RECYCLING LOW GRADE WASTE HEAT TO ELECTRICITY

*N. Razavinia, F. Mucciardi and F. Hassani

McGill University
Mining &Materials Engineering
Wong Building
3610 University Street
Montreal, Quebec H3A 2B2
*(*Corresponding author: nasimalsadat.razavinia@mcgill.ca)*

M. Al-Khawaja

Mechanical Engineering
Qatar University, Qatar

RECYCLING LOW GRADE WASTE HEAT TO ELECTRICITY

ABSTRACT

Most mining and metallurgical industries produce relatively large quantities of low grade waste heat which they vent, for the most part, to the environment. To date, little is being done to recover some of this heat and transform it from low grade to a high grade energy form such as electricity. A few decades back this was also true of paper, plastics and metals. Recycling was not a prominent activity. Today, we all know that it is and that recycling is a must for sustainable development. To this end, we feel that we are now at that point in time when the recycling of waste heat to electricity must be given serious consideration. By recycling waste heat one can achieve at least one if not two of the 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.

We have developed a process that captures, concentrates and converts (3 C's) waste heat to electricity. The process comprises 3 distinct interacting units. 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. It also uses heat pipe technology to achieve this. The combination of the 3 units forms a unique system for recycling waste heat. This paper describes the system and it presents some results that show how the system can be made to be economically viable.

KEYWORDS

Waste heat, low grade energy, geothermal energy, heat pipe, external combustion engine, energy recovery, electricity

INTRODUCTION

Production of energy from renewable sources was initiated in the late 20th century. The rapid depletion of fossil fuel reserves along with the environment pollution caused by the misuse of this main source of energy was one of the predominant motives for scientist and engineers to explore every possibility to move from the traditional fossil fuel based energy to green energy production. This resulted in extensive researches in the production of energy from renewable sources and improvements in efficiency of current technologies.

The most attractive characteristic of renewable resources is their infinite nature. Employing renewable energy also contributes to a green environment. However the energy available from renewable sources is much less concentrated than that provided by fossil fuels and nuclear energy. This makes the processes based on renewable energy less efficient and more costly for large scale industrial uses in most cases.

Governments' policies and subsidies in favor of renewable energy opened the doors to a new era in the field of renewable energy: the production of energy from renewable sources at a cost that is competitive with fossil fuels. The sun, wind, water and biomass were the first renewable sources to be explored; however they are limited by the environmental condition and they require relatively large investments. Geothermal and waste off gases from industries and mines are the next group of renewable resources to explore. This energy is often referred to as low grade waste heat. Most of this energy is simply vented to the environment. In the future it will be necessary to capture and convert some of the low grade heat to a valuable form such as electricity if we are to improve on the efficiency of energy usage.

The authors are exploring the possibility of producing a valuable form of energy from low grade thermal energy which until recently was simply discarded.

Current State of Energy in Canada

A statistical study by U.S. energy information administration office shows that non-renewable sources of energy (petroleum, coal, natural gas and uranium) constituted 62% of the total energy sources, shown in Figure 1 (US Energy, 2012). The renewable sources of energy (biomass, hydropower, wind, solar and geothermal) comprised the remaining 38%. Industries consume 37% of total energy consumption. Primary metal manufacturing and the non-metallic mineral production sector consume 27.7% of produced energy. Mining industry alone uses about 4% of total energy production. What the reports and statistics do not show is how much of the energy which is fed to a process or a device is then dissipated as waste heat. It is estimated that over 100 tetra joules/year of waste heat which is typically less than 250^{o}C is dissipated from industrial processes to the environment (CanmetENERGY, 2008). What has been notable until recently is that this source of energy was discarded and there was little attempt to recover some of this low grade waste heat.

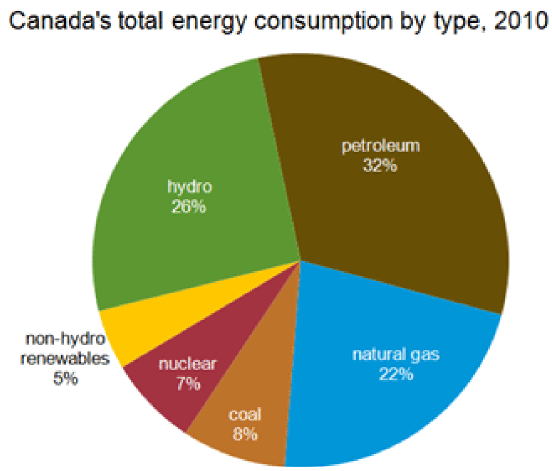


Figure 1 - Total energy consumption in Canada by type (US Energy, 2012)

In the future, industries will be more inclined to capture and convert low grade energy to a valuable form such as electricity. This is the result of the pressure from societies and governments for reduction in both fossil fuel energy reserves consumption and environment pollution. However, the first steps should be taken by the researchers to devise ways by which this can be done. In light of this, the primary objective of our research is to increase the efficiency of energy usage by capturing some of the 'waste' heat in such process streams as off-gases and then converting this heat to a valuable energy form such as electricity. Subsequent sections of this paper describe how we propose that low grade energy be captured, concentrated and converted to a valuable form such as electricity.

OBJECTIVES & METHODOLOGY

Our overall objective of the research is to demonstrate that the capture, concentration and conversion of waste heat into electricity (the 3 C's) are viable from a scientific prospective and that they are economically feasible. Our approach is summarized by the following statements:

1) To develop heat pipe technology to the point that it can capture and concentrate low grade waste heat.
2) To develop an engine that can convert the concentrated energy into electricity.
3) To couple the heat pipe and engine to create the Heat Pipe-Engine combo that can take waste heat and transform it into electricity at efficiency levels which will make it competitive with (subsidy free) wind and solar power.

For the purpose of this paper, our objective is to introduce the reader to the subject of the 3 C's and the cycle's major units i.e. the heat pipe and the engine – both of which have been developed at McGill University.

HEAT PIPE TECHNOLOGY

Heat Pipe Theory

A heat pipe is a heat transfer device that utilizes the vaporization and condensation of a working substance contained within to move energy from the evaporator section to the condenser section. It is, in effect, a 'superconductor' of heat energy. Tests have shown that a heat pipe can be as effective in transporting energy as 1,000 times the equivalent quantity of copper under similar heat transfer conditions. In the following section we first describe a conventional heat pipe and subsequently we describe our patented heat pipe design which we refer to as the McGill heat pipe and will be used in this study.

Conventional Heat Pipe

For the purpose of illustrating the operation of a conventional heat pipe, it is instructive to consider the simple orientation illustrated in Figure 2. The heat pipe consists of a sealed pipe shell, circular or otherwise, containing a working substance (e.g. water, thermex, sodium etc.). During heat pipe operation, heat is introduced to the pipe from the heat source. At this section of the heat pipe, the working substance evaporates (#1 in Figure 2). Thus, the section of the heat pipe exposed to the heat source is termed the 'evaporator'. The vapour flows (#2) to the heat sink section of the heat pipe (the 'condenser') where it condenses on the pipe wall (#3) and returns to the evaporator by gravity in liquid form (#4). One will note that the classical heat pipe depicted in Figure 2 involves two-phase counter current flows. The reader is directed to the work in the reference list (Peterson, 1994) for additional details.

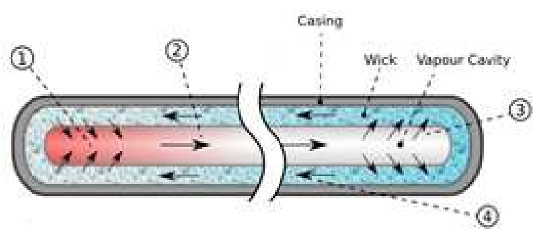


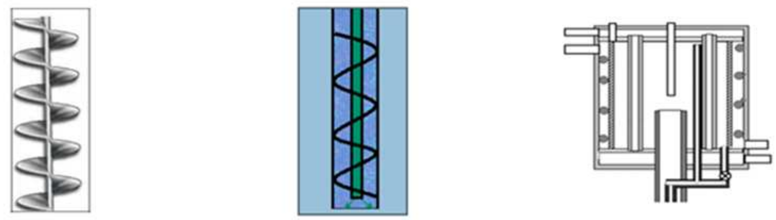
Figure 2 - Schematic of the conventional heat pipe (Wikipedia, 2006)

New Developments in Heat Pipe Technology – McGill Heat Pipe

A heat pipe that has been produced by evacuating the free space can transport heat over a wide temperature range even at negative gauge pressures that approach relatively low values (e.g. 0.01 atm). However, it has several significant disadvantages especially if the liquid phase has a relatively low thermal conductivity. A major difficulty that arises is the formation of a stable vapour film on the surface of the containment wall. This vapour film can act to separate the liquid from the wall. When this happens we have a condition referred to as film boiling. With the onset of film boiling, heat transfer at the interface decreases rapidly by as much as 90% or more. This phenomenon is well documented in the literature and has been confirmed many times by our research group (F. Mucciardi, Zheng, 2000).

When water is the working substance, film boiling usually becomes a rate limiting parameter even at low heat fluxes. It is for this reason that water based heat pipes have seen limited success and essentially no success at high heat fluxes. This was true until we developed the McGill heat pipe which has turned this situation around. The McGill heat pipe as described in the next section has led to the development of a new generation of heat pipe technology.

In 2006, McGill University was granted US Patent 7,115,227 (F. Mucciardi, Gruzleski, Zheng, Zhang, Yuan, 2006). The inventors came up with a new configuration for the heat pipe that could overcome the 2 most serious limitations of a conventional heat pipe. One of these is film boiling and the other is the levitation of liquid from the leading end of the heat pipe. The new heat pipe, termed the McGill heat pipe (see Figure 3), overcomes these limitations by incorporating 2 features in the design in such a way as described in the literature to form the McGill heat pipe.



An example of a heat pipe swirler — Evaporator of the McGil heat pipe — Condenser of the McGil heat pipe

Figure 3 - Distinct features of McGill heat pipe

One of the deficiencies was the occurrence of film boiling even at low heat fluxes (especially when the operating pressure was low). The McGill heat pipe has been shown to overcome film boiling by creating a swirled flow within the heat pipe. A conventional heat pipe has the vapour moving longitudinally along the inside of the pipe. However, the McGill heat pipe rearranges the flow (primarily vapour) such that it is swirling. This causes the liquid phase within the flow to be pushed up against the heat pipe wall. An example of what a swirler might look like is shown in Figure 3.

Another aspect of the McGill heat pipe is that the configuration of the counter current flow which one typically finds in a conventional heat pipe has been converted to a co-current flow. In a conventional heat pipe, vapour moves upward from the evaporator to the condenser while liquid moves downward from the condenser to the evaporator. This is an unstable configuration which is prone to the levitation of liquid (i.e. entrainment) by the vapour flow. Thus, one cannot be certain that sufficient liquid returns to the extremes of the heat pipe. In the McGill heat pipe, this configuration has been modified such that the returning liquid from the condenser is carried to the extremities of the evaporator by a separate line. This avoids the entrainment problem and it ensures sufficient return of liquid. Schematics of the evaporator and the condenser as embodied in the patent are shown in Figure 3.

ENGINE

In our research at McGill we have designed an innovative waste heat engine which functions in a way that is similar to a heat pipe. The engine functions by controlling the quantity of working vapour on the intake stroke. Moreover, one can also control the absolute pressure of the working vapour. Increasing these parameters will increase the piston's power and speed. Our design focussed on maximizing the variability in operating parameters to experiment with power output and alternative working fluids. 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 vapour, we decided to call our engine – a heat pipe engine. The heat pipe 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 4. 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 shown by the dotted portions of Figure 4. With this design it is possible to add several engines to the system, without adding new boilers and condensers with each power producing engine. The boiler creates steam which is fed into the engine cylinder. An injection valve is used to control injection of steam into the engine cylinder. An exhaust valve controls the timing when the expanded steam is exhausted into the condenser. 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. A block diagram of the engine unit is also illustrated in Figure 4.

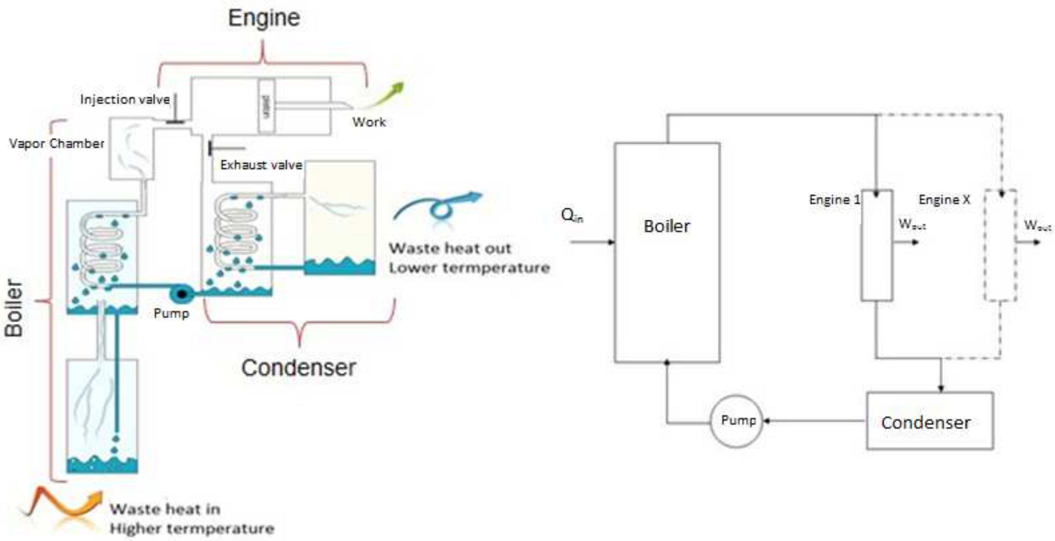


Figure 4 - Heat pipe cycle

The heat being provided is waste heat, and is therefore essentially free from a cost perspective. However, in order to maximize power output, thermal efficiency is an important consideration. The engine is being modelled using ideal processes to determine a first order approximation of the energy output. To measure the success of our engine design, certain metrics or quality characteristics were considered such as power output, size, efficiency, valve timing adjustability, the rate of steam injection and exhaust, cycle time of valves, boiler pressure control, cylinder pressure control and material requirements. Although this is not an exhaustive list, these characteristics were chosen as the most important metrics. The heat pipe engine design is based on steam. However, it is also designed for experimental use, and as such may use a working fluid besides water, such as an organic. In this paper working fluid and steam are both referred to and represent the same function.

ENGINEERING DESIGN

This paper describes the basis of the design of the waste heat recovery system that comprises 3 distinct (and separate) units. As described in the previous section the engine comprises central unit of the waste heat recovery system. As one can appreciate, the physical sizes of the unit will depend on a number of parameters. Thus, it is not possible at this early stage of the research to justify why certain parameters were sized the way they were. For now it suffices to state the overall design of the system was based on a 2 cylinder engine with dimensions given in. The heat capture unit and the heat dissipation unit were sized to satisfy the constraints imposed by the engine.

Heat capture Unit – Heat Pipe

As noted earlier, heat pipe technology is used to capture waste heat as well as to dissipate heat that cannot be converted. Thus the area of heat transfer is of great importance. To be able to increase the surface area without increasing the size of the device it is decided to make an annular heat pipe. The heat pipe is sized at an outer diameter of 25 cm, inner diameter of 15 cm, and length of 1 m to achieve a rate of heat transfer of 12 kW. It is nested in an external duct of 30 cm in diameter. It is important to note that 12 kW 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.

Engine

Improving the power output/size ratio of the engine is one of the primary goals of the project. A design which experiences fewer losses will likely have a larger ratio. Furthermore, systems which are able to perform a cycle more quickly are likely to have a higher power-to-size ratio since each cycle outputs a discreet amount of work in joules, increasing cycles per second increases output wattage. The engine design is likely to have the largest ratio, being able to run most quickly and experience the fewest losses. Ease of manufacturing and controlling and sensing properties are other factors in the design of this prototype.

Figure 5 shows the current design of the engine and Table 1 summarizes the engine parameters.

Table 1 – Engine's parameters

Diameter cylinder(m)	0.076 m
Piston Area (m^2)	0.0045 m^2
Height Bottom Dead Center (m)	0.025 m
Height Top Dead Centre (m)	0.049 m
Injection pressure (atm)	2 atm
Expanded Pressure (atm)	1 atm
Injection time (s)	0.15 s

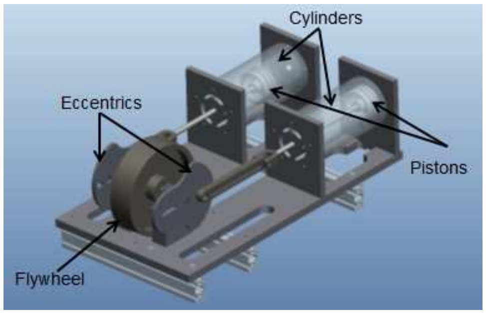


Figure 5- Double cylinder engine

Heat Dissipating System – Heat Exchanger

The purpose of the heat dissipater is to remove the excess waste heat that the heat pipe engine cannot convert to work. It intakes the wet steam leaving the heat pipe engine. In the heat dissipater, the rejected steam interacts with a fluid. Heat is transferred from steam to the fluid, and the steam is condensed to its liquid state which will be diverted back to the heat pipe via a pump, where the liquid will be re-vaporized to steam. This process can be accomplished using a radiator, or simply a system of interconnecting tubes. In this stage of the research, it was decided to design a heat exchanger and use a cool stream of water to achieve our goal. Cool water will flow through the coils and absorb heat from the working fluid. At the end of the coil, the water is now warmer than it was when it entered. This warm water can be used as a hot water source in the plant or factory, saving some energy normally used to power the hot water tank.

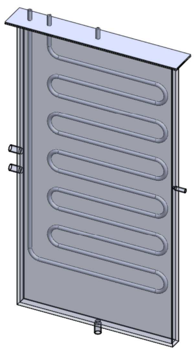


Figure 6 - Heat dissipater

As shown in Figure 6, there is a series of coils made out of copper, which are used to pass the cooling tap water through our system. The coils have an inner diameter of 7.7 mm and an outer diameter of

9.5 mm. They are arranged horizontally in a wave-like pattern, with 12 passes. Each pass has a length of 25 cm, and each pass is 5.08 cm apart from one another. The total footprint of the coil setup is approximately 66 cm by 36 cm. The coils are nested in a stainless steel chamber in the shape of a tall rectangular prism, which is 40 cm wide, 75 cm tall, and 3 cm thick.

RESULTS

Operating Results

As outlined in the objectives, the waste heat recovery system comprises 3 units. The first 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 (Razavinia, 2010), a thesis that was produced by one of the authors of this paper. 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).

Theoretical Results

The other component of the research focuses on the engine. We successfully made a heat pipe engine. The work done by this engine can be calculated from Equation 1 using the engine parameters listed in Table 1 (TDB and BDC are referred to Top Dead Centre and Bottom Dead Center respectively).

$$W = (P_{Boiler} - P_{Condenser}) * (V_{BDC}) + [((P_{Condenser} * (V_{TDC}) - P_{Boiler} * (V_{BDC}))/ (1-\Upsilon)] \quad \text{(Equation 1)}$$

$$W=46.8 \text{ [J]}$$

Using an assumed cycle time of 0.55 s, the power output would be 85 Watts per cylinder. Testing of the engines will begin May 2013. Preliminary results should be available at the time of the ISARC 2013 conference. The presentation will highlight some of the results.

ACKNOWLEDGMENTS

This publication was made possible by NPRP 09-1043-2-404 from the Qatar National Research Fund (a member of Qatar Foundation).The authors gratefully acknowledge the Qatar Foundation for funding this project.

REFERENCES

Canmetenergy. (2008). Conversion Of Low-Grade Waste Heat To Electricity. *Canmetenergy, Cetc Number 2008-56 / 2006-02-28.*

Mucciardi, F , Zheng. (2000). *Heat Transfer In The Boiling Regime.* Paper Presented At The J. M. Toguri Metallurgical Society Symposium.

Mucciardi, F, Gruzleski, Zheng, Zhang, Yuan. (2006). Us Patent No. 7,115,227.

Peterson, G.P. (1994). *An Introduction To Heat Pipes*, . Newyork: John Wiley & Sons.

Razavinia, N. (2010). *Waste Heat Recovery With Heat Pipe Technology.* (M.Eng), Mcgill University, Canada.

Us Energy. (2012). Energy Information Canada, : U.S. Energy Information Administration.

Wikipedia. (2006). Heat Pipe Mechanism Diagram Showing Thermal Cycle And Components.