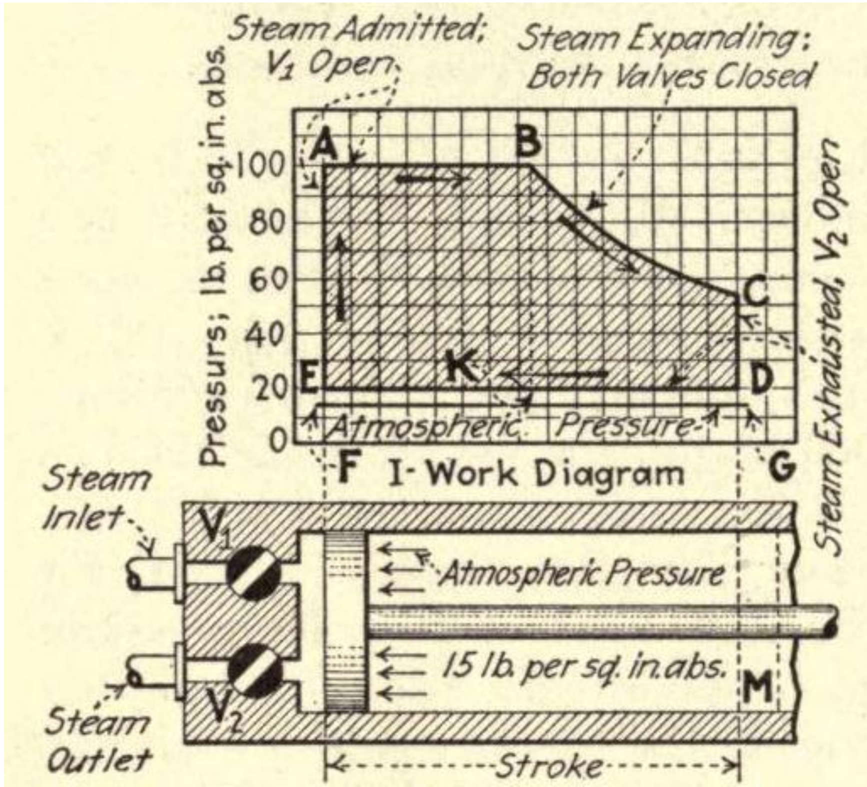


Figure 3-12 PV Diagram for steam engine [81]

E→ A : Pressure increase with constant volume: The injection valve is opened and air is injected into clearance volume of piston. This is the driving force for piston movement.

A→ B: Isobaric steam injection: The injection valve is opened and piston expands. This produces the major amount of work as the piston moves during volume addition.

B→ C: Adiabatic expansion: Both injection valve and exhaust valve are closed. The piston moves until it gets to point C. This produces additional work output for the cycle.

C→ D: Constant volume pressure drop: The exhaust valve opens and a sudden pressure drop occurs.

D→ E: Isobaric heat rejection: The piston compresses, preparing the cylinder for air injection. [81,82,83]

Mathematical Calculations for Steam Engine

The work done by the engine per stroke is:

$$W = P_m \times V_s$$

Equation 3-18

Where,

P_m : Mean effective pressure

V_s : Swept volume

P_m is calculated with values of input pressure (P_i) and back pressure (P_b) and fraction of stroke completed at cut off (1/r). The pressure values are recorded during the experiments and "r" value is provided by the steam manufacturer as 70%.

$$P_m = \frac{P_i}{r}[1 + \ln r] - P_b \; [Pa]$$

Equation 3-19

V_s is calculated with the cylinder bore (D) and length of stroke (L). These values are also provided by the engine manufacturer:

$$V_s = \frac{\pi}{4} D^2 L \;\; [m^3]$$

Equation 3-20

The indicated power for one double acting engine is calculated with the values of the mean effective pressure (P_m), the swept volume (V_s), and the RPM of the engine (N):

$$Power = \frac{2P_m \times L \times N \times A}{60}\ [W]$$

Equation 3-21

Work done per minute is calculated based on PLAN formula:

$$W = P_m \times L \times 2A \times N$$

Equation 3-22

Thermal efficiency is calculated with mass of consumed steam (m_s), enthalpy of supplied steam to the engine (h_1) and enthalpy of water returned to the condenser (h_f):

$$\eta_{Th} = \frac{Indicated\ Power}{Heat\ supplied}$$

Equation 3-23

$$\eta_{Th} = \frac{Power}{m_s \times \left(h_i - h_f\right)}$$

Equation 3-24

Chapter 4 Heat Cycle's Components

Despite the differences between the cycles described in the previous chapters, they all consist of 3 major units:

1. **Energy extraction unit** that extracts the available energy out of the stream of hot fluid and concentrates or stores it.
2. **Energy conversion unit** that converts the extracted energy to a valuable form of energy, e.g mechanical or electrical
3. **Energy dissipation unit** that is a sink for the excess energy that cannot be converted to a valuable form of energy.

Each unit also holds a working fluid which undergoes the change of state. Below each unit is discussed briefly.

Energy Extraction Unit

The technologies to recover waste heat are varied based on the application. In most of the waste heat recovery systems, heat is transferred from one fluid to another. Waste heat can be transferred to the process directly by means of pipes or indirectly by transforming it into steam or other secondary fluids. [17] These technologies can be divided into the following general categories:

• *Recuperative Heat Exchangers:*

In this type, the hot and the cold fluids move simultaneously in separate passages, transferring the heat continuously through a solid dividing wall. The heat transfer mechanisms are conduction and convection. [18] There are three types of recuperative heat exchangers:

- Shell and tube heat exchangers
- Plate heat exchangers
- Flat plate recuperator

• *Run-around coils:*

It consists of a flowing fluid, typically a mixture of water and antifreeze fluid, in a pipe loop to connect two recuperative heat exchangers in order to extract heat from the hot stream and transfer it to the cold stream. Figure 4-1 schematically shows a Run-around coils system. The application of Run-around coils is for those cases that the physical distance between two fluid streams is such that the use of a recuperative heat exchanger is not practical. This method imposes higher energy consumption since a pump is required in the cycle. The heat loss in the secondary fluid is also a potential source for decreasing the overall effectiveness of the cycle and therefore insulating the pipework circuit is important. [19]

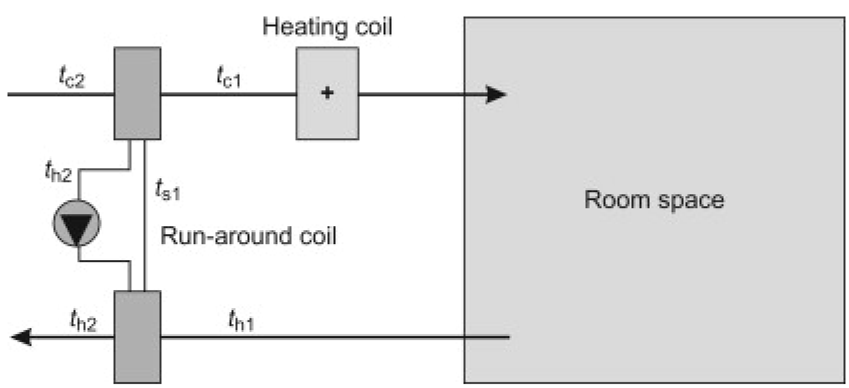


Figure 4-1 Run-around Coils System [20]

• ***Regenerative Heat Exchangers:***

In this type of heat exchanger the stream of hot and cold fluid passes through a matrix cyclically. First the hot fluid passes and releases its heat to the matrix and then the cold fluid passes through and extracts the heat from the matrix. The disadvantage of these heat exchangers is the possibility of cross contamination of the fluids as they share the same passage. [18] Figure 4-2 displays a regenerative heat exchanger.

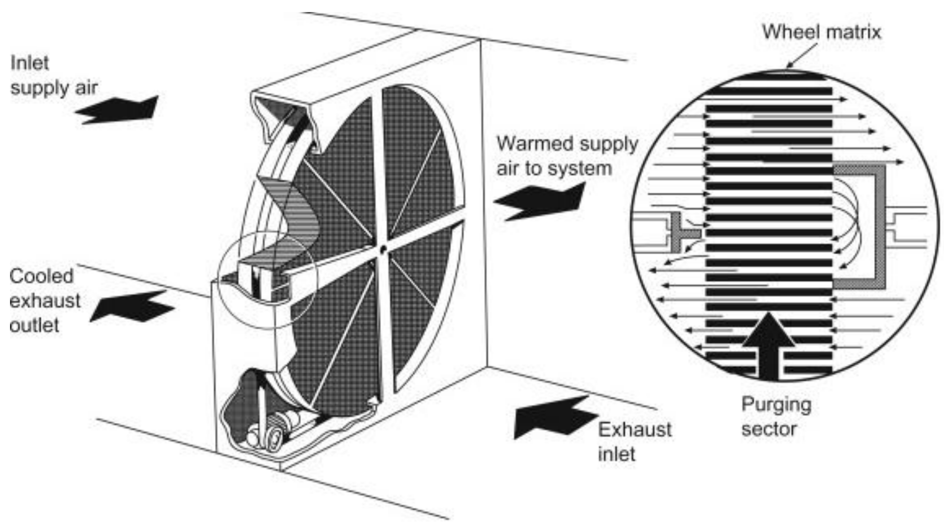


Figure 4-2 Regenerative heat exchangers [18]

• ***Heat Pumps:***

It is a machine that raises the temperature of low grade thermal energy to a level that it can be used. Figure 4-3 shows schematically the heat pump function as well as its pressure-enthalpy diagram. It is employing a vapour compression cycle to transfer heat between the hot and cold streams. In this cycle the condenser is a high temperature sink and the heat produced in this section is being utilized.[20,21]

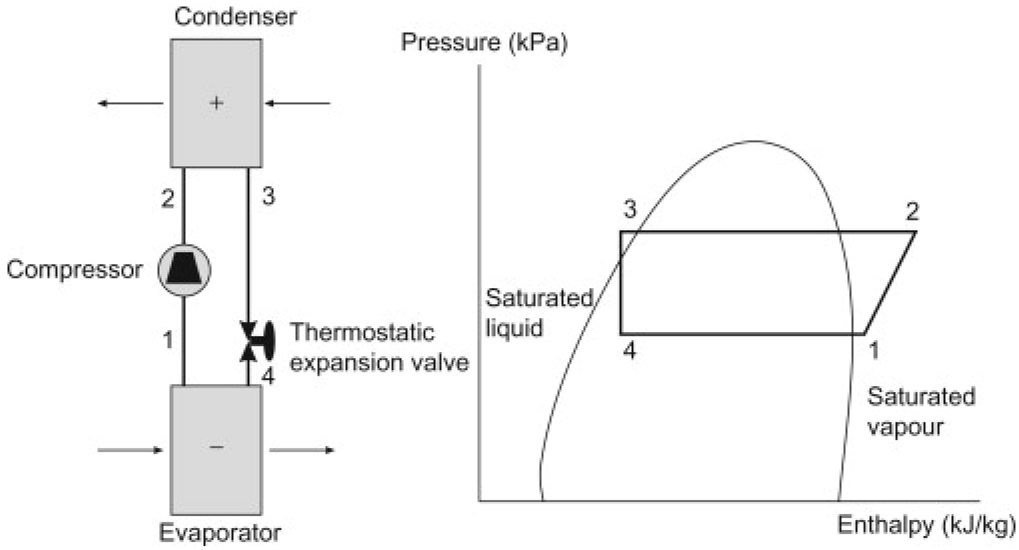


Figure 4-3 heat pump function & pressure-enthalpy diagram [20]

Beside the above most common technologies, there is a less explored technology: the heat pipe which is used in this research and it is discussed in the next section.

Heat Pipe

The conventional heat pipe was initially developed as part of the US space program [22,23], and gradually established its place as an efficient heat transfer device.

A heat pipe has such a high thermal conductance that it is sometimes referred to as a "superconductor" of heat. Its operation is very similar to a thermosyphon that uses the vaporization and condensation of a working fluid to transfer thermal energy from a hotter segment, the evaporator, to a colder segment, the condenser. They are both two phase closed systems and take advantage of the large latent heat of vaporization to transfer large quantities of heat from one point to another over small temperature changes with minimum heat loss. However, the evaporator section of a thermosyphon should be located at the lowest point possible to use the gravitational forces to transfer liquid from the condenser section. While in a heat pipe it is not necessary to use gravitational forces. As shown in Figure 4-4 a conventional heat pipe is a sealed, self-contained cylinder with a capillary structure named the "wick", filled with a vaporizable liquid called the working fluid. [24,25]

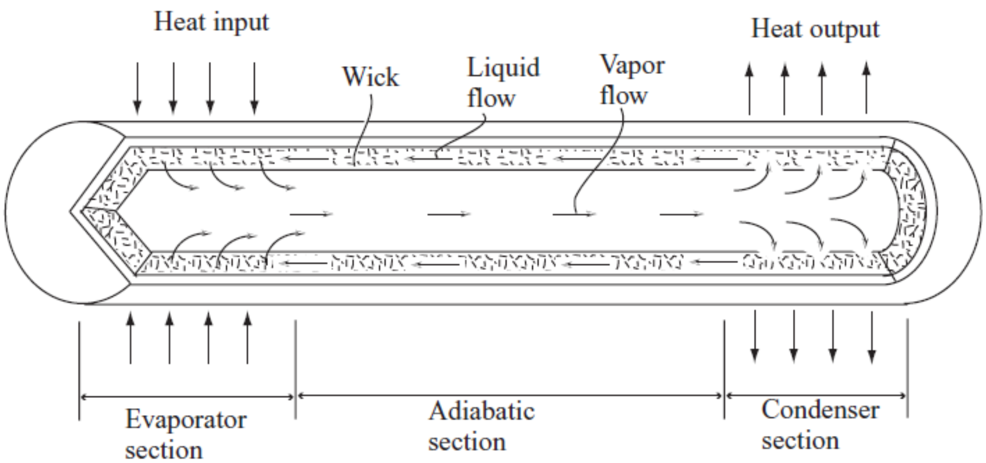


Figure 4-4 Conventional Heat pipe and the flow of heat and working fluid [25]

Design consideration

The three main elements of a heat pipe have an important role in the proper functioning of the heat pipe and therefore special attention should be paid in choosing each element.

Working fluid

As the working fluid is the main component of heat transfer, it receives special consideration. When choosing the working fluid, the following should be reflected upon:

Compatibility of the working fluid with container and wick's materials

1) High thermal conductivity and latent heat corresponding to the application

2) Adequate vapour pressure over the range of operating temperature
3) Low viscosity in both liquid and gaseous states

Container

The container holds the working fluid and the wick. The characteristics that are of high importance can be summarized as:

1) Material compatibility with working fluid
2) High thermal conductivity
3) Leak-proof
4) High strength-to-weight ratio
5) Ease of fabrication

Wick

The wick has the responsibility of transferring condensate to the evaporator section while breaking the vapour layer on the wall of the heat pipe. Therefore the most important factors to consider in choosing the wick are:

1) Material compatibility with working fluid
2) Homogeneous structure
3) Ease of forming to the shape of the container
4) Low cost [26]

Heat transfer with boiling phenomena

Heat pipes use boiling as the method of heat transfer. Boiling is convective heat transfer simultaneously with a phase change. During this process evaporation occurs at a solid-liquid interface. It takes advantage of the latent heat of vaporization as a means to store and transfer heat.

Several boiling regimes are identified: natural convection boiling, nucleate boiling and film boiling. [69]

The A-E curve in Figure 4-5 describes pool boiling. It shows that the heat flux as a function of the temperature driving force at the solid/fluid interface. The natural convection boiling is the A-B section of the curve. In this regime natural convection is responsible for fluid mixing. On nucleation sites some isolated bubbles are formed. Moving on the curve from B to C nucleate boiling occurs. In this section the heat transfer surface is covered with coalesced bubbles and creates a bubble interface. This interface impedes the flow of water near the heat transfer surface. This event causes the heat transfer coefficient to decrease while the temperature is still increasing until the maximum heat flux is achieved and is known as critical heat flux. This is illustrated by point C in Figure 4-5. Beyond this point film boiling is dominated. The C-D section of the curve is known as transition boiling where partial film boiling occurs, whereas the D-E section represents the Leidenfrost effect. [71,72,73].

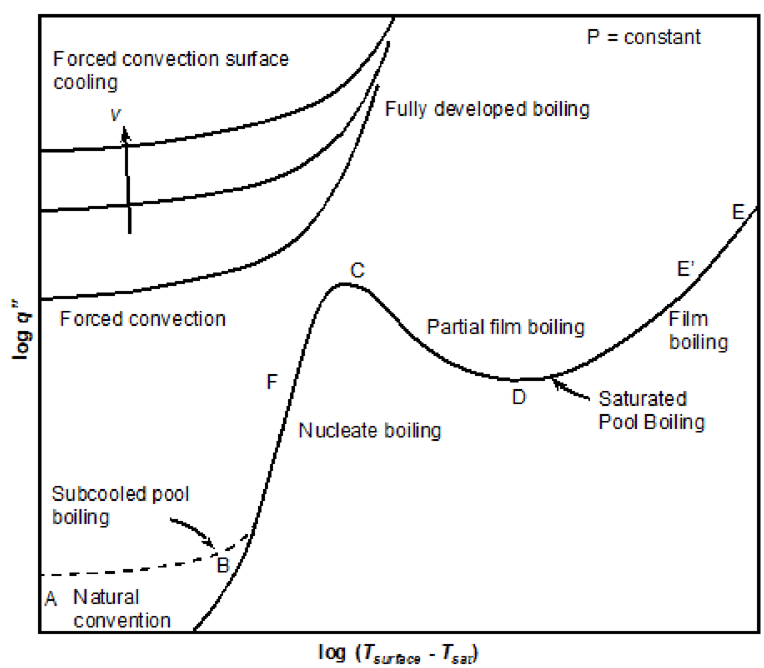


Figure 4-5 Natural and forced convection boiling curves [60]

In practice, heat exchangers are designed to operate in the nucleate boiling regime and not beyond. However this is a limitation that a conventional heat pipe can face because there is no external force. If the heat flux exceeds the critical heat flux point of the heat pipe, film boiling will start. This will result in failure of the heat pipe in the operation.

The upper-left corner of Figure 4-5 shows the curves for forced convection boiling. From the graph it is evident that a larger heat extraction is expected with force convection boiling. Moreover as the velocity increases the curves shift upwards. This can be explained by the effect of the turbulence that prevents formation of the vapor film on the heat transfer surface [74,75]. This is the same solution that the McGill heat pipe is proposing for suppressing film boiling in the conventional heat pipe as it will be described in a subsequent section.

Forced convection boiling flow also consists of several regimes: the bubbly flow regime, the slug flow regime, the annular flow regime, the transition regime, and the mist flow regime. As illustrated in the heat transfer coefficient graph in Figure 4-6 for a heat exchanger to achieve maximum heat extraction, it should be operated in the annular flow regime.

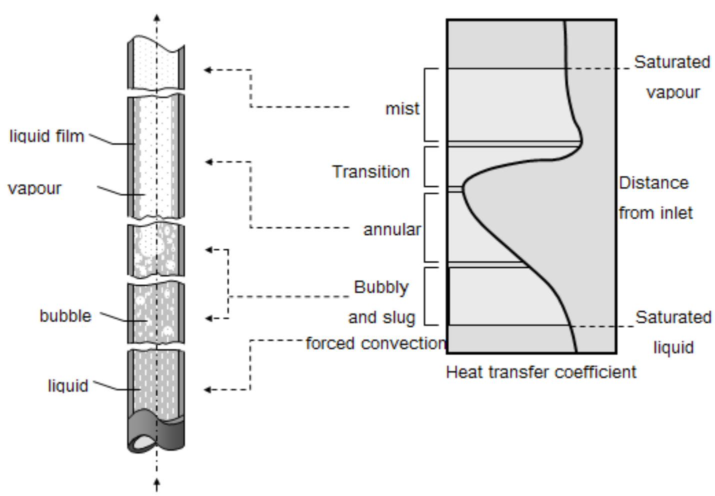


Figure 4-6 Internal forced convection boiling flow regimes [76]

Heat pipe Operation

The working fluid in the evaporator section receives the heat from the incoming hot stream of fluid by conduction and convection. The working fluid in contact with the surface of the heat pipe wall creates bubbles at the nucleation sites. It moves towards the surface while increasing convective heat transfer and promoting boiling of the liquid and converting it into vapor. As a result of the increase in local vapor pressure, evaporated fluid flows in the pipe towards the condenser section. In the condenser section, heat is extracted by a separate cooling circuit which causes the vapor to transform back into liquid. The cycle is completed when the condensate liquid returns to the evaporator section.[27]

Applications

Application of the heat pipe in energy recovery is gaining attention from researchers and scientists. To name a few examples of applications of heat pipes in the low grade thermal energy recovery/ renewable energy industry: in conjunction with Stirling engine to recover solar energy [28], solar collectors heat pipe [29], heat pipe heat exchanger for the purpose of heat recovery in hospital and laboratory buildings [30], and horizontal heat pipe heat exchangers as an energy recovery unit in air conditioning systems in tropical climates [31].

Pros & Cons

Heat pipes are capable of rapid and consistent heat delivery with a very small temperature gradient. They transfer the thermal energy three orders of magnitude greater than equivalent conductor materials. Since they are a passive thermal apparatus with no moving parts, they require minimum maintenance. [32]

However beside all the positive aspects, there are a few limitations in using the conventional heat pipes.

Depending on the application, each of these negative aspects has a higher impact on the performance and the efficiency of the heat pipe. In the context of waste heat the most important ones are: [32]

- **Minimum and maximum operating temperature:** Overheating the heat pipe or insufficient heat load on the evaporator section of the heat pipe reduces the thermal conductivity of the heat pipe to that of the metal container. In the case of overheating there is also possibility of creating damage to the heat pipe.

- **The entrainment of liquid:** The counter-current flow of fluid within conventional heat pipes creates a shear force at the free liquid/vapor interface. If the vapor velocities are large, the returning liquid can be entrained into the vapor stream, resulting in a dry-out condition at the evaporator section.

- **The film boiling:** In a conventional heat pipe, the capillary force of the wick is the main driving force for the liquid working fluid to return to the evaporator. Meanwhile at elevated heat fluxes, the wick can act as a shield to keep the vapor at the liquid/gas interface. This effect creates an obstacle for liquid working fluid to reach the wick causing a stabilized vapor film on the walls of the evaporator and enhancing film boiling.

McGill Heat Pipe

At McGill an improved heat pipe, the McGill Heat pipe, was developed [33] to overcome the limitations of a conventional heat pipe.

Essentially the two types of heat pipes are similar, i.e. they both consist of a condenser, an evaporator, and a working fluid contained within. However the wick in the McGill heat pipe is replaced by a flow modifier. Flow modifiers in the heat pipe cause the vapor swirl and this motion creates centrifugal force inside the evaporator section of the heat pipe. The capillary force of the wick in the conventional heat pipe is replaced by the centrifugal force of the flow modifiers. [23] Figure 4-7 shows the evaporator of the McGill heat pipe with flow modifier inserted.

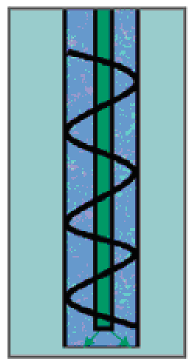


Figure 4-7 Flow modifier in the evaporator section of McGill heat pipe

The other difference between the two heat pipes is the flow direction of the liquid and vapor. In the McGill heat pipe a co-current flow configuration is considered. In a conventional heat pipe the vapor moves from evaporator towards the condenser and the condensate moves from condenser to the evaporator in the same chamber, Figure 4-8. This flow configuration is the reason of entrainment limitation in the conventional heat pipe.

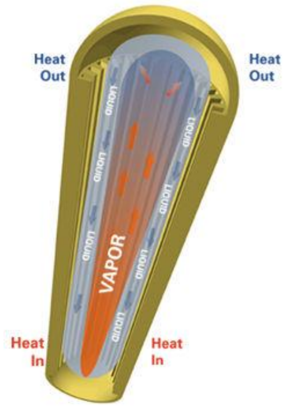


Figure 4-8 Counter-current flow in conventional heat pipe[35]

This is addressed in the McGill heat pipe by changing the configuration of the flow to co-current. This is achieved by locating the condenser section (Figure 4-9) above the evaporator and physically separating it. The evaporator and the condenser are then connected to each other by separate passages for the condensate and vapor. [36] By this change the adequate amount of liquid in the evaporator section is guaranteed. With this configuration the McGill heat pipe also takes advantage of gravity as well as the vapor pressure built within the heat pipe.

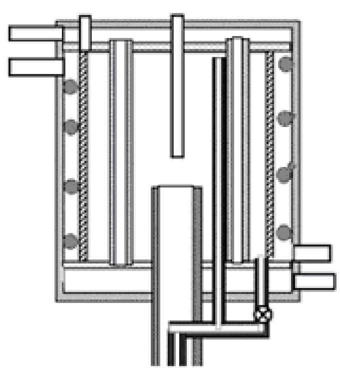


Figure 4-9 Condenser of McGill heat pipe

In this research the McGill heat pipe was used and its design and characteristics will be discussed in the following chapter.

Energy Conversion Unit

The next step is to convert the extracted energy to a valuable form, such as mechanical or electrical work. Mechanical work is a desirable energy form as it can be converted to electricity through high efficiency generators. As stated and discussed in detail in the previous sections, in this research, two different engines, the Stirling and steam engines, were studied and the steam engine was selected for the project.

Energy Dissipation Unit

The heat dissipator unit is responsible for removing the excess waste heat that the heat engine cannot convert to work. It takes in the rejected wet steam by the heat engine and condenses it with the aid of a coolant/low temperature fluid. Heat is transferred from the steam to the fluid, and the steam is condensed to its liquid state. It then moves to the condenser of the heat pipe via a pump, and the liquid is re-vaporized to steam. This process can be accomplished using a radiator, or simply a system of interconnecting tubes. Also it can use the same technology that was used in the energy extraction unit in cascading heat extraction systems.[63]

Numerical Modeling

Modeling is a valuable tactic when designing and analyzing of an engineering system. Modeling by definition is applying simplifications to real physical problems to achieve the closest-to-reality solution and answers. Modeling can be categorized into two general groups: physical modeling and theoretical modeling. Physical modeling is the tests performed in the laboratories on a physical prototype. The theoretical modeling consists of three major stages:

1. The modeler should formulate the physical problem. This includes defining the boundary conditions and the appropriate governing equations.
2. In engineering, the governing equations usually consist of a series of complex partial differential equations that cannot be solved analytically and using numerical approach is a must. Therefore a numerical model needs to be developed and validated with experimental data.
3. The last step is the analysis of the obtained data which consists of evaluating the results and transforming them into comprehensive format such as graphs. [64]

The fields of fluid dynamics and heat transfer are defined largely by complex partial differential equations. Therefore applying the numerical modeling software can greatly enhance the design of the equipment or the processes.

Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) is a tool to predict fluid flow, heat and mass transfer, and other related phenomena. In order for CFD to model a process, it requires that one solves the governing equations for conservation of mass, momentum and energy. [65,66] In fluid mechanics and heat transfer systems, the governing equations are:

Mass transport equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{v}\right) = S_{mass}$$

Equation 4-1

Momentum transport equation:

$$\frac{\partial}{\partial t}\left(\rho\vec{v}\right)+\nabla\cdot\left(\rho\vec{v}\vec{v}\right)=\nabla P+\nabla\cdot\left(\overline{\overline{\tau}}\right)+\rho g+S_{momentum}$$

Equation 4-2

Energy transport equation:

$$\frac{\partial}{\partial t}\left(\rho E\right)+\nabla\cdot\left(\vec{v}\left(\rho E+P\right)\right)=\nabla\cdot\left(k_{eff}\Delta T-\sum_{j}H_{sensible,j}J_{j}+\left(\overline{\overline{\tau}}_{eff}\cdot\vec{v}\right)\right)+S_{energy}$$

Equation 4-3

where ρ is the density (kg/m^3)

t is time (s)

$\vec{v}$ is the velocity vector (m/s)

S is the source term for either mass (kg/m^3·s), momentum (N/m^3), or energy (W/m^3)

P is the pressure (Pa)

$\overline{\overline{\tau}}$ is the stress tensor (Pa)

g is gravitational acceleration (m/s^2)

E is the sum of the potential, kinetic and pressure energy (J)

k_{eff} is the effective thermal conductivity (W/m·K)

$H_{sensible,j}$ is the sensible enthalpy of species j (J/kg)

J_j is the diffusion flux of species j (kg/m^2·s)

There are several methods of solving the governing equations for a system: finite differences, finite elements, spectral methods, and finite volumes. In this thesis, for CFD modeling ANSYS –FLUENT version 14.0 is used. This software uses the finite volume method. In this method the domain is discretized into a finite set of control volumes (meshing). The governing equations are solved on this set of control volumes and the cell values of the domain (e.g. pressure, temperature, velocity, etc.) are stored in the respective cell centers. Partial differential equations are discretized into a system of algebraic equations which will be solved numerically to render the solution field [67].

Solution Procedure

The first step is to define the domain. This means isolating a piece of the physical system that will be studied. A clean and simplified geometry is crucial in the success of the model. The next step is to create a mesh meaning that the domain is required to be divided into discrete cells (meshed) where the governing equations are solved. This is followed by the next step which is the solver setup. This step includes:

- Defining material properties
- Selecting appropriate physical models
  – Turbulence, combustion, multiphase, etc.
- Prescribing operating conditions, boundary conditions at all boundary zones: The accuracy of the results depends on the proper defining of these conditions.
- Obtaining initial values (initialization) which is considered as a "First guess" or providing previous solution information. This is done in order for the solver to achieve convergence. The discretized governing equations are solved iteratively until the changes in solution variables from one iteration to the next are negligible [65,67]. Figure 4-10 demonstrates the steps for CFD modeling with ANSYS-Fluent.

Figure 4-10 Modeling steps

Economics of Recovering Low Grade Thermal Energy

The industries that produce large quantities of waste heat can greatly benefit from waste heat recovery. Waste heat recovery can increase the overall efficiency of the process in two ways:

1) Reducing the energy input
2) Increasing effective output

Therefore a secondary power generation in the plants, if it justifies the cost, contributes to the profitability of the plants.

Power cost which will be compared in this research is the cost that industries pay to purchase electricity. Figure 4-11 shows the price paid for electricity by industries in different countries. As it can be seen, the price of electricity is about 8 cents per kWh in Canada. It would be beneficial to compare this price with the estimated cost per kWh for waste heat recovery. The cost estimation is dependent on the investment cost, and payback time.[84]

In order to estimate the investment cost, the cost of all components required to start the operation needs to be considered. The list includes but is not limited to:

- Boiler / Heat pipe / Heat exchanger

- Condenser
- Machinery such as pumps and engines
- Electric power generators

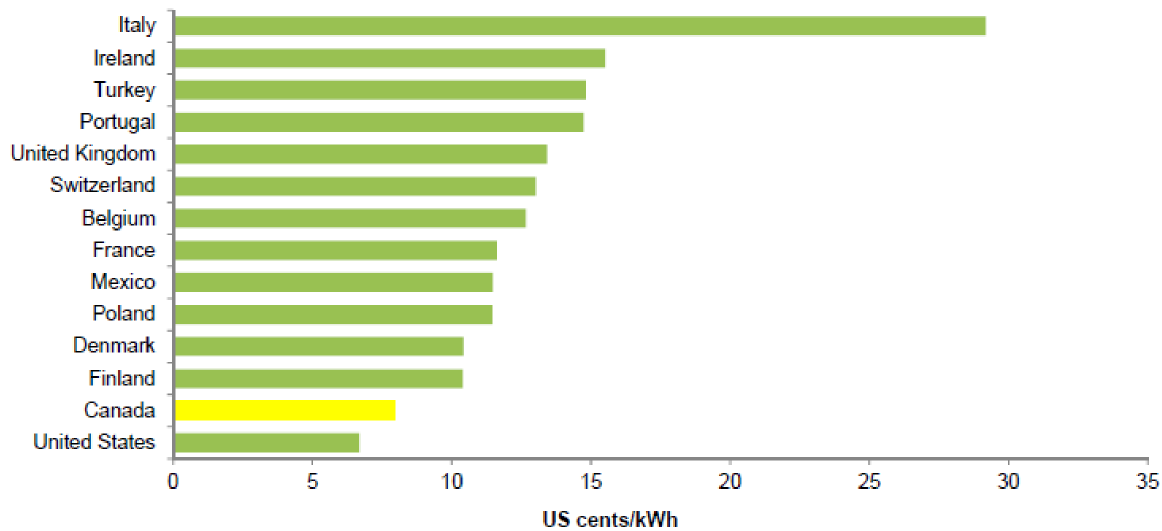


Figure 4-11 Typical cost of electricity for different sectors in [87]

Payback Period

Payback analysis is the most primary method to appraise a proposed project. The payback period is the length of time that the investment cost is paid and profit is achieved. [85,86] To calculate the payback period the investment cost or capital cost and annual net cost saving should be known:

$$PB = \frac{Capital\ Cost}{Annual\ net\ Cost\ saving} = \frac{CC}{AS}$$

Equation 4-4

Chapter 5 Heat Pipe Cycle: Design and Modelling

Introduction

At McGill University, we have coupled heat pipe technology with reciprocating engine technology to create a low grade heat recovery system that we call the “Heat Pipe Cycle”. The capture of waste heat and the dissipation of excess heat are carried out with heat pipe technology. As in any heat cycle, a boiler, an energy conversion unit, a condenser and a pump are needed. In the heat pipe cycle, a McGill heat pipe is used as the boiler. Steam engines are used to convert the thermal energy to mechanical work and a water cooled heat exchanger is used as the condenser. Our design has the possibility for expansion for multiple piston/cylinder units. Given that our engine is tied into an evaporator and a condenser and given that the fluid in the engine circuit cycles between liquid and vapor, we decided to call our engine – a heat pipe engine. The steam engine is coupled with a high temperature heat pipe system on one side and a low temperature heat pipe or heat exchanger system on the other side. The engine is a closed system, in which there is no flow into or out of the boundaries of the engine. These 3 closed loop systems are shown schematically in Figure 5-1. The general layout for the heat pipe engine system comprises a boiler, a pump, a condenser and the mechanical engine with a possible expansion of the design to include other engines. With this design it is possible to add several engines to the system, without adding new boilers and condensers with each power producing engine. Looking at the full system layout (Figure 5-1) it is possible to see how the different components have been separated and it is possible to use a different working fluid in each unit. The boiler creates steam which is fed into the engine cylinder. A pump feeds condensed working fluid from the condenser to the boiler, thus completing the closed cycle. The pump is necessary to transfer the condensed liquid from the 'low' pressure condenser back to the boiler which is at a higher pressure. [63]

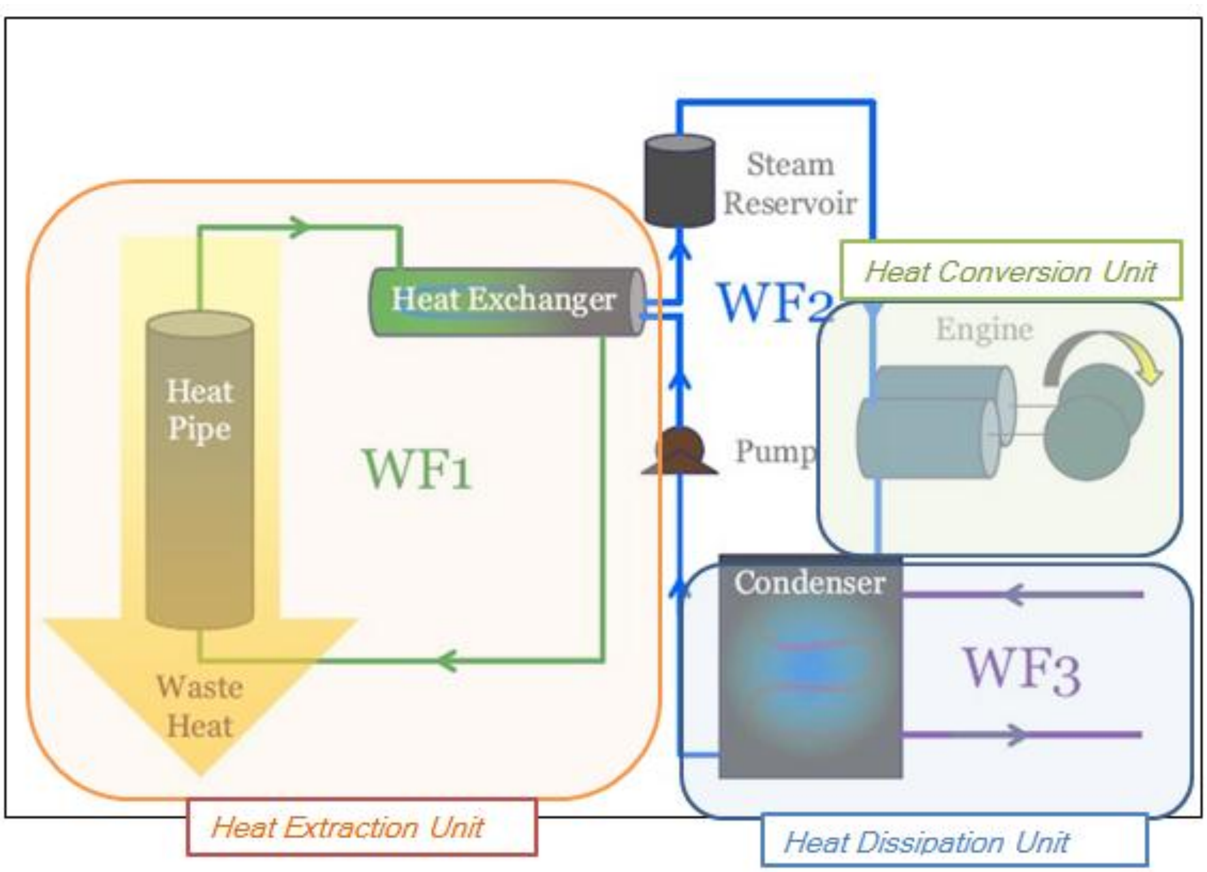


Figure 5-1 Overall schematic configuration of the Heat Pipe Cycle

In this chapter the basis of the design of the proposed waste heat recovery system that comprises 3 distinct and separate units is described. The engine comprises the central unit of the waste heat recovery system. The overall design of the system was based on a 2 cylinder engine with dimensions given in Table 5-3. The heat capture unit and the heat dissipation unit were sized to satisfy the constraints imposed by the engine.

Design Parameters

The design of each unit was a dependent of the overall efficiency of the heat cycle as a whole. Thus the first step was to determine the efficiency of the cycle. For this purpose Engineering Equation Solver software (EES) version 4.7 was used to model the efficiency of the cycle under various conditions. Figure 5-2 shows the major parts of the heat pipe cycle and the thermodynamics calculations.

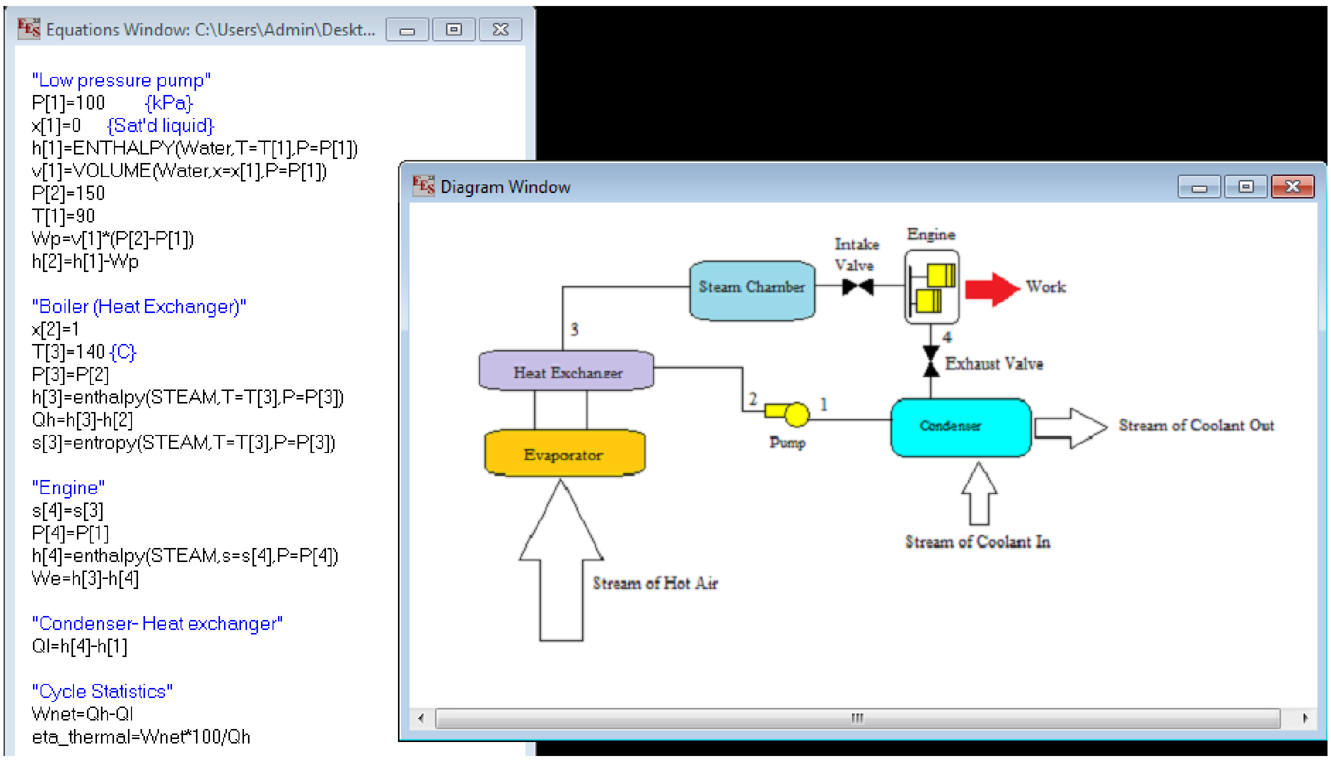
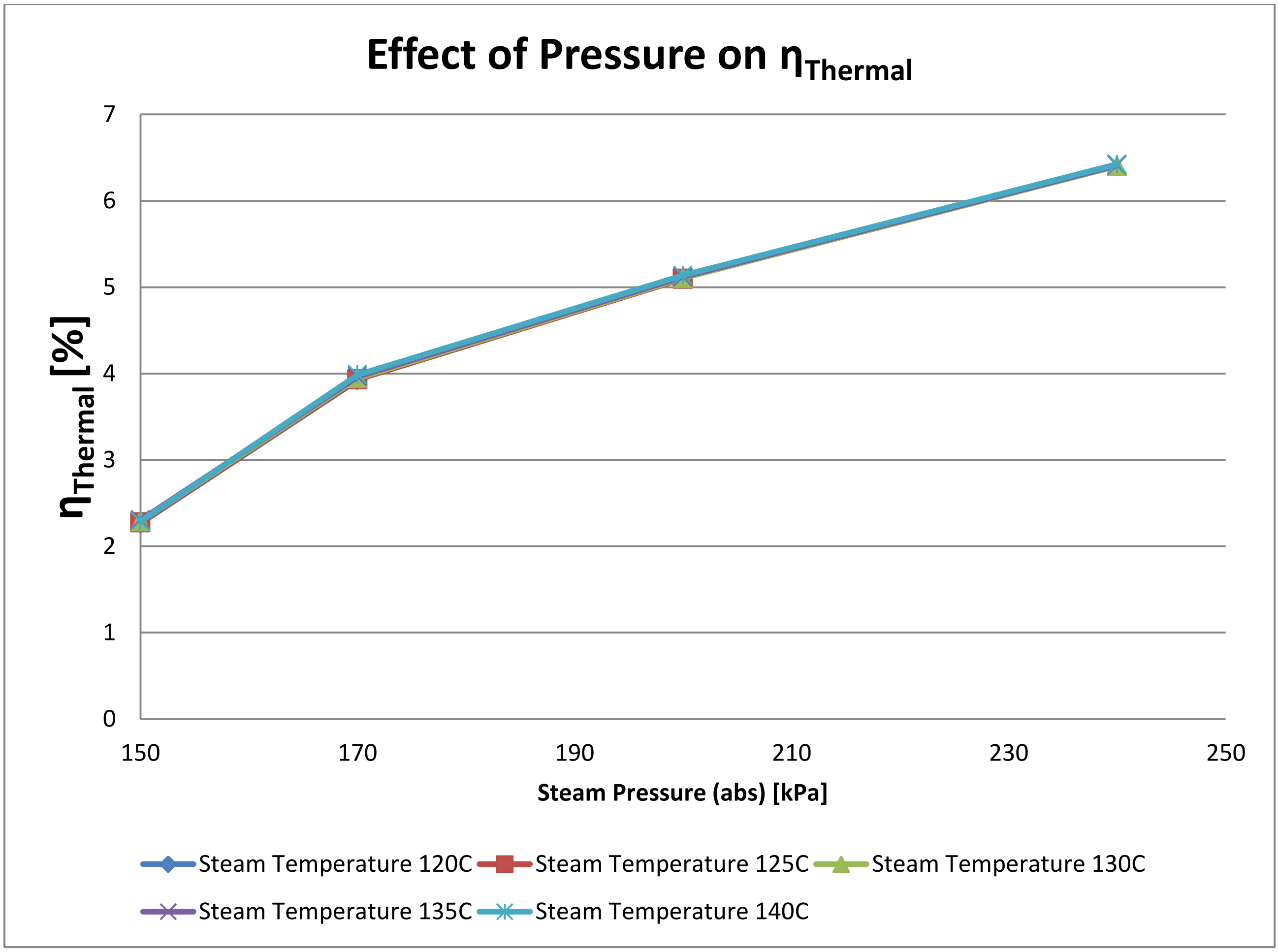


Figure 5-2 EES Model & Heat pipe cycle diagram

Various temperatures and pressures were considered for the steam that was fed to the engine. Figure 5-3 shows the theoretical thermal efficiencies based on the input steam pressure to the engine. The model indicates that the efficiency of the cycle is about 5%. It also indicates that unlike the Carnot efficiency the thermal efficiency of the heat pipe cycle is not dependent on the temperature of the steam.

Figure 5-3 Effect of Pressure on the cycle efficiency



In order to have 1 kW of work output considering an average 5% efficiency of the cycle, 20 kW of input energy is required.

Design Considerations – Heat Extraction Unit

The primary goal of this unit is extracting waste heat from a hot airflow in the temperature range of 150°C - 300°C and providing pressurized steam to an engine. This was envisioned by using three main parts, a heat pipe to harness the energy, and a heat exchanger to transfer this energy to a useful medium, and a steam reservoir to maintain steady pressure to an output with a fluctuating flow rate. A general concept for each of these components was generated and the design details were formulated based on a combination of theoretical calculations and analysis, computational modeling, and material and component availability. The design parameters and fabrication of each component is explained in the next few sections.

Design of The Heat Pipe

The design of a heat pipe to accomplish a particular duty involves two main processes:

- Selection of materials
- Selection of appropriate size and geometry

Selection of Materials: Working Fluid, Container, Flow Modifier

In low grade thermal energy recovery the heat pipe applications fall within 60^0C -300^0C. The fluids that can be used are ammonia, acetone, the Freon compounds, and water. [68]

Water is one of the best working fluids that can be used in a heat pipe with low temperature applications. It is not only safe to use but also has good thermo-physical properties such as large heat of vaporization, specific heat and surface tension. In this research water was chosen as the working fluid in all different sections of the heat cycle.

Durability and performance of a heat pipe can highly be affected by selecting compatible material for the container and the flow modifier with the used working fluid. [68] Table 5-1 provides the compatibility of materials used for heat pipe construction. [24] As stated in this table, water is well compatible with stainless steel and copper. In this research, stainless steel was chosen as the container material of the heat pipe. The flow modifier that was inserted inside the heat pipe was constructed from copper.

Table 5-1 Compatibility of Material and working fluids in heat pipes [24]

Working Fluid	Compatible Material	Incompatible Material
Water	Stainless Steel[a], Copper, Silica, Nickel, Titanium	Aluminum, Inconel
Ammonia	Aluminum, Stainless Steel, Cold Rolled Steel, Iron, Nickel	
Methanol	Stainless Steel, Iron, Copper, Brass, Silica, Nickel	Aluminum
Acetone	Aluminum, Stainless Steel, Copper, Brass, Silica	
Freon-11	Aluminum	
Freon-21	Aluminum, Iron	
Freon-113	Aluminum	
Heptane	Aluminum	
Dowtherm	Stainless Steel, Copper, Silica	
Lithium	Tungsten, Tantalum, Molybdenum, Niobium	Stainless Steel, Nickel, Inconel, Titanium
Sodium	Stainless Steel, Nickel, Inconel, Niobium	Titanium
Cesium	Titanium, Niobium, Stainless Steel, Nickel-based superalloys	
Mercury	Stainless Steel[b]	Molybdenum, Nickel, Tantalum, Inconel, Titanium, Niobium
Lead	Tungsten, Tantalum	Stainless Steel, Nickel, Inconel, Titanium, Niobium
Silver	Tungsten, Tantalum	Rhenium

[a]Sensitive to cleaning; [b]with Austenitic SS

Selection of appropriate size and geometry

At this point Computational Fluid Dynamic (CFD) modeling was used to determine the size of the heat pipe. The CFD software that was used in this research is ANSYS-FLUENT version 14.0. The boundary conditions used in this section are:

- A temperature difference of 200° C was assumed between the stream of the hot air and heat pipe walls.
- The flow in the pipe was considered fully developed and the velocity of hot air stream was set to 10m/s with k-epsilon turbulence model considering 4% intensity and 0.3m hydraulic diameter. Thus:

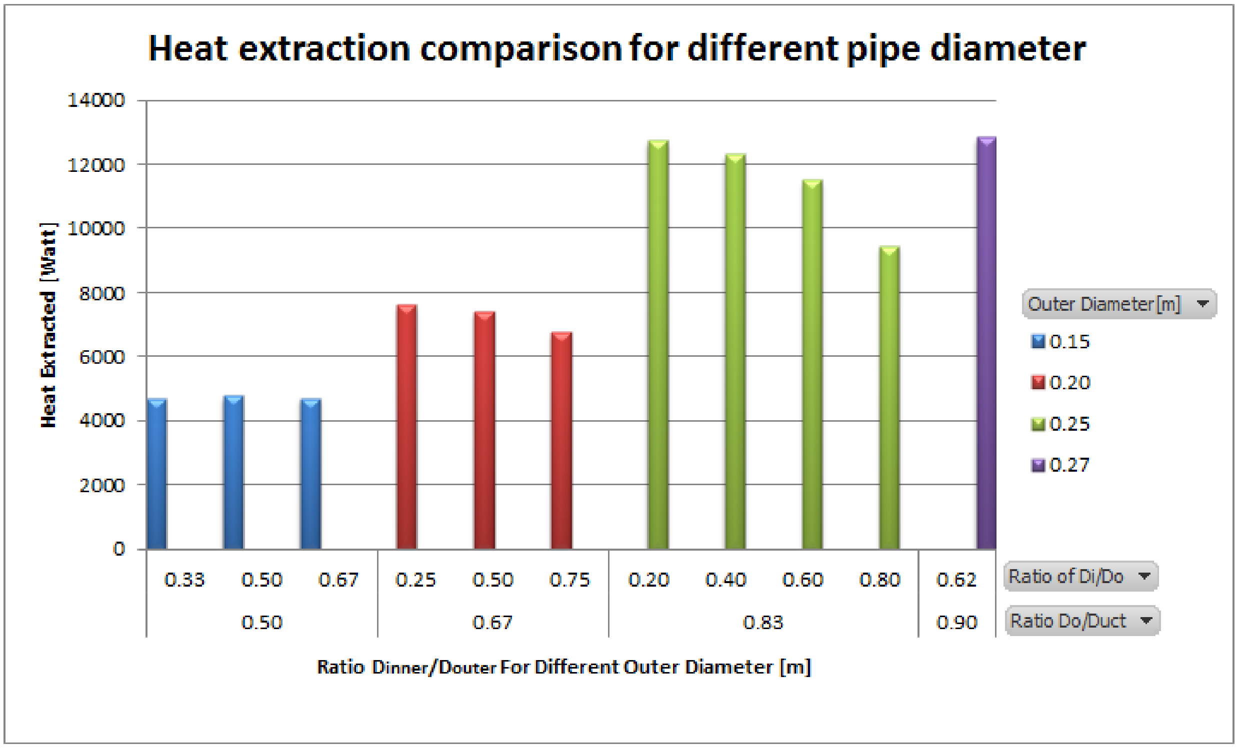
$$Re = \frac{\rho v D}{\mu} = 10^5$$

For fully developed pipe flow the turbulence intensity can be calculated as:

$$I = 0.16 \times Re^{-1/8} \cong 4\%$$

An external duct of 0.3m was selected considering our physical model is a small scale prototype. The heat pipe was decided to be an annular heat pipe as it would provide higher contact surface for heat transfer. Different ratios of pipes were considered in this modeling to decide the best combinations. The result of the modeling based on the ratio of the outer diameter of the heat pipe to duct diameter and the ratio of inner diameter to the outer diameter of the heat pipe is summarized in Figure 5-4:

Figure 5-4 Heat extraction comparison based on pipe size



The heat pipe was sized at an outer diameter of 0.25m, inner diameter of 0.15m, and length of 1m to achieve a rate of heat transfer of 12kW. The inner diameter of the heat pipe would offer an adequate working space to mount the control devices, i.e. thermocouples and to weld fittings for the condensate inlet and the steam outlet. These dimensions were rounded up to the nearest standard pipe sizes of 0.27m (NPS 10) and 0.17m (NPS 6). The larger diameters offer additional heat flux, resulting in a slight safety factor. It is important to note that 20kW of heat is not necessary for the operation of the heat pipe. If less heat is extracted from the heat source, the engine will simply produce less power. Figure 5-5 shows the SolidWorks drawing of the evaporator of the McGill heat pipe.

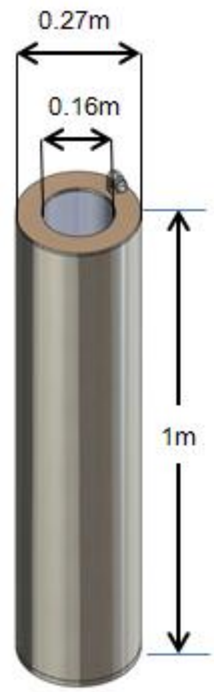


Figure 5-5 Heat pipe Design Evaporator section

Fabrication of Heat Pipe

Evaporator Section

Based on the SolidWorks drawings, the heat pipe was constructed from two standard NPS pipes, NPS-10 (0. 273m) for the outer diameter and NPS-6 (0.168m) for the inner with length of 1m (Figure 5-5). A helical swirler is housed within the heat pipe to inhibit film boiling. The swirler was constructed of two 0.0127m (1/2”) outer diameter copper pipes bent into a helix of 0.1m pitch and 0.17m diameter and brazed together one inside the other. (Figure 5-6 & Figure 5-7)

Figure 5-6 Flow modifier in McGill heat pipe

Figure 5-7 Annular McGill heat pipe

Two flat annular rings (Figure 5-8) of 0.0127m (1/2″ thickness) of stainless steel seal each end and allow fittings to be mounted for the steam exit, condensate return, and a thermocouple. The end caps were machined from 0.0127(1/2″) stainless steel plate. The top and bottom pieces both had 0.16m holes machined though the center to create the annulus shapes and the outer edges were beveled to allow for welding them to the pipes. Two 0.019 m holes were drilled on the top and bottom caps to accommodate the steam exit and condensate return fittings which were welded to the heat pipe. Finally, a 0.003m (1/8″ NPT) threaded hole was drilled and tapped on the top end cap so the thermocouple fitting could be placed.

(a) (b)

Figure 5-8 Top (a) and bottom (b) cap of McGill heat pipe

Condenser Section

The condenser of the heat pipe is a heat exchanger which extracts the energy of the steam and transfers it to the second working fluid which enters the engine. The heat exchanger specifications were dictated by the heat transfer characteristics of the heat pipe. A common shell and tube design was adopted with the following (Table 5-2) design requirements for operation:

Table 5-2 Heat exchanger design specifications

Parameter	Value
Temperature	Greater than 120 Celsius
Pressure	Minimum capacity of 6 atm
Heat Transfer	12 kW
Steam Quality	100%
Condensation	100%

Constructing a heat exchanger is a delicate process and it was beyond the capabilities of our machine shop. Thus the heat exchanger used in this research was custom ordered from ManuRep and was manufactured. The heat exchanger is shown in Figure 5-9.

The heat exchanger is composed of two primary components. The first, primary component is a 0.11 m (4 ½″) outer diameter stainless steel shell which acts as the housing for the tube bank, the secondary component. The tube bank is made out of 9, 0.013 m (0.508″) outer diameter tubes that form a U inside of the shell. The outer shell is capped with a 0.1m (4″) nominal size weld cap at one end and a 0.1m (4″) nominal size flange that acts as a manifold cover for the tube bank.

In terms, of couplings and fittings a 0.019m (¾″) steam hose was selected to couple the heat exchanger and reservoir to the condenser and engine groups. To connect the heat exchanger (condenser) to the heat pipe's evaporator two 1.5 m lengths of high temperature steel braided hose was selected. In terms of control valves that were used, a needle valve was installed between the heat exchanger tube bank and the condenser to control the flow rate of the water returning to be reheated. A gauge was placed downstream of the needle valve to measure the pressure decrease.

To control the flow rate of the steam entering the shell side of the heat exchanger a globe valve was installed between the steam inlet and the heat pipe. In this section of coupling, a gauge was placed before the valve to be able to determine the state of temperature and pressure in the heat pipe.

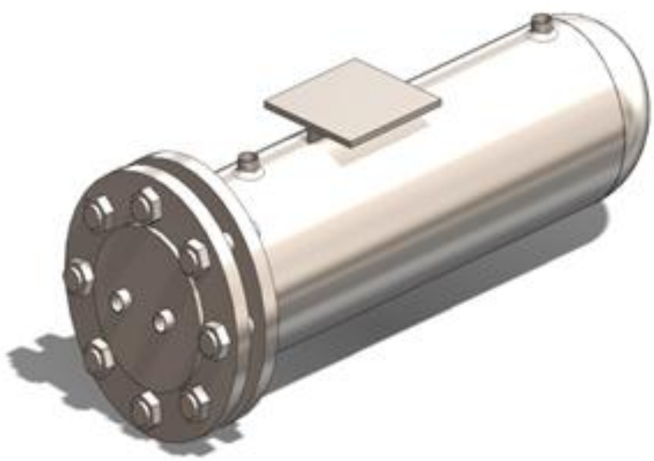


Figure 5-9 Heat pipe condenser

Steam Reservoir

Design of Steam Reservoir

The steam reservoir is a cylindrical tank, which houses the steam prior to injection into the engine cylinder to drive the piston. The main purpose of the steam reservoir is to minimize any pressure variations of the steam driving the engine. Pressure variations in the system are a result of the cyclical, unsteady flow of steam to supply to the engine. The outflow of steam to the piston will occur only during the intake stroke of the engine at a relatively high flow rate, where steam outflow from the heat exchanger will be constant with a lower flow rate. The key function of the steam reservoir is to minimize the variation in pressure of steam outflow admitted to the engine cylinders. The steam reservoir acts as a buffer between the heat exchanger and the pistons, holding a sufficient volume of steam to be used in the engine at all times. Pressure variations in the tank are not desirable as it will result in unsteady outflow of steam to supply to the engine which in return may cause condensation in the engine cylinder or decreasing the efficiency of the engine.

As the reservoir will be in constant contact with hot steam and condensate, it is important to choose a material that is resistant to corrosion. Stainless steel was used to construct the steam reservoir as it is compatible with both water and steam.

The reservoir is storing hot steam and thus will tend to lose heat to the environment and form condensation in the tank. This causes a direct reduction on the efficiency of the system. Thus the proper insulation of the steam reservoir is of great importance to avoid large amount of condensation in the tank. Nevertheless small quantities of liquid water are expected to form in the tank. Though not problematic in small amounts, if there is a buildup of condensation it will decrease the quality of steam entering the engine. Several ideas were investigated including a steam trap, a two-way valve and a pump, but in the end, a simple gravity drainage design was used. By orienting the steam reservoir directly above the heat exchanger, all condensate will be able to drain directly back down into the heat exchanger for re-evaporation.

Fabrication of Steam Reservoir

The main body of the steam reservoir consists of 2 stainless steel plates that are 0.219m (8.625″) in diameter and 0.0127m (0.5″) in thickness that cap a stainless steel 8 NPS, schedule 10 pipe. The two end caps are welded to the top and the bottom of the pipe to create a sealed reservoir. On the top cap of the reservoir (Figure 5-10 - a), three holes were drilled and threaded: Two 0.003m (1/8″) NPT threads for the pressure transducer and thermocouple housing, and one 0.019m (¾″) NPT thread for the tube fitting which connects the steam output hose. On the bottom (Figure 5-10 - b), a single 0.019 m (¾″) NPT thread for the tube fitting is implemented which connects to the steam input hose.

Figure 5-10 Top (a) and Bottom (b) of steam reservoir

Figure 5-11 illustrates the heat extraction unit and the direction of the flow of steam (red arrows) and condensate (blue arrow). The prototype is very robust in order to withstand the variety of stresses and pressures that it will be subjected to. It is heavy and physically large due to its sturdiness. The majority of the components that are subject to high heat are made of stainless steel because it can withstand heat and maintain the required strength.

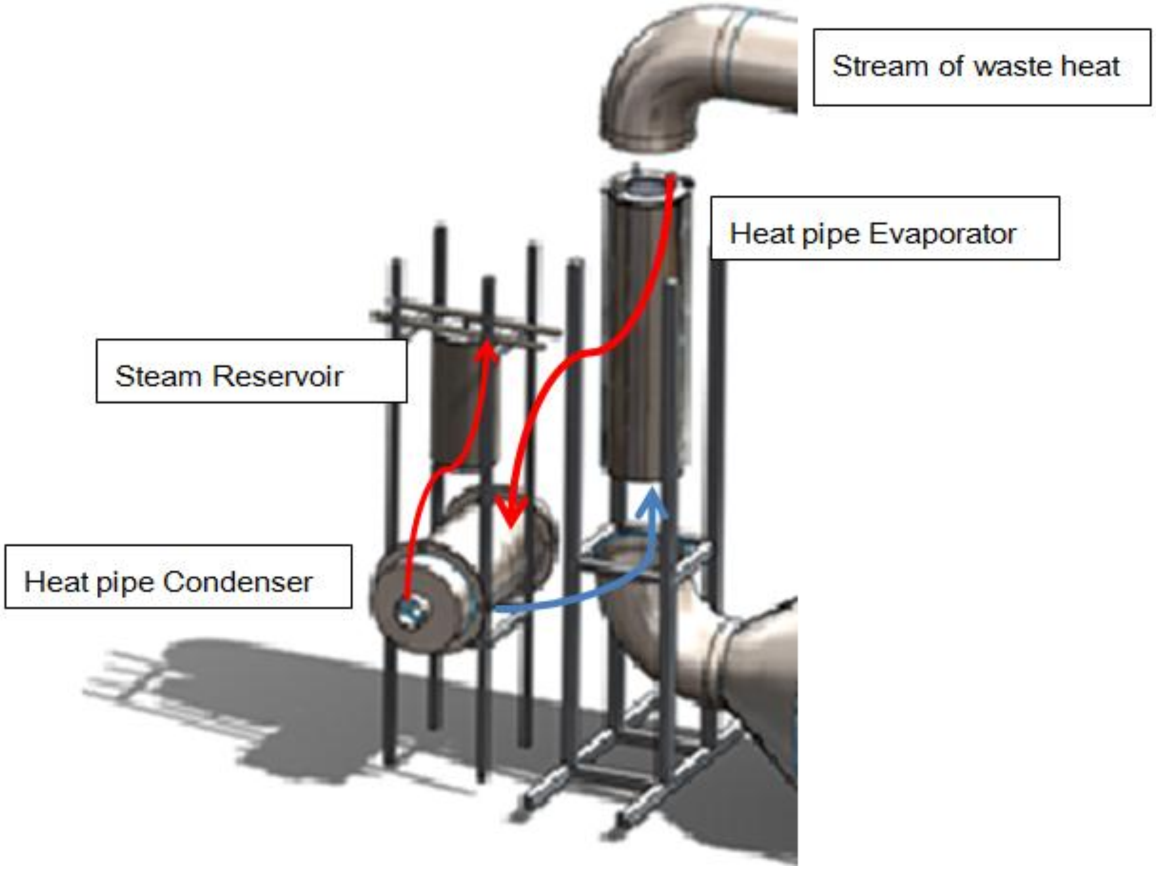


Figure 5-11 Heat Extraction unit

Heat conversion unit

The unit is essentially a conventional Watt steam engine, using valves to inject and exhaust steam to an external boiler and condenser respectively. A double acting, twin cylinder 3hp engine was purchased and used as the energy conversion device due to the self-starting characteristic of this engine as compared to a single cylinder (Figure 5-12)

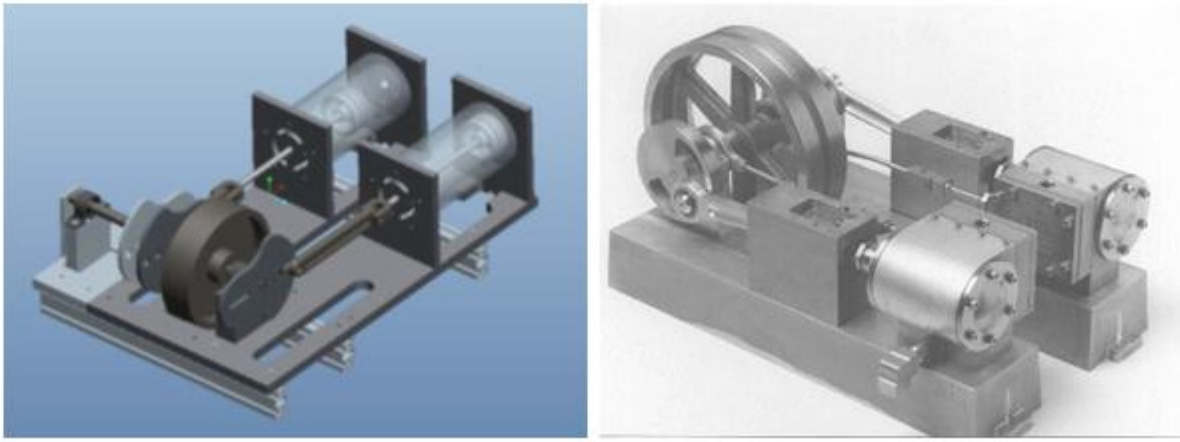


Figure 5-12 Double acting twin cylinder 3hp steam engine

Table 5-3 summarizes the steam engine's parameters.

Table 5-3 Steam engine parameters

Flywheel Diameter (m)	0.19m
Piston Area (m^2)	$0.04m^2$
Length of stroke (m)	0.057m
Height of Engine (m)	0.2m
Length of Engine (m)	0.43 m
Width of Engine (m)	0.33 m

Heat Dissipation Unit- Design and Fabrication

This section details the design of the condensing heat exchanger, which dissipates the waste heat from the system. The main purpose of this unit is to remove the excess steam from the exhaust of the heat engine and condensate it. To this end a shell and tube heat exchanger with a tap water fed cooling pipe was designed. As shown in Figure 5-13, a series of copper coils are used to pass the cooling tap water through our system. The coils have an inner diameter of 0.007m and an outer diameter of 0.009m. They are arranged horizontally in a wave-like pattern, with 12 passes. Each pass has a length of 0.25m, and each pass is 0.05 m apart from one another. The total footprint of the coil setup is approximately 0.66m by 0.36 m. The 5m copper tube is bent to specification in a planar arrangement with parallel lengths alternating at 180◦ bends. The coil is welded to the removable cover of the chamber.

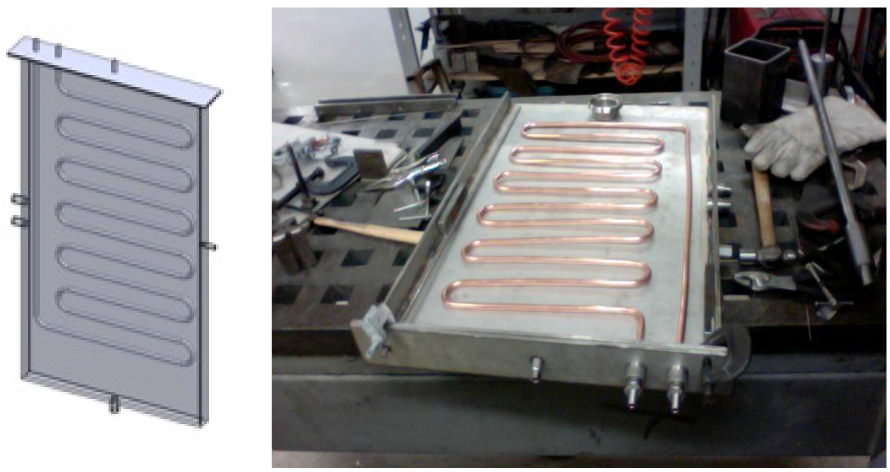


Figure 5-13 Heat Dissipater heat exchanger

The case is made of stainless steel and the coil is made of copper. It is approximately 0.75m high, 0.45m wide, and 0.038m deep, with a 0.025m flange around the top. Three holes are positioned on the cover: two holes for the coils, which will connect to the water supply and one hole of 0.006m diameter that is located at the center of the cover, protrudes from the cover and attached to a valve used for air evacuation. The evacuation of air from the chamber is necessary to allow the steam to occupy the entire chamber without any impedance. At the beginning of the process a predetermined amount of water into the bottom of the chamber is injected to serve as a buffer so the system can operate continuously. Exhaust steam leaves the engine and enters into the chamber from the side entrances located halfway up the shorter side in order to allow it to disperse evenly. At the same time, cold tap water enters the long section of the coils and cools and condenses the steam while passing through the coils. The temperature gradient between the hot steam and the cold tap water causes the steam to condense on the coils, and then fall to the bottom of the chamber into the pool of water. From the bottom of the chamber, the water flows towards a pump where it is pressurized and flow back to the condenser of the heat pipe and hence completes the cycle. The final system is surrounded by Styrofoam insulation in order to ensure that as little heat as possible leaves the chamber through the walls. The steam enters the container at a temperature of about 100 °C.

In order to monitor the status of our system, we made use of thermocouples and flow meters. The thermocouples entered through the hole on the right side of the chamber, and provided us with temperature readings of the steam. In addition, we installed flowmeters outside the condenser to determine the mass flow rate of the cooling water.

Cost

The cost of equipment is comprises the cost of the energy extraction unit, the energy conversion unit and the energy dissipation unit. In reality the cycle can be expanded while maintaining one reservoir and one heat dissipation unit and multiple engines. However in this paper the cost of all components are calculated for the total electricity generated. The cost of piping was neglected as different architecture requires different piping equipment.

Heat pipe:

- The evaporator section: $1500
- The condenser section: $4500

Steam Reservoir: $200

Engine: $2500

Heat dissipator heat exchanger: $300

The total investment cost for heat pipe cycle prototype with one engine and one evaporator is estimated to be approximately $10,000.

Modeling

In this research for modeling the heat extraction procedure, ANSYS Workbench software package version 14.0 was used. ANSYS Workbench is a project-management tool. Workbench (Figure 5-12) links the data between ANSYS Geometry, Mesh, solver and Post-processing tools.

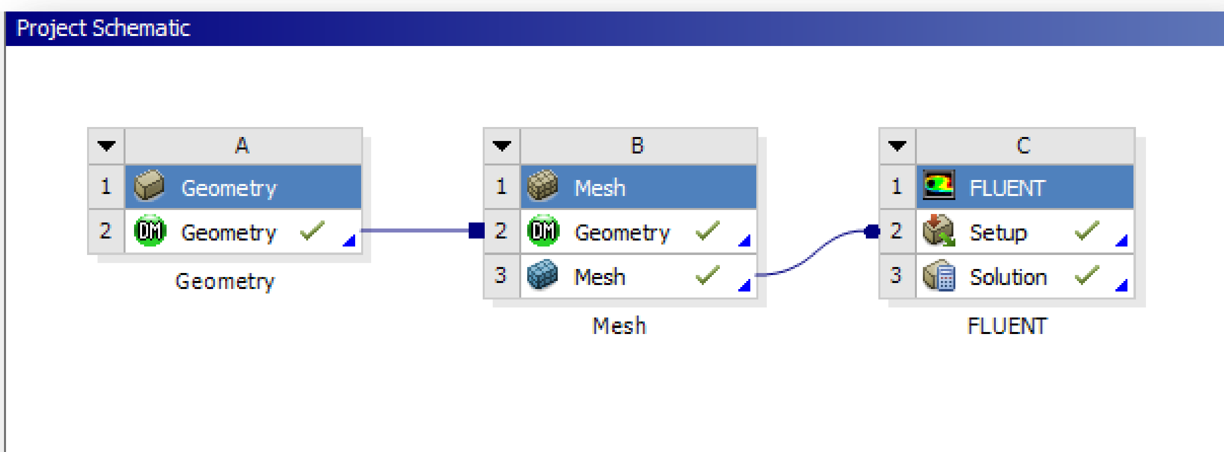


Figure 5-14 ANSYS Workbench project schematic

Heat Extraction Modeling

Geometry, Mesh and boundary conditions

Geometry

The geometry used for this model was based on the design of the heat pipe explained in the previous sections. The non-symmetry characteristic of this design only allowed a 3D modeling (Figure 5-15).

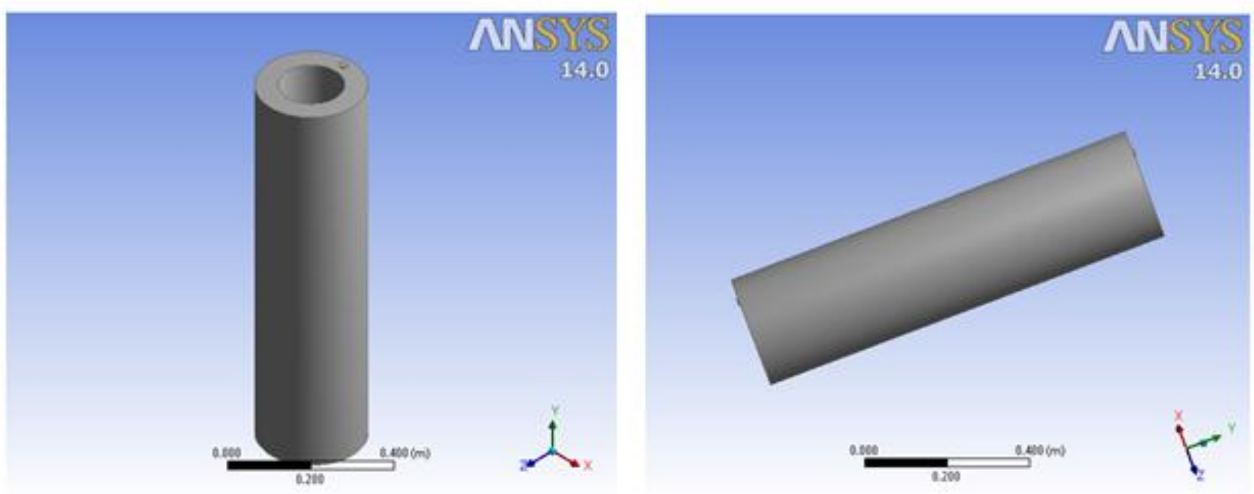


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Figure 5-15 Heat pipe evaporator geometry

Mesh

Orthogonal quality was checked to ensure the quality of mesh. The values close to 1 show high quality of mesh. As Figure 5-16 illustrates in most parts this value is more than 0.8. To assure high quality of mesh, gradiant adaptation was used to refine the mesh based on the gradiant of the velocity, temperature and pressure.

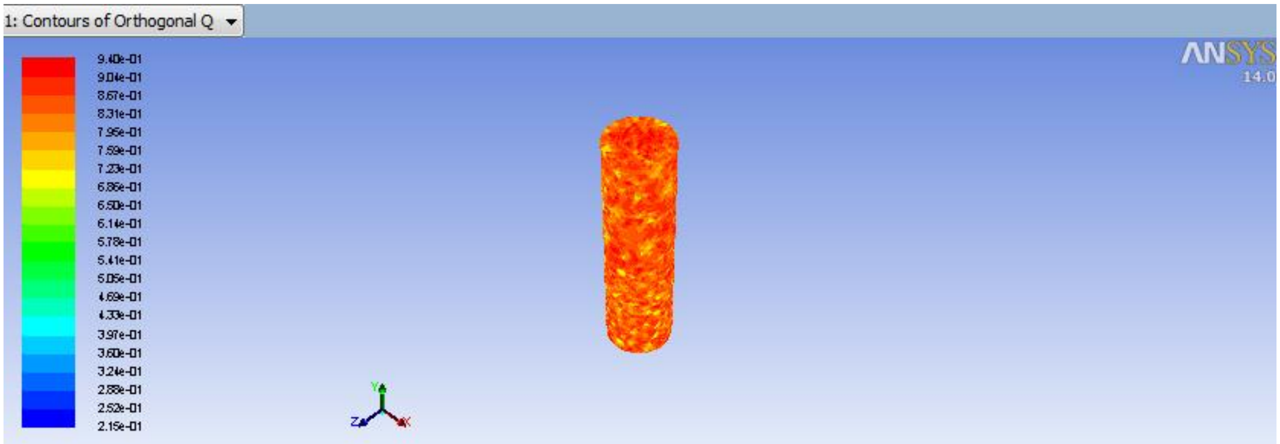


Figure 5-16 Mesh quality

Boundary Conditions

Figure 5-17 and Figure 5-18 and Table 5-4 present the boundary conditions used in the model. These boundary conditions were adequate for a well defined problem. The flow of waste heat stream was considered fully developed flow.

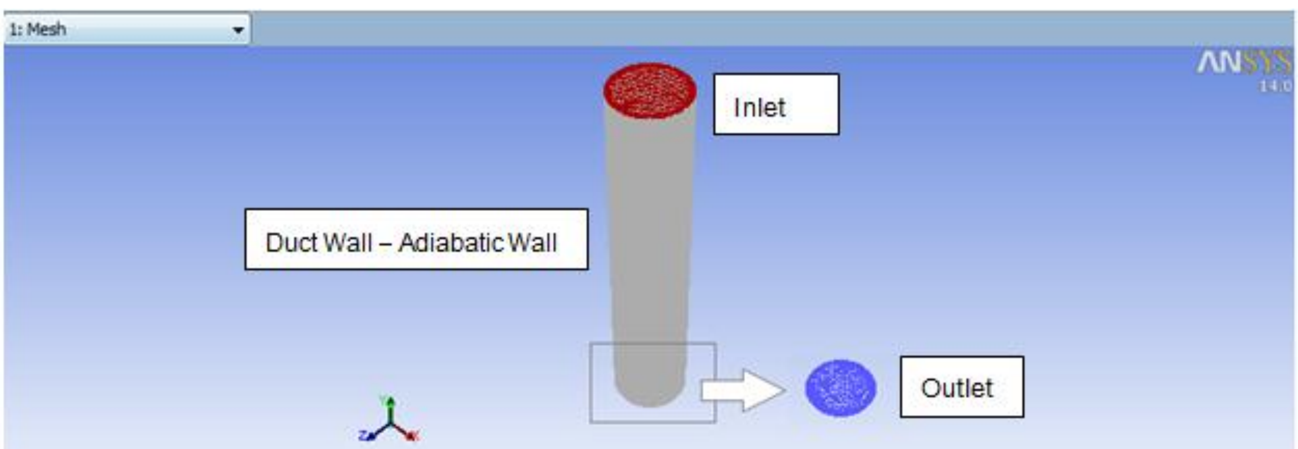


Figure 5-17 Inlet and Outlet for waste heat duct

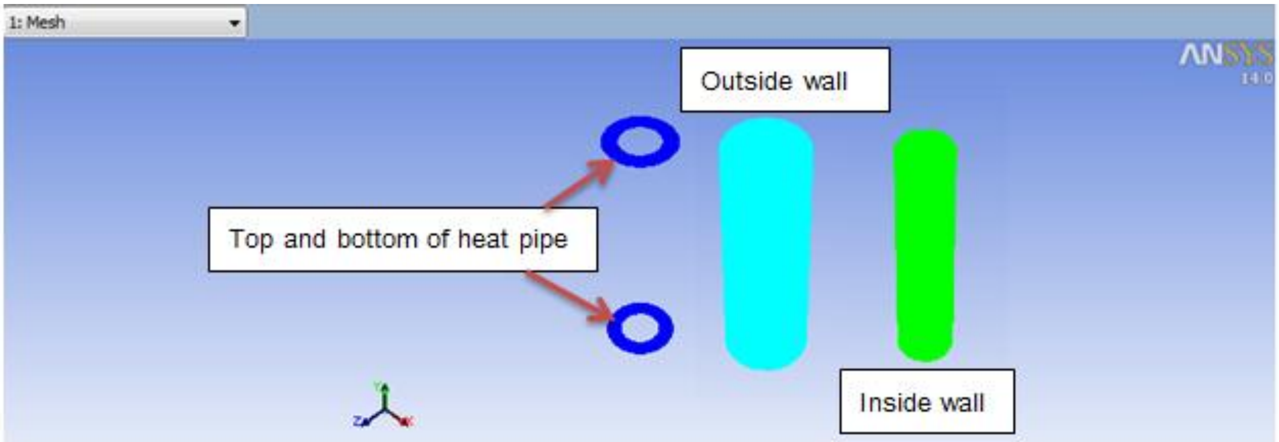


Figure 5-18 Different zones of heat pipe

Table 5-4 Boundary Conditions

Boundary name	Description	Parameter	Value in the model
Inlet	Inlet for incoming stream of hot air		
		Velocity [m/s]	Range of 2-12
		Turbulance Intensity[%]	4-5% depending on the Re
		Hydraulic Diameter [m]	0.3
		Temperature[K]	Range of 423-573
Outlet	Pressure Outlet		
		Gauge Pressure[Pa]	0
Duct Wall	Adiabatic wall		
		Stationary Wall	
		Heat flux[w/m^2]	0
Heat pipe Walls	Constant temperature Wall		
Top- inside & outside walls		Stationary Wall	
		Temperature[K]	Range of 373-523
Heat pipe Walls	Constant temperature Wall		
Bottom wall		Stationary Wall	
		Temperature[K]	Range of 363-513

Model

The energy, mass and momentum conservation equations were considered along with the turbulence model. From the boundary conditions the Reynolds number was calculated. The flow of waste heat stream is well into the turbulent flow regime. The k-epsilon model was used. In the Reynolds Averaged Navier-Stokes (RANS) approximation, k is the mean value of the kinetic energy of the turbulent fluctuations, i.e. the fluctuations around the mean value of the turbulent, fluctuating velocity. Epsilon is the dissipation of the kinetic energy of the fluctuations, i.e. the rate at which the energy of turbulence is dissipated from the flow, eventually in the form of heat. The k-epsilon has good convergence rate and relatively low memory requirements and it performs well for external flow problems around complex geometries.

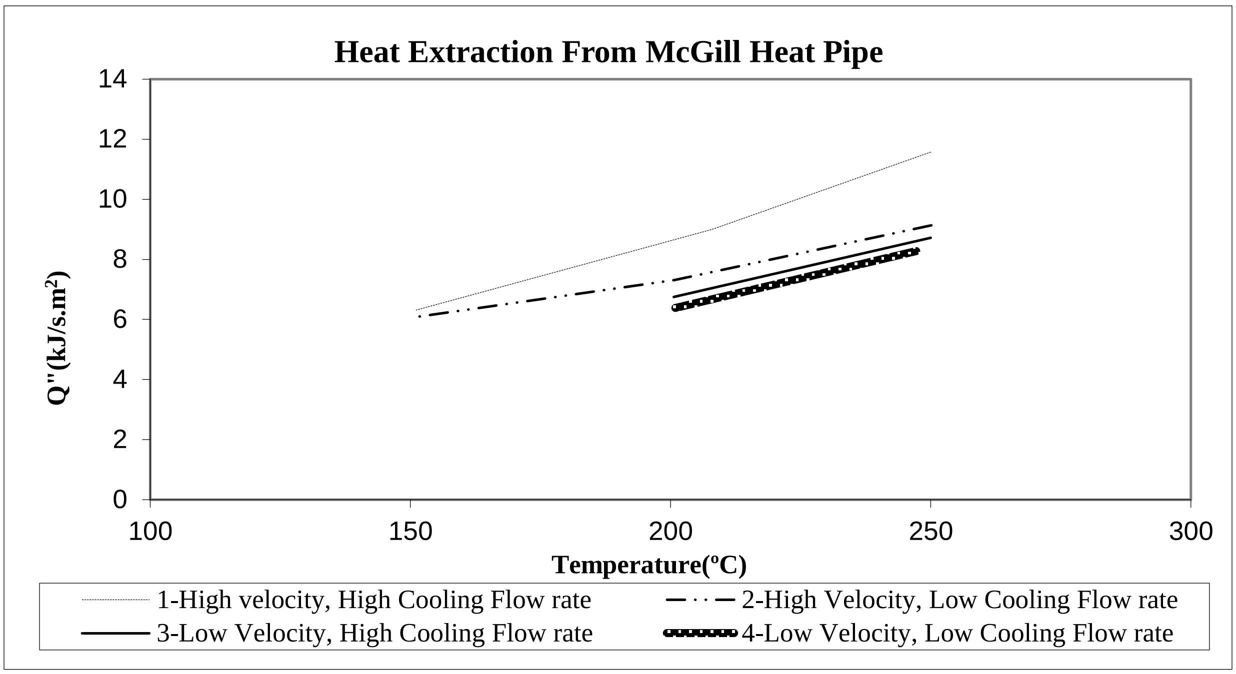
Chapter 6 Experimental Procedure & Modeling

As shown in Figure 5-1, the overall heat extraction system consists of 3 stages. While the working substance in each stage can be different, water is used in all stages for this research. The heat engine comprises the second stage. The engine is fed pressurized vapor (steam in our example).The steam is generated in the condenser of the first stage where the vapor that the waste heat generates condenses and in so doing boils the liquid working substance used in stage 2- the heat pipe engine.

The engine is a piston-cylinder configuration. It generates mechanical rotation which drives the power generator unit. The pressurized (saturated) vapor in the engine pushes the piston as it expands. As it does, some vapor condenses. At some point the low pressure vapor (and liquid) is forced into the condenser. It was decided that it would be much more effective to have a single condenser external to our engine that could be used by any number of engines. For this purpose a heat exchanger running on a water cooling system is used. The vapor is completely condensed to liquid in Stage 3 (the heat rejection unit) by extracting heat from the unit. The condensed liquid in stage 2 is pumped (i.e. repressurized) and vaporized with the heat provided by stage 1 and the cycle repeats.[78]

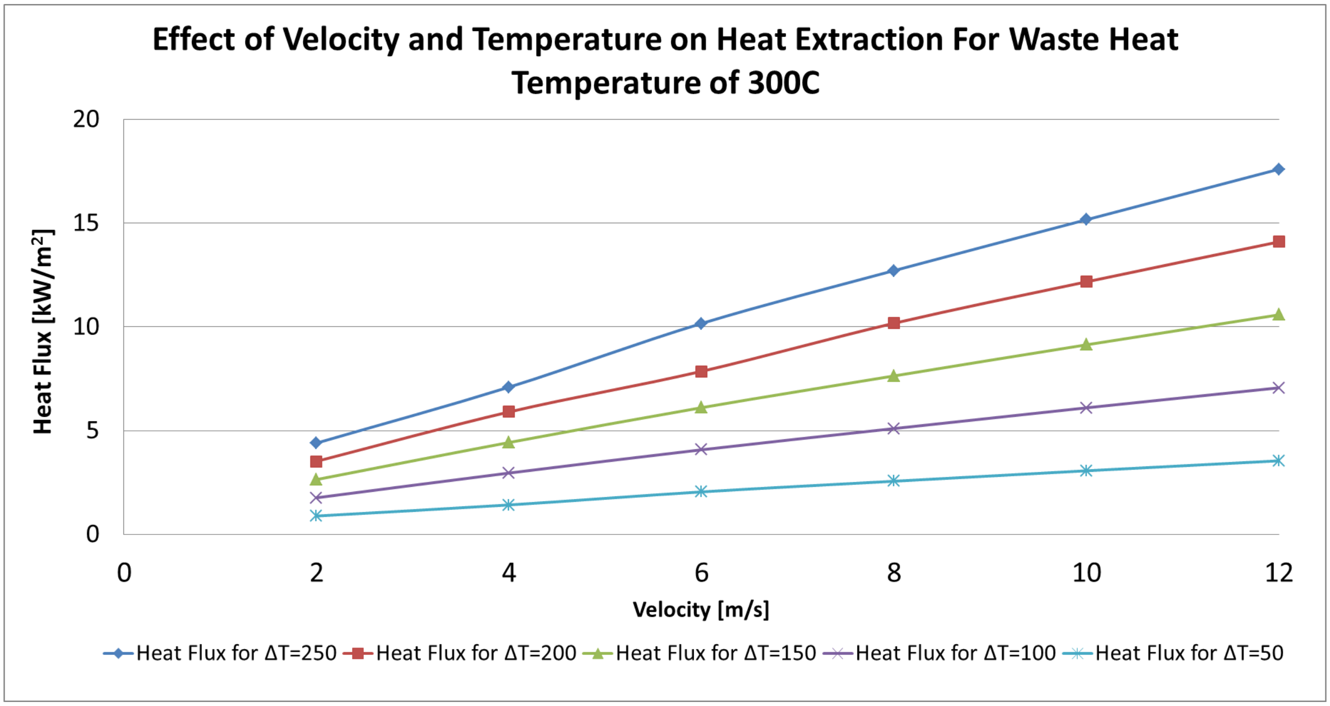
The first stage relates to the capture and concentration of waste heat with heat pipes. This work has been successful and has yielded positive results which are detailed in reference [77]. The experiments were performed on a stream of hot air with the temperature varying between 150^0C and 250^0C and with a velocity of hot air changing from 5 m/s to 12 m/s and with a mass flow rate of cooling water set to 10 and 20 ml/s. The findings of the work showed that it is not only possible to capture waste heat but it can be concentrated by as much as a 50:1 ratio (based on surface area). As demonstrated in Figure 6-1, the velocity of the waste heat stream has a vital role in energy extraction from waste heat due to direct effect of turbulence created around the heat pipe. At higher velocities there is an increase in the convection heat transfer to the heat pipe. Also the quality of waste heat (temperature) is of importance. The higher the temperature of the heat stream, the higher is the rate of energy extraction.

Figure 6-1 Effect of waste heat temperature and velocity and cooling rate in energy extraction



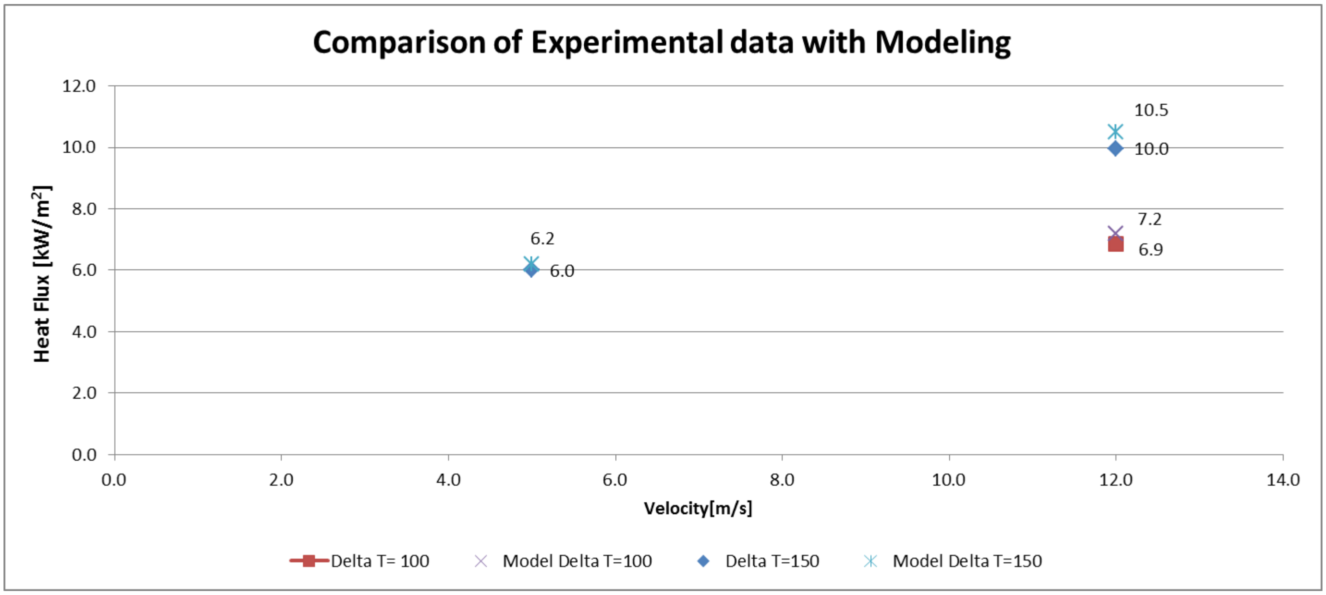
Since the experimental results were limited to the laboratory equipment, computational fluid dynamic modeling was done to compare the previous experimental design and to predict future applications of heat pipes for waste heat extraction. The result of the modeling that was discussed in the previous chapter is shown in Figure 6-2. The modeling was performed for waste heat temperature ranging between 150ºC and 300ºC. The velocity of the waste heat stream was considered in the range on 2[m/s] to 12[m/s]. The heat pipe temperature was varied between 100ºC and 250ºC depending on the temperature of the incoming flow of hot air. All graphs have the same trends with minimal differences as the results are dependent more on the temperature difference between the stream of waste heat and the heat pipe rather than on the temperature of waste heat stream alone.

Figure 6-2 Effect of velocity and temperature on extracted energy with McGill heat pipe for waste heat of 300°C



A comparison between the experimental results and the model was performed. Figure 6-3 illustrates the results. This graph is based on the temperature difference between the waste heat stream and the heat pipe verses the velocity of waste heat flow. It is evident that although in modeling, results can be calculated for low temperature and velocities, in reality it is not possible to achieve these results. The results that were compared in Figure 6-3 are the correspondence values in the model. They agree with 95% accuracy for the higher temperature difference ($\Delta T=150^0C$) however no data could be collected for lower temperature difference ($\Delta T=100^0C$) at lower velocity.

Figure 6-3 Comparison between Model and Experiments



Experimental setup and procedure

The energy extraction stage of the cycle was completed before this study and the results were discussed in the author's thesis [77]. However, following that work a series of events forced us to comply with new directives of McGill University facilities and as a result the procedure of providing the waste heat stream to the heat pipe was modified such that heaters were installed on the outer wall of the heat pipe instead of having a flow of hot air. One should note that the closure of the lab in the Wong building and subsequent operational difficulties that were imposed in the Frank Dawson Adams building seriously compromised the integrity of our research. The use of band heaters instead of hot air flow is one example of how we had to change our designs to accommodate the circumstance. These heaters are ceramic band heaters that are capable of providing the heat pipe with adequate temperature and heat flux (Figure 6-4).

Figure 6-4 Ceramic band heater [68]

Four heaters were installed on the heat pipe (Figure 6-5). Ceramic band heaters produce approximately 32 $kW/m^2$of heat flux. The inner diameter is 0.273 m and the width is 0.14m. Each requires up to 15 amps and 240 VAC single-phase electricity. They are connected to solid-state relays and a programmable temperature controller (Figure 6-6). Two extra heaters were installed for further expanding the experiments but during this research were not used.

Figure 6-5 Ceramic band heaters on the evaporator of heat pipe

The thermocouple that contols the temperature is located at the bottom of the heat pipe. There are 4 other thermocouples installed on different height of the heat pipe to provide feedback about the proper functioning of the heat pipe as well as information about vapor generation inside the heat pipe.

Figure 6-6 Temperature controller of heaters

The thermocouples are connected to National Instrument thermocouple input module (NI 9211) and the data are recorded with LabView program.

The steam produced by the heat extraction unit is stored in the steam reservoir. A pressure transducer and a thermocouple are placed on the steam reservoir. A valve is installed on the passage of the steam to the engine. It allows building up the pressure inside the steam reservoir. A pressure transducer is placed on the passage of steam to the engine (Figure 6-7) and one at the exhaust of the engine

Figure 6-7 - Pressure transducer on the steam flow path

The data from the pressure transducers are recorded with National instrument bridge analog input module (NI 9237). Figure 6-8 demonstrates the data acquisition program in LabView that reads both temperature and pressure information from the control devices.

The pressure measurements are used to determine the work output from the engine. With a non-contact tachometer, the RPM of the engine is measured. Using PLAN (Pressure, Length of Stroke, Area and RPM) formula, the work produced by the engine can be calculated.[80]

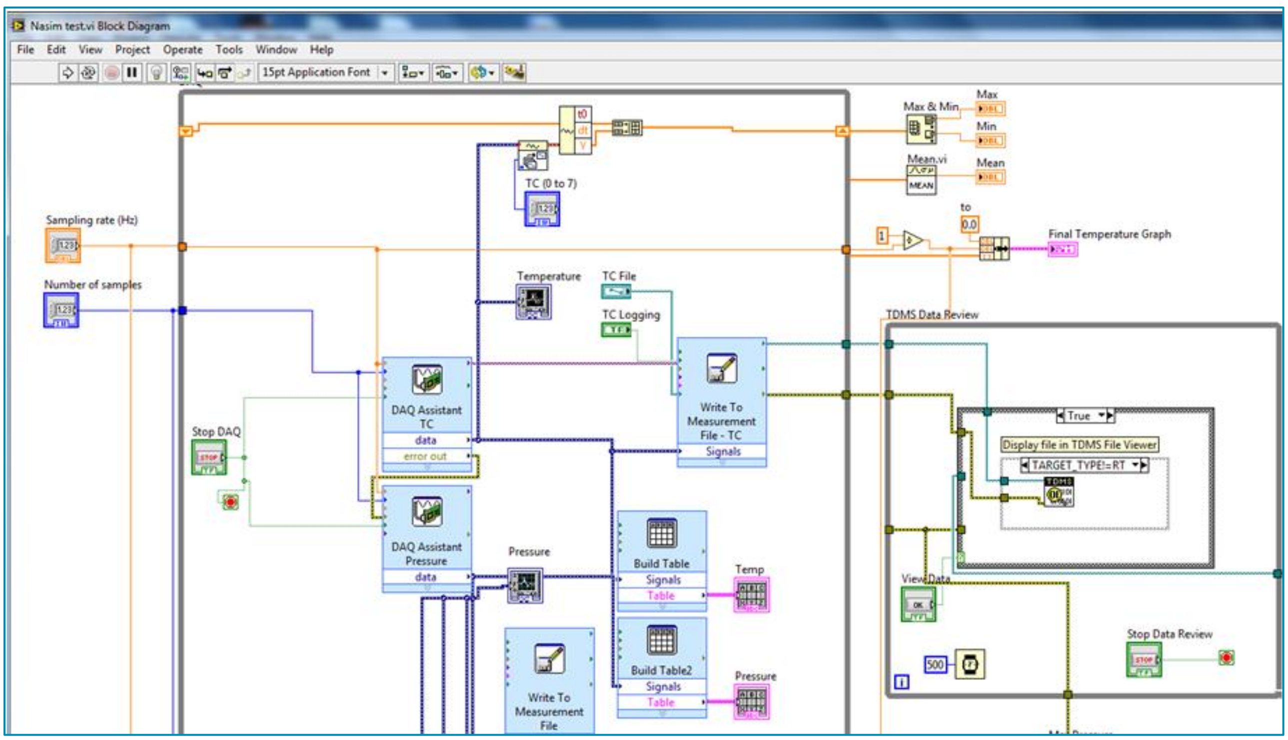


Figure 6-8 - LabView Code for recording temperature and pressure data

Designing the experiment

The next step is to select variable parameters that will affect the energy conversion. It is obvious that the temperature of the waste heat stream is an important factor. Thus the first variable is the temperature of the source. This is the temperature that the heat pipe will experience and directly affects the temperature of the produced steam.

The second variable is the pressure behind the engine's piston. The minimum pressure required for the engine to function properly and the maximum pressure that the system will achieve at a certain temperature of waste heat flow will determine the extent of the experiment.

The last variable is the volume of fluid inside the heat pipe evaporator. The proper volume of fluid in the evaporator has a significant effect on both performance of the heat pipe and operation of the engine. Overfilling the heat pipe causes the excess liquid to partially fill the condenser and may cause an increase in the thermal resistance and consequently decrease in the heat transfer. On the other hand under filling the heat pipe reduces the maximum heat transfer.[68]

Therefore in this research 4 filling volumes of water in the heat pipe were considered. In each scenario, 4 groups of waste heat temperature were applied. For each temperature, 5 different pressures were tested.

- Volume of fluid in heat pipe: Full- 3/4 -1/2-1/4 capacity of heat pipe
    - Temperature applied on heat pipe: 300-250-200-150^{0}C
        - Pressure range: 15-20-25-30-35 Psi (Gauge)

Experimental Procedures

The heat pipe is first filled with the desirable volume of water. The total volume of the heat pipe is 0.033 m^3 or 33 liters. Therefore for full- 3/4-1/2-1/4 capacity of heat pipe the volume of water would be 32 – 24 – 16 – 8 liters respectively. The next step is heating up the heat pipe to create steam and store it in the steam reservoir. When appropriate pressure in the reservoir is achieved, the valve will be opened and the steam is directed to the engine. At this point the RPM of the engine is recorded.

Phase One

In the first phase, exploratory tests were carried out to delineate the following parameters:

- Amount of working fluid in the heat pipe
- Minimum and maximum pressure
- Minimum temperatures applied on the heat pipe

Amount of Working Fluid in The Heat Pipe

The tests were run with 1/4 of the heat pipe filled:

At 150^{0}C the pressure of steam in the reservoir did not exceed 15 Psi. The engine did not work at this condition.

At 200^{0}C the pressure of steam in the reservoir did not exceed 25 Psi. The RPM of the engine was recorded as 400 for 25 Psi , 260 for 20 Psi. The run of the engine was less than 10 seconds.

At 250^{0}C the pressure of steam in the reservoir did not exceed 30 Psi. As soon as the valve is opened the pressure drops significantly and only the RPM of the engine was recorded as 410 for 25 Psi. The run of the engine was less than 10 seconds.

The same tests repeated for heat pipe filled to its half capacity. Similar results were obtained. The engine would run for less than 20 seconds. The fluctuation in the results were so high that although some data could be recorded but it was not enough to be analyzed. Since these two sets of tests were not sustained runs, it was concluded that the amount of fluid in the heat pipe is not enough to produce and maintain the steam flow. Therefore the volume of liquid filling 1/2 and 1/4 volume of the heat pipe were disregarded.

Minimum and Maximum Pressure

The engine was run with compressed air to obtain the minimum pressure at which the engine would start working. This was recorded at 12 Psi. However this is not true with steam. Since steam is a condensable gas, at low pressures, the steam condenses in the cylinders of the engine and impends the engine from performing work. During the test it was observed that the engine does not perform well (or in some cases at all) with pressure of the steam under 20 Psi. Thus the tests planned for pressure of steam under 20 Psi were disregarded.

More tests were run to obtain the maximum pressure that can be produced. In all cases obtaining 35 Psi was possible. Exceeding 35 Psi was only possible at 300ºC waste heat temperature while the heat pipe was filled with water at full or 3/4 of the capacity of the heat pipe.

Minimum Temperatures Applied on The Heat Pipe

Other sets of tests were conducted to determine the minimum temperature of the waste heat stream that can produce work. It was observed that at 150ºC no pressurized steam is produced. Therefore the minimum temperature for the experiments was set at 200ºC.

Phase Two

In this phase the actual tests were run and the results were recorded for analysis. Table 6-1 presents the overall results of the experiment. In the next chapter this results are discussed in greater details.

Table 6-1Final results of the experiments

Volume of liq in heat pipe[lit]	Heat pipe Temperature[^{o}C]	Reservoir pressure [Psi]	Mean Pressure[Psi]	RPM	Power [watt]
24	200	20	18.39	673	341.4
		25	21.73	819	491.0
		30	27.15	850	636.4
		35	28.45	921	722.6
	250	20	18.40	721	365.8
		25	22.17	896	547.9
		30	25.52	966	679.9
		35	29.78	1000	821.5
	300	20	18.55	890	455.5
		25	22.11	1004	612.2
		30	26.47	1030	751.9
		35	30.45	1060	890.4
32	200	20	19.26	694	368.7
		25	21.98	824	499.5
		30	27.52	924	701.3
		35	30.18	1010	840.7
	250	20	19.92	785	431.3
		25	21.73	975	584.2
		30	27.66	1030	785.8
		35	29.83	1046	860.7
	300	20	23.11	1020	650.2
		25	27.02	1050	782.6
		30	30.51	1065	896.3
		35	36.68	1135	1148.4

Chapter 7 Results and Discussion

From the results the following are chosen for discussion:

- Effect of volume of liquid in the heat pipe
- Effect of the temperature of the waste heat stream
- Effect of the mean pressure of the steam
- Effect of condenser's pressure

But before starting to go through the above results and discussion, it is necessary to calculate the values of the mean pressure of the input steam and the work produced by the engine.

Next section is dedicated to these calculations.

Calculations of Values

As discussed in chapter 3, the work done by the engine per stroke is:

$$W = P_m \times V_s$$

Where,

P_m the mean effective pressure is calculated with values of input pressure (P_i) and back pressure (P_b) and the fraction of the stroke completed at cut off (1/r). The pressure values are recorded during the experiments and "r" value is provided by the steam manufacturer as 70%.

$$P_m = \frac{P_i}{r}[1 + \ln r] - P_b\ [Pa]$$

V_s the swept volume is calculated with the cylinder bore (D) and length of stroke (L). These values are also provided by the engine manufacturer:

$$V_s = \frac{\pi}{4} D^2 L\ \ [m^3]$$

The indicated power for double acting engine is calculated with the values of the mean effective pressure (P_m), the swept volume (V_s), and the RPM of the engine (N):

$$Power = \frac{2P_m \times L \times N}{60}\ [W]$$

Work done per minute is:

$$W = P_m \times L \times N \times 2A$$

Thermal efficiency is calculated with mass of consumed steam (m_s), enthalpy of supplied steam to the engine (h_i) and enthalpy of water returned to the condenser (h_f):

$$\eta_{Th} = \frac{Indicated\ Power}{Heat\ supplied}$$

$$\eta_{Th} = \frac{Power}{m_s \times (h_i - h_f)}$$

Results

Effect of Volume of Liquid in the Heat Pipe:

The volume of working fluid in the heat pipe affects the continuous production of steam and therefore the performance of the engine. As the volume increases the amount of power produced was increased. This effect can be seen in Table 6-1 in the previous chapter.

Effect of Condenser's Pressure

The back pressure directly affects the mean effective pressure. Low back pressure increases the expansion ratio of steam. This in turn increases the efficiency of the cycle. The lower the back pressure the higher would be the work output from the engine.

Comparison of the Results Based on the Waste Heat Temperature

The higher the waste heat temperature, the higher the quality of the waste heat and therefore more energy can be extracted. With increase of waste heat temperature, the extracted heat flow increases. Therefore it should have the same direct effect on the overall work output. The results contain 2 factors: Temperature and its corresponding pressure of incoming steam. It can be interpreted that with the increase in waste heat temperature, the possibility of achieving higher steam pressures and higher steam temperature increases. The results of the experiments support the above idea and are shown in Table 7-1 through Table 7-4 and Figure 7-1 through Figure 7-4 summarize the results:

Table 7-1 Effect of temperature on the work output for operating steam pressure 20Psi

Volume of liq in heat pipe[lit]	Heat pipe Temperature[^oC]	Reservoir pressure [Psi]	Mean Pressure[Psi]	RPM	Power [watt]
24	200	20	18.39	673	341.4
	250	20	18.40	721	365.8
	300	20	18.55	890	455.5
32	200	20	19.26	694	368.7
	250	20	19.92	785	431.3
	300	20	23.11	1020	650.2

Figure 7-1 Effect of temperature on the work output for operating steam pressure 20Psi

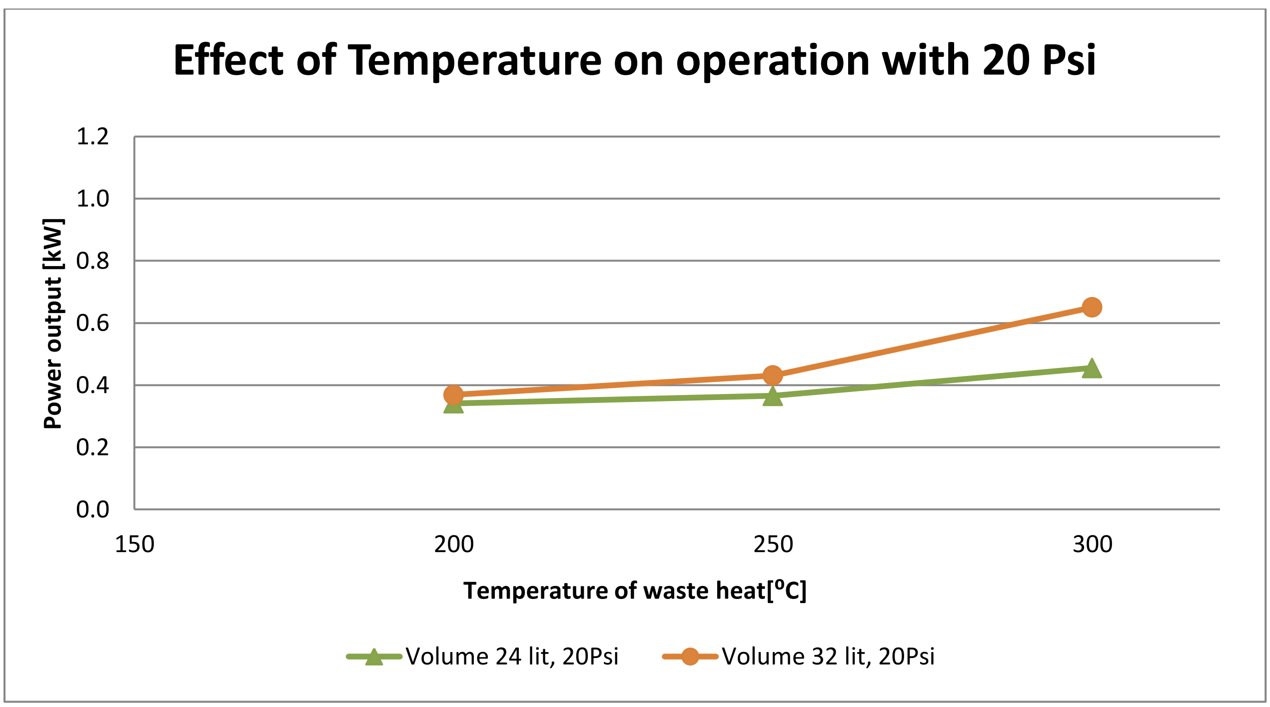


Table 7-2 Effect of temperature on the work output for operating steam pressure 25Psi

Volume of liq in heat pipe[lit]	Heat pipe Temperature[^oC]	Reservoir pressure [Psi]	Mean Pressure[Psi]	RPM	Power [watt]
24	200	25	21.73	819	491.0
	250	25	22.17	896	547.9
	300	25	22.11	1004	612.2
32	200	25	21.98	824	499.5
	250	25	21.73	975	584.2
	300	25	27.02	1050	782.6

Figure 7-2 Effect of temperature on the work output for operating steam pressure 25Psi

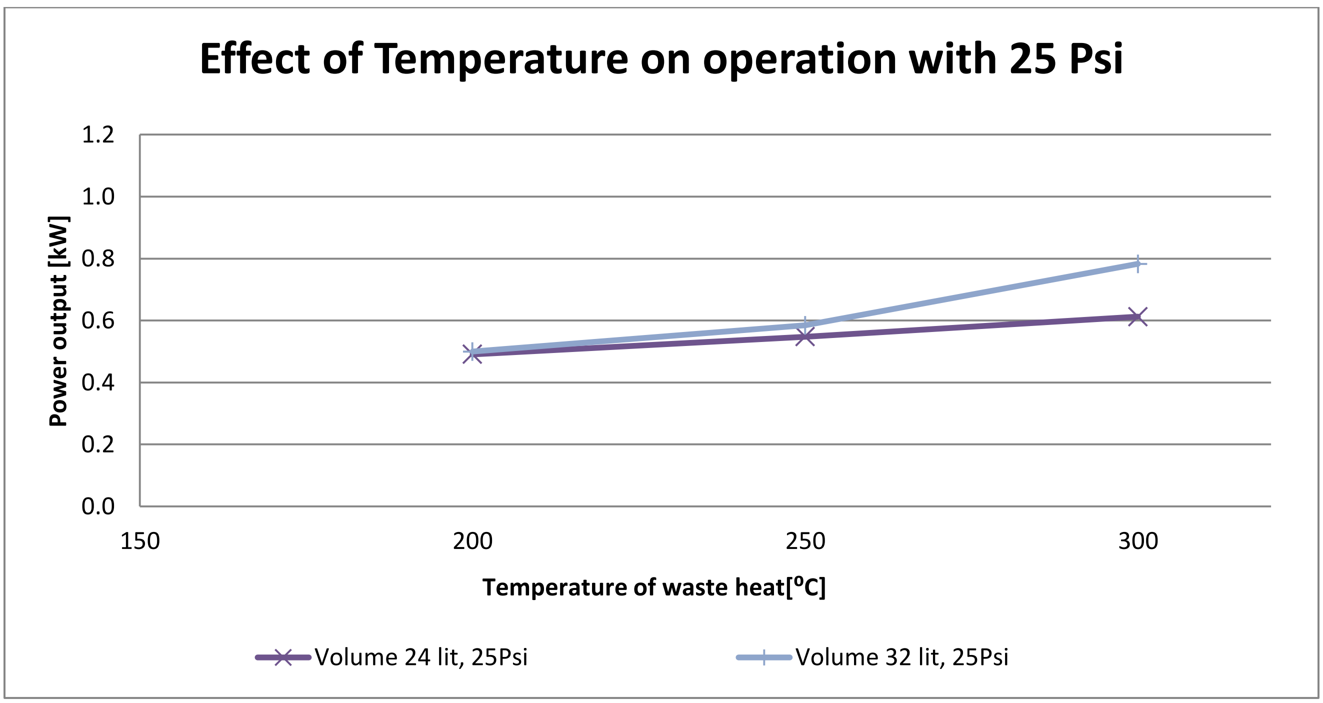


Table 7-3 Effect of temperature on the work output for operating steam pressure 30Psi

Volume of liq in heat pipe[lit]	Heat pipe Temperature[^oC]	Reservoir pressure [Psi]	Mean Pressure[Psi]	RPM	Power [watt]
24	200	30	27.15	850	636.4
	250	30	25.52	966	679.9
	300	30	26.47	1030	751.9
32	200	30	27.52	924	701.3
	250	30	27.66	1030	785.8
	300	30	30.51	1065	896.3

Figure 7-3 Effect of temperature on the work output for operating steam pressure 30Psi

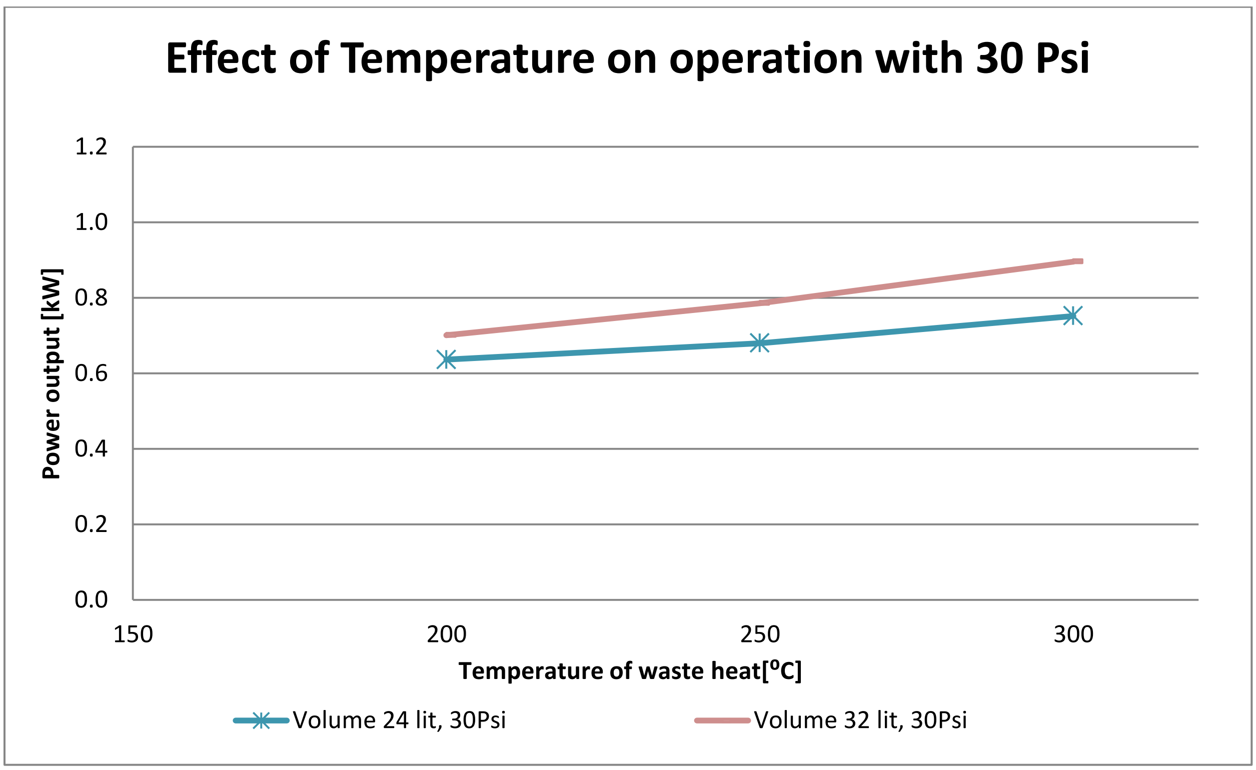
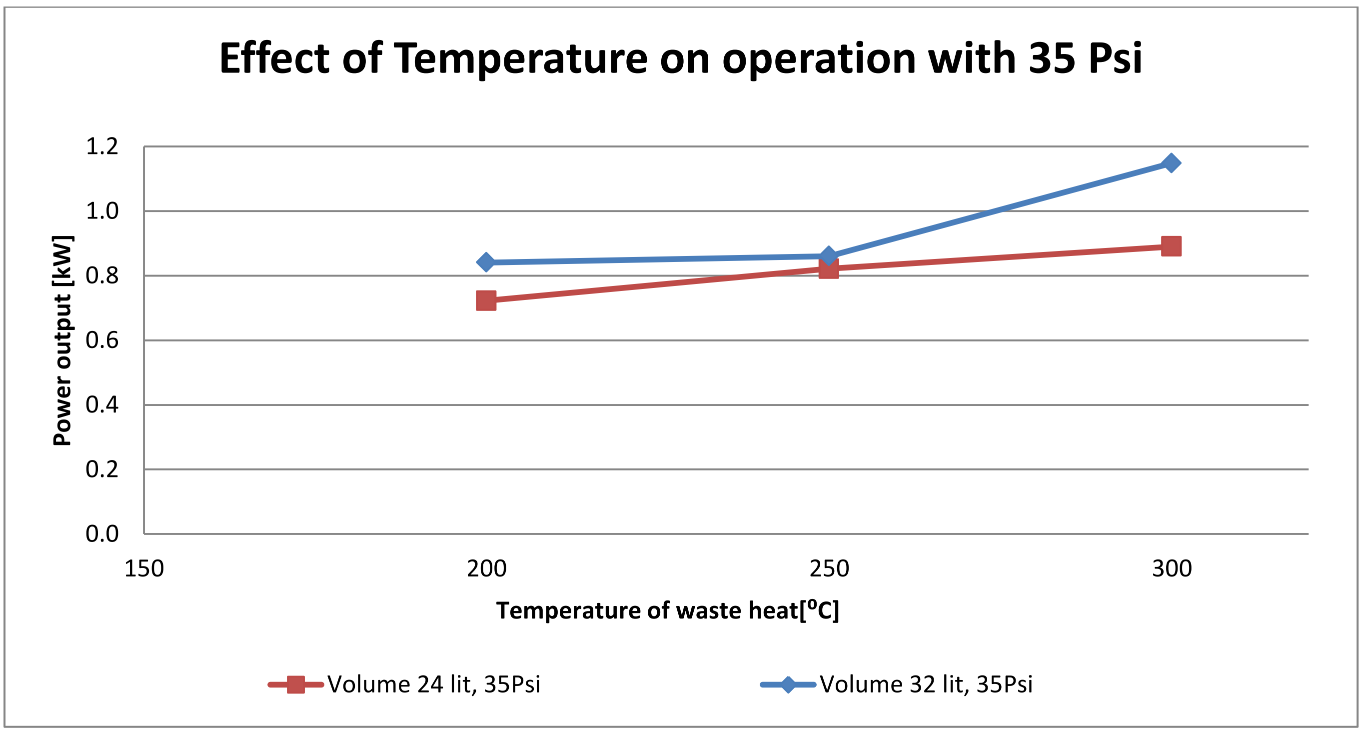


Table 7-4 Effect of temperature on the work output for operating steam pressure 35Psi

Volume of liq in heat pipe[lit]	Heat pipe Temperature[°C]	Reservoir pressure [Psi]	Mean Pressure[Psi]	RPM	Power [watt]
24	200	35	28.45	921	722.6
	250	35	29.78	1000	821.5
	300	35	30.45	1060	890.4
32	200	35	30.18	1010	840.7
	250	35	29.83	1046	860.7
	300	35	36.68	1135	1148.4

Figure 7-4 Effect of temperature on the work output for operating steam pressure 35Psi



Effect of the Mean Pressure of Steam

Mean effective pressure of the steam admitted to the engine is proportional to the work output, indicated power and thermal and mechanical efficiency of the engine. It is evident that as the mean effective pressure of the steam increases, the work output and the power of the engine will increase.

The results of the experiments which support the above statements are listed in Table 7-5 and Table 7-6 and illustrated in Figure 7-5 and Figure 7-6:

Table 7-5 Effect of Mean effective pressure on the work output for heat pipe 3/4 of volume full

Volume of liq in heat pipe[lit]	Heat pipe Temperature[^oC]	Reservoir pressure [Psi]	Mean Pressure[Psi]	RPM	Power [watt]
24	200	20	18.39	673	341.4
		25	21.73	819	491.0
		30	27.15	850	636.4
		35	28.45	921	722.6
	250	20	18.40	721	365.8
		25	22.17	896	547.9
		30	25.52	966	679.9
		35	29.78	1000	821.5
	300	20	18.55	890	455.5
		25	22.11	1004	612.2
		30	26.47	1030	751.9
		35	30.45	1060	890.4

Figure 7-5 Effect of Mean effective pressure on the work output for heat pipe 3/4 of volume full

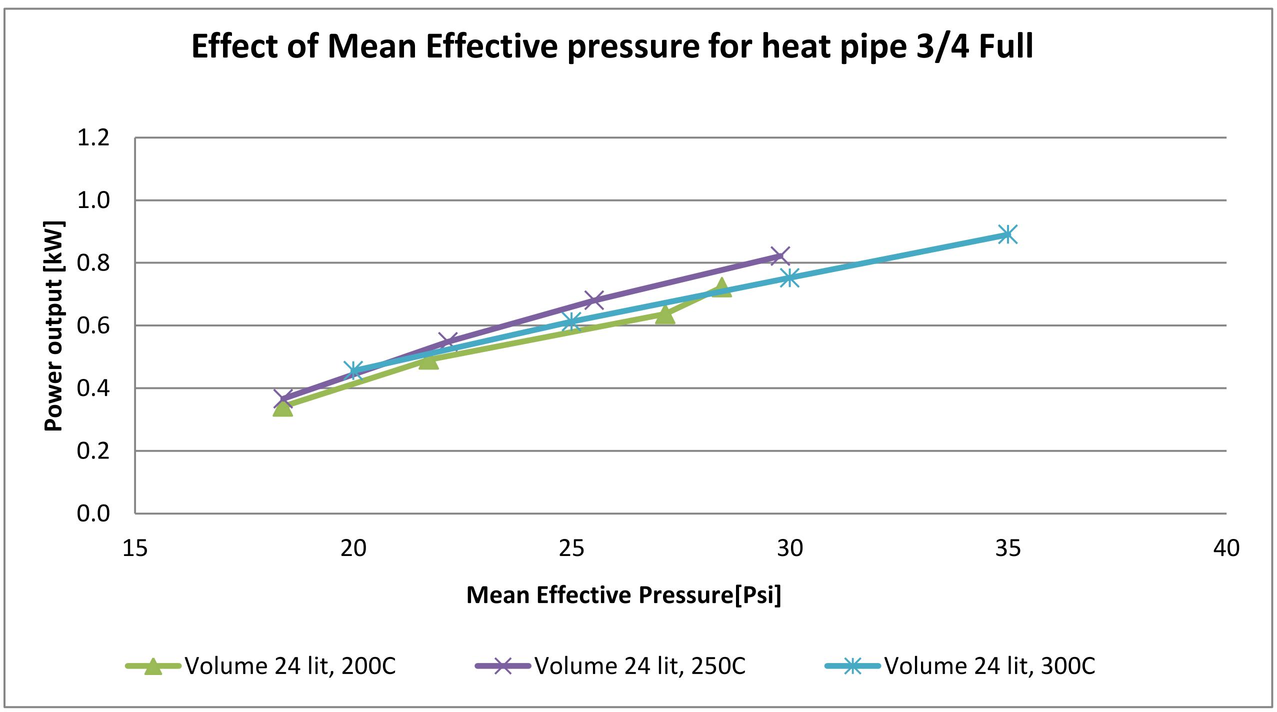
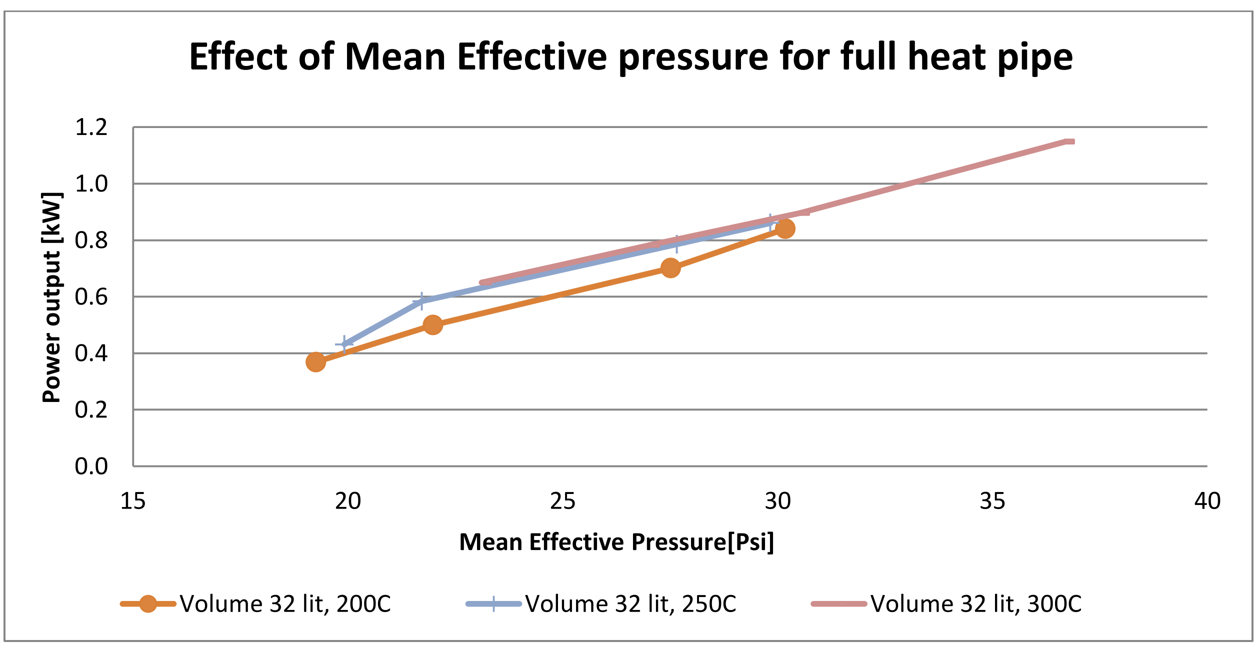


Table 7-6 Effect of Mean effective pressure on the work output for heat pipe full

Volume of liq in heat pipe[lit]	Heat pipe Temperature[^oC]	Reservoir pressure [Psi]	Mean Pressure[Psi]	RPM	Power [watt]
32	200	20	19.26	694	368.7
		25	21.98	824	499.5
		30	27.52	924	701.3
		35	30.18	1010	840.7
	250	20	19.92	785	431.3
		25	21.73	975	584.2
		30	27.66	1030	785.8
		35	29.83	1046	860.7
	300	20	23.11	1020	650.2
		25	27.02	1050	782.6
		30	30.51	1065	896.3
		35	36.68	1135	1148.4

Figure 7-6 Effect of Mean effective pressure on the work output for heat pipe full



Discussions

To be able to analyze the results appropriately two comparisons were performed:

- Comparison of the thermal efficiency of the system
- Comparison of the relative efficiency

Relative efficiency is defined as:

$$\eta_{Relative} = \frac{\eta_{Thermal}}{\eta_{Carnot}}$$

Equation 7-1

Comparison of The Thermal Efficiency of The System

To obtain the thermal efficiency of the system, the heat added to the system and the heat rejected from the system was calculated based on the enthalpy of steam or water at each state. The values are extracted from the steam tables for the corresponding temperatures. These temperatures were recorded with various thermocouples places on the heat pipe, steam reservoir, and condenser.

The results of this comparison are presented in Figure 7-7 and Figure 7-8. This comparison provided rather different prospective. Although in the results the higher power output corresponded with higher temperature and pressure, the efficiency of the system does not follow the same path. The efficiency of this system was higher for the lower temperature of the waste heat flow. As the temperature of the waste heat increases, the work done is increased too; however this is achieved at the cost of extra heat supplied to the system and thus the thermal efficiency decreases. At higher temperatures the effect of pressure however becomes stronger than the effect of temperature. And that is illustrated as the big jump on the graph for data of 300ºC curves in Figure 7-7.

Figure 7-7 Comparison of thermal efficiency for heat pipe filled full capacity

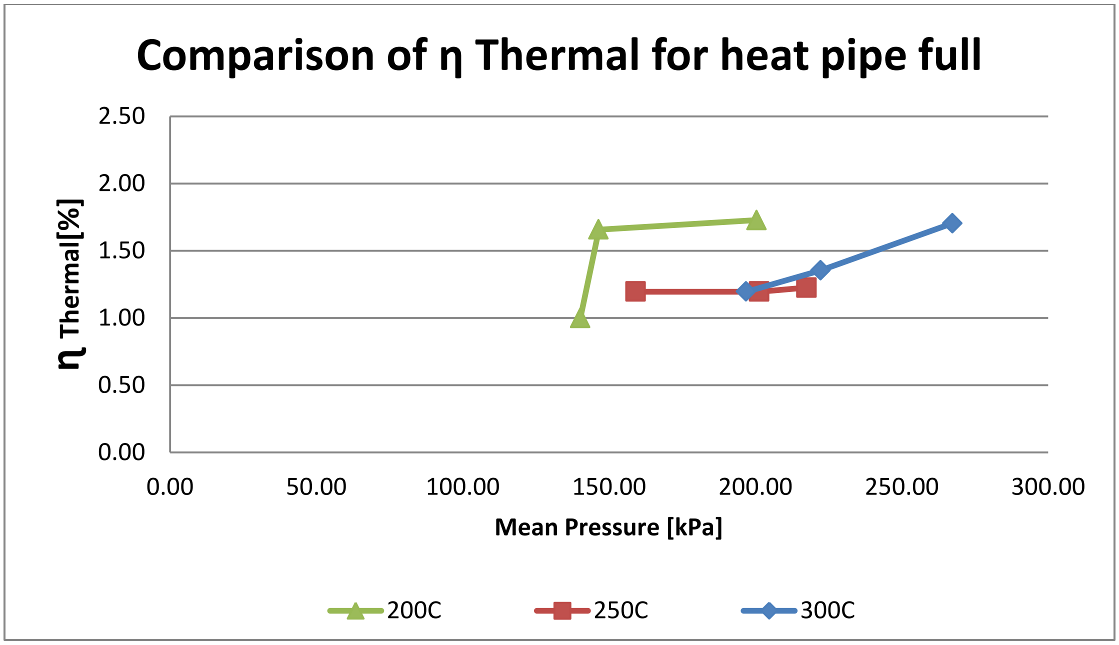
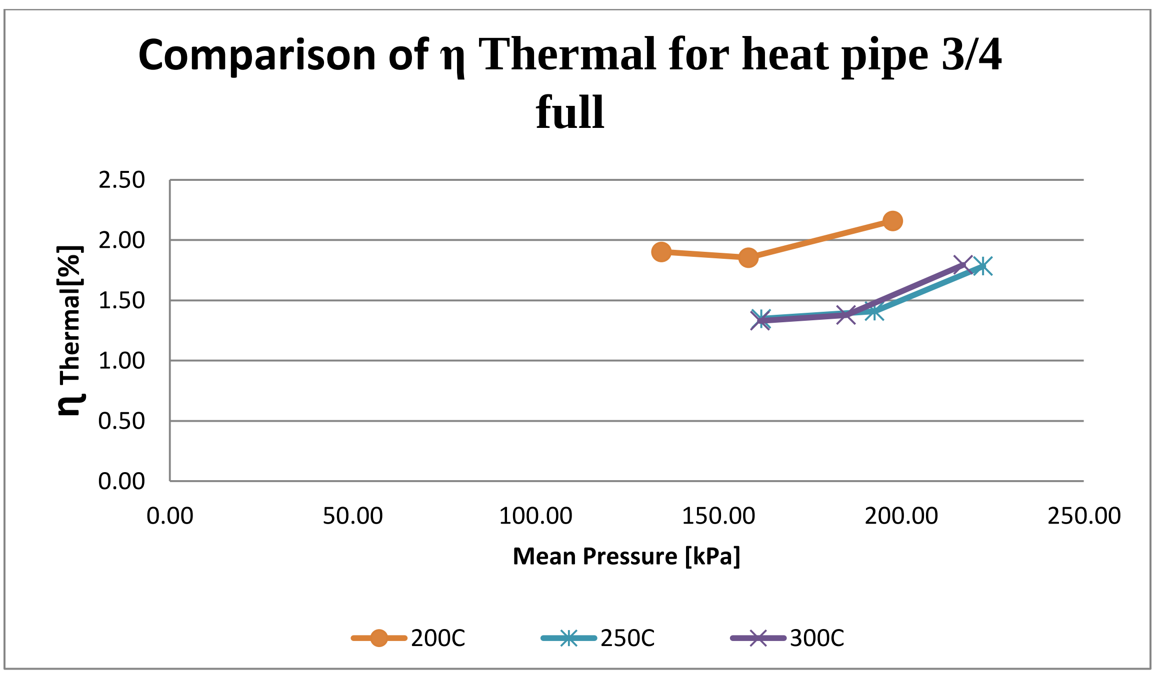


Figure 7-8 Comparison of thermal efficiency for heat pipe filled 3/4 capacity



Comparison of Relative Efficiency

The relative efficiency of a system demonstrated the effectiveness of the system. Carnot efficiency is the maximum theoretical efficiency that a system could hypothetically achieve. The relative efficiency on the other hand, illustrates how realistic it is to select an approach. As illustrated in Figure 7-9 and Figure 7-10, the efficiency of the heat pipe cycle is 19-22% of the Carnot efficiency. However, at higher temperature and pressure a decrease in the relative efficiency is observed. This can be explained as the effect of high temperature on the thermal efficiency in the proposed system.

Figure 7-9 Relative efficiency for heat pipe filled full capacity

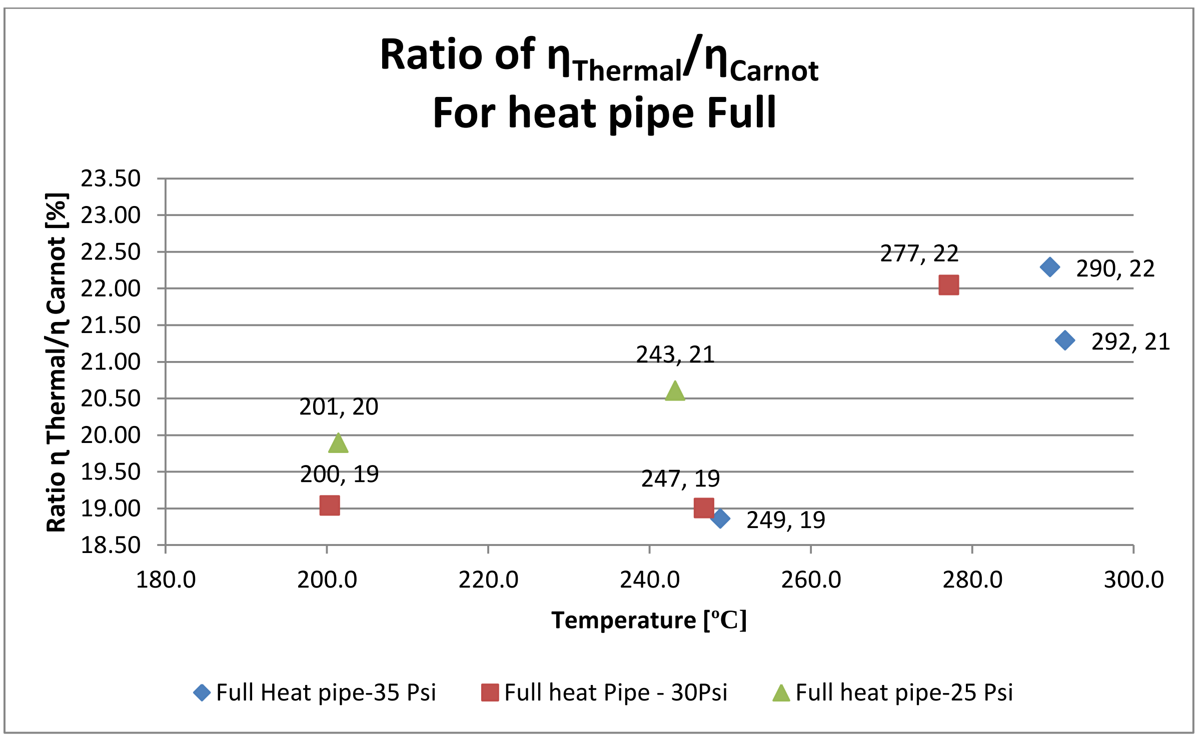
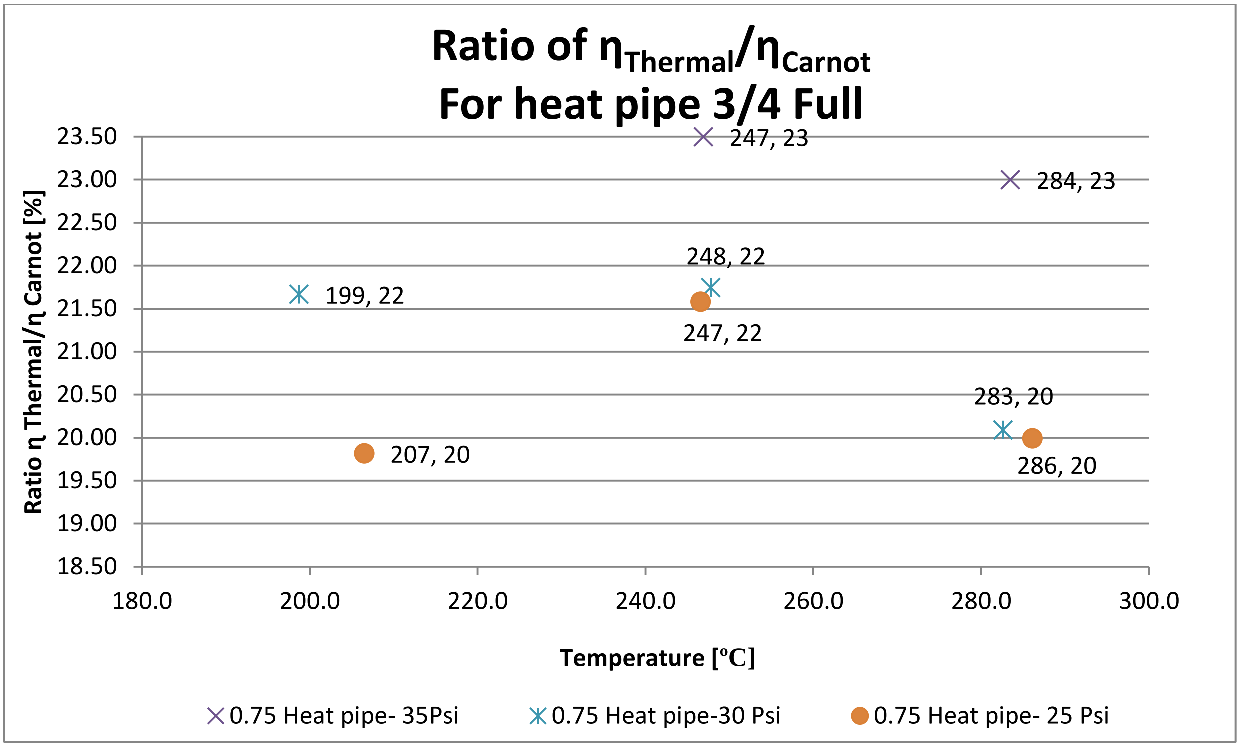


Figure 7-10 Relative efficiency for heat pipe filled 3/4 capacity



Economic Viability of the Heat Pipe Cycle

Table 7-7 summarizes the payback period for the different setups. The results are based on the payback method that was discussed in Chapter 4 and the cost of the pilot project unit used in this research.

As it is expected the payback year is directly proportional to the power output of the engine. Therefore for the higher pressure of the steam, the payback year is lower.

Table 7-7 Payback year for different experiment's scenarios

Volume of liq in heat pipe[lit]	Heat pipe Temperature[^oC]	Reservoir pressure [Psi]	Power [watt]	Kwh for 1 year	Net saving per year	PB year
24	200	20	341.4	2543.4	203.5	49.1
		25	491.0	3657.8	292.6	34.2
		30	636.4	4741.7	379.3	26.4
		35	722.6	5383.9	430.7	23.2
	250	20	365.8	2725.5	218.0	45.9
		25	547.9	4082.1	326.6	30.6
		30	679.9	5065.3	405.2	24.7
		35	821.5	6120.3	489.6	20.4
	300	20	455.5	3393.3	271.5	36.8
		25	612.2	4561.0	364.9	27.4
		30	751.9	5602.2	448.2	22.3
		35	890.4	6633.4	530.7	18.8
32	200	20	368.7	2746.6	219.7	45.5
		25	499.5	3721.7	297.7	33.6
		30	701.3	5224.6	418.0	23.9
		35	840.7	6263.8	501.1	20.0
	250	20	431.3	3212.9	257.0	38.9
		25	584.2	4352.7	348.2	28.7
		30	785.8	5854.2	468.3	21.4
		35	860.7	6412.2	513.0	19.5
	300	20	650.2	4844.2	387.5	25.8
		25	782.6	5830.5	466.4	21.4
		30	896.3	6677.3	534.2	18.7
		35	1148.4	8555.7	684.5	14.6

However this is the study of one heat pipe in the stream of hot air. In reality there would be a number of heat pipes extracting the energy and a larger engine would be used to convert this energy to mechanical work.

Let's put this idea into prospective. In Chapter 5 the cost of the pilot setup was estimated at $10,000. This includes 1 heat pipe and 1 engine with a power of 3hp. Our study shows that the average mechanical work produced by this system is about 1hp. If we increase the number of heat pipes to 3, the increase in cost is only related to the new evaporator section of the heat pipes. This change will impose an extra $3000 on the setup cost. This would result in a 56% reduction in payback year. Table 7-8 shows the comparison in details.

Table 7-8 Comparison of pay back years with expanding the design for 3 heat pipes

Volume of liq in heat pipe[lit]	Heat pipe Temperature[°C]	Reservoir pressure [Psi]	Power [watt]	Power [watt] for 3 heat pipes	Kwh for 1 year	Net saving per year	PB year for 3 heat pipes	PB year for 1 heat pipe	% of decrease in Pay back years
24	200	20	341.4	1024.2	7630.2	610.4	21.3	49.1	56.7
		25	491.0	1472.9	10973.3	877.9	14.8	34.2	56.7
		30	636.4	1909.3	14225.0	1138.0	11.4	26.4	56.7
		35	722.6	2167.9	16151.6	1292.1	10.1	23.2	56.7
	250	20	365.8	1097.5	8176.4	654.1	19.9	45.9	56.7
		25	547.9	1643.8	12246.4	979.7	13.3	30.6	56.7
		30	679.9	2039.7	15196.0	1215.7	10.7	24.7	56.7
		35	821.5	2464.5	18360.9	1468.9	8.9	20.4	56.7
	300	20	455.5	1366.4	10179.9	814.4	16.0	36.8	56.7
		25	612.2	1836.6	13682.9	1094.6	11.9	27.4	56.7
		30	751.9	2255.8	16806.5	1344.5	9.7	22.3	56.7
		35	890.4	2671.1	19900.3	1592.0	8.2	18.8	56.7
32	200	20	368.7	1106.0	8239.8	659.2	19.7	45.5	56.7
		25	499.5	1498.6	11165.1	893.2	14.6	33.6	56.7
		30	701.3	2103.8	15673.8	1253.9	10.4	23.9	56.7
		35	840.7	2522.2	18791.4	1503.3	8.6	20.0	56.7
	250	20	431.3	1293.8	9638.8	771.1	16.9	38.9	56.7
		25	584.2	1752.7	13058.0	1044.6	12.4	28.7	56.7
		30	785.8	2357.3	17562.5	1405.0	9.3	21.4	56.7
		35	860.7	2582.0	19236.6	1538.9	8.4	19.5	56.7
	300	20	650.2	1950.6	14532.6	1162.6	11.2	25.8	56.7
		25	782.6	2347.8	17491.6	1399.3	9.3	21.4	56.7
		30	896.3	2688.8	20032.0	1602.6	8.1	18.7	56.7
		35	1148.4	3445.1	25667.1	2053.4	6.3	14.6	56.7

Expanding this idea with a 10 horse power engine and 10 heat pipes would increase the initial cost by $15000; however the payback years will be reduced by 75%. In large industrial scale the heat pipe cycle may be considered as an economically viable process.

Chapter 8 Conclusions

The conclusions from the experimental results presented in this thesis are summarized as follows. It should be noted that all the results are based on having water as working fluid in all 3 units of the heat pipe cycle.

As an overall conclusion, it can be stated that conversion of waste heat to mechanical power is possible with heat pipe cycle with thermal efficiencies relative to the Carnot efficiency ranging between 19-23%.

Effect of The Volume of The Liquid in The Heat Pipe

- The maximum power output from the heat pipe full of liquid is 1148 watt and for heat pipe filled at 3/4 is 890 watt.
- The minimum power output from the heat pipe full of liquid is 368 watt and for heat pipe filled at 3/4 is 341 watt.
- The relative efficiency of the cycle is higher when the heat pipe is filled at 3/4.
- For heat pipes filled at 1/4 and half, proper data could not be achieved as the pressure of the steam fluctuates greatly.

Effect of Temperature of Waste Heat

- At waste heat temperature of 150°C, obtaining steam pressure of 20Psi is impossible.
- Waste heat temperature of 200°C is necessary to have the heat pipe cycle functional.
- At waste heat temperature of 300°C, obtaining steam pressure of 60Psi is possible however, 300°C is considered as medium grade waste heat.

- The thermal efficiency of the heat pipe cycle is higher for lower grade temperatures.
- Heat pipe cycle is not suitable for medium grade temperatures.

Effect of Pressure of Steam

- Minimum incoming steam pressure of 20Psi is required for the heat pipe cycle to be functional.
- At temperature of 200°C and 250°C producing pressure higher than 35 Psi is not possible.

Efficiency

- Heat pipe cycle demonstrated higher efficiencies for low grade thermal energy compared to medium grade thermal energy.
- The maximum Carnot efficiency of heat pipe cycle considering different temperatures and pressures is about 10%.
- The maximum thermal efficiency obtained in this research was 2%. This corresponds to the situation of 200°C and 30 Psi when the heat pipe is filled at 75% water as working fluid.
- The minimum thermal efficiency obtained in this research was 1%. This corresponds to 200°C and 20 Psi when the heat pipe is filled at 100% water as working fluid.

Statement of Originality

In the research presented in this thesis, McGill heat pipe technology and steam engine were used to form a novel heat cycle. Although neither heat pipe nor steam engines are new technologies, the combination of the two is distinct. The heat pipe cycle showed potential as a low grade thermal recovery solution. The original contributions from this work are explained below.

Through the application of McGill heat pipes and steam engine a truly distinct heat and power cycle has been developed and demonstrated as a viable complementing process for any industrial processes that produce large quantity of waste heat.

A Novel Heat Cycle to Recover Low Grade Thermal Energy

The waste heat with temperature under 300°C is often released to atmosphere with minimum attempt to recover it. The heat pipe cycle is a novel process to capture this waste heat and convert it into valuable form of energy i.e. electricity or mechanical shaft work.

The heat pipe cycle is the first heat cycle based on the science of the modified Rankine cycle that does not require the input of extra energy to create superheated steam. Superheat steam is a necessity in heat cycles using turbines to create electricity. The heat pipe cycle overcomes this challenge by employing a reciprocating engine.

Using water as working fluid in such low temperatures is another distinct aspect of the heat pipe cycle. This is achieved by extracting energy from waste heat using the McGill heat pipe to capture the energy of waste heat and concentrate it. Water's safe nature makes it a superior fluid to use when compared to many working fluids currently in use in the organic Rankine cycle.

The heat pipe cycle tests are the first successful tests of the recovery of low grade thermal energy by employing the combined McGill heat pipe technology and reciprocating engines using water as working fluid.

Future Work

As noted in the thesis there are large quantities of waste heat produced every day by various processes. The quantities of recoverable energy are so great that they may compensate for the relatively low efficiencies. Thus, it would be of great benefit if this project and prototype move to the next level of assessment. Considering the lab restrictions that this project encountered, the integrity of the project was seriously affected. Nonetheless, it is recommended that the research presented in this thesis be considered as a foundation for a number of other projects including but not limited to the following outlined below:

Experiments

Performing the experiments with the original setup

Because of the limitations in the lab facilities, it was not possible to test the original setup. An alternative design as described in the thesis was tested instead. The original setup was to simulate the flow of hot air similar to the flow of effluent gas in the exhaust ducts in industry. Thus the design of the heat pipe was based on the source of energy being the flow of hot air. The heat pipe is the main component in this research. By modifying the source of energy, the heat pipe could not perform to its full potential. The experiments with the original setup may yield enhanced results and they certainly will be more representative of reality.

Performing the experiments with various working fluids

The stream of hot gases with temperatures lower than 150°C did not provide any results in this research. However this doesn't mean that the energy stored in hot air of 150°C or less cannot be recovered. In this research it was presented that the pressure of vapor/steam on the piston has the highest impact on the overall energy output. If one can provide high vapor pressures at low temperatures then the heat pipe cycle can be tested for lower temperatures. We are confident that such testing would yield meaningful results. This testing can be achieved by studying the effect of working fluids other than water. There has been extensive research on various working fluids used in the ORC but there is none for the heat pipe cycle.

Researching real data from the industries and performing a comprehensive analysis

Industries may be in possession of much information about their waste heat production. This information may include data on the temperatures of different waste heat streams in various processes within the plant, the quantity of released waste heat and/or the chemical contamination of the waste heat streams. The information, if provided by industry, can be of benefit for establishing the extent of the application of the heat pipe cycle. These data can then be used to compare with the experimental results and be used to propose a suitable model.

Performing in-depth analysis of economic viability

In this research a brief economic study was performed; however the viability of this project is highly affected by the economics. A detailed economic analysis of the heat pipe cycle is essential.

Modeling

CFD modeling the boiling phenomena inside the heat pipe

The CFD modeling in this research was limited to the study of the behavior of the heat pipe under various circumstances. The boiling phenomena inside the heat pipe are extremely complex. The heat pipe that was used in this research is not a conventional heat pipe and modeling the centrifugal forces inside the heat pipe would be a significant contribution to scientific knowledge.

Thermodynamic modeling of the heat pipe cycle

The T-S diagram is a useful tool to demonstrate the heat transfer process within various segments of the heat pipe cycle and to analyze the cycle. Indeed creating the T-S diagrams requires detailed information about the various parts of the cycle. Thus the thermodynamic modeling complements the experimental results when they are carried out as a package.

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