Harnessing Thermoacoustics for Waste Heat Recovery

by

Alex Aguilar

Submitted to the
Department of Mechanical Engineering
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Signature of Author:

Department of Mechanical Engineering
May 22, 2020

Certified by:
Sili Deng
Assistant Professor of Mechanical Engineering
Thesis Supervisor

Accepted by:
Maria Yang
Professor of Mechanical Engineering

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ABSTRACT

Environmental concerns and economic incentives have created a push for a reduction in emissions and an increase in efficiency. The U.S. Department of Energy estimates that 20 to 50% of the energy consumed in manufacturing processes is lost in some form to waste heat. The purpose of this study is to review the waste heat recovery technologies currently available in both commercial and research applications to determine how thermoacoustics may serve a role in furthering the use of waste heat recovery units. A literary review of the most common waste heat recovery units was compiled to determine the advantages and disadvantages of the different technologies by comparing components and their governing processes. An existing model of a thermoacoustic converter (TAC) was reviewed and a conceptual analysis written to suggest improvements for future experimental designs.

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For ensuring my ability to be here, and continued support, when life's challenges prolonged my stay. Thank you, MIT Admissions team, Student Support Services, and the Poitras family, for giving so generously in every way you could.

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1. Introduction

The trend of rising fuel prices and concerns around global warming have pushed manufacturers to look toward better industrial practices in reducing emissions and improving energy efficiency. Today, the U.S. industrial sector has contributed to approximately one third of the fossil-fuel-related greenhouse gas emissions. The current methods to improve industrial energy efficiency consist of reducing energy consumption by equipment used in manufacturing (such as boilers, furnaces, motors, pumps, etc) or changing the techniques used in the process of manufacturing products. According to a report by the U.S. Department of Energy, as much as 20 to 50% of energy consumed in manufacturing processes is lost in some form to waste heat. [1] This intrinsic heat loss associated with all industrial processes has led studies into a promising alternative of capturing and reusing this "waste heat." This process, known as waste heat recovery, has the potential to improve energy efficiency by 10% to as much as 50%, tapping into a 5-13 quadrillion Btu/yr source of unrecovered energy in the industrial sector. If harnessing only a fraction of this potential increase in efficiency in smaller, commercial applications is possible, the implications of this research will be revolutionary.

Understanding the economic and environmental impact of waste heat recovery in industry is only the first step to understanding the promise of this technology. Making use of emission-free waste heat not only reuses energy that would otherwise be dumped into the environment, therefore requiring less fuel, but also makes the overall system more efficient. The type of waste heat being recovered determines its grade (i.e. low, medium, high) that gives information about the original heat source and the temperature range for optimal waste heat recovery. Along with the grade, determining the appropriate waste heat recovery unit that integrates with the source of heat loss (e.g. direct combustion, exhaust of combustion units, or from the parts, products and equipment) and the governing heat transfer mode (e.g. conduction, convection, or radiation) is crucial for choosing the appropriate technology for optimal waste heat recovery.

In order to make use of waste heat, a WHR method must be chosen that best suits the requirements and type of system from which the waste heat is being recovered. WHR methods of interest vary among those taking advantage of mechanical, thermal and acoustic WHR units; the technologies found in commercial or research projects. Mechanical units are typically found in cogeneration systems, thermal are the most common, often being incorporated adjunct to other systems, and acoustic systems are under development, including some newer technologies such as thermoacoustic converters.

An accessible source of waste heat and having the available technology to make use of such sources of heat are only two legs of the waste heat recovery process. Lastly, within the third and final leg, we consider the end use of this captured energy. The conversion of waste thermal energy to practical work takes on a new challenge with a focus on design. We compared different energy conversion schemes, such as direct heat-to-electrical work (thermal), mechanical-to-electrical (mechanical), and a combination of both (hybrid), in a process known as thermoacoustics. By comparing the alternative waste heat recovery methods and categorizing the advantages of each energy conversion method, we aim to analyze each waste heat recovery unit and offer improvements on component design. [2]

2. Background

2.1 General Waste Heat Recovery

Waste heat is the energy generated in thermal processes that is either lost or dumped into the environment without having been put to practical or useful work. When speaking of waste heat recovery (WHR) systems, methodologies, or techniques, the general theory behind these ideas is the capturing and transferring of waste heat, whether by way of exhaust gas, liquid by-product or other fluid, and introducing this media back into the system with the purpose of regaining an extra energy source. This currently unutilized energy source may be repurposed to create additional heat, redirected to do mechanical work or harnessed to generate electrical power. It follows that if we combine or intertwine these paths for WHR, creating constructive new paths, it may be possible to optimize energy recovery even further. First, though, we must understand where these paths take on their beginnings.

The sources of waste heat are mostly derived from heat loss that is transferred through conduction, convection and radiation from industrial products, equipment, and processes as well as the by-products of combustion in these same systems. Heat loss is characterized by one, or a combination, of three types: high, medium and low temperature grades. Every range of temperatures has an optimal efficiency that may be reached if certain WHR systems are applied to that range. High temperature WHR systems are commonly applied to those processes at temperatures greater than 400 °C, medium WHR ranges from 100 to 400 ℃, and low WHR contains processes at temperatures less than 100 ℃. Direct combustion processes account for a majority of high temperature grade waste heat, medium grade originates typically from the exhaust of combustion units, and low grade comes from the parts, products and equipment of process units.

At the core of WHR principles, the consensus holds that, despite the origin, the higher the temperature, the higher the quality (or grade) of the waste heat we will find and the easier it may be to maximize the energy recovered of such a process intended for waste heat recovery. In order to develop a way to measure and compare different processes, we must establish the maximum amount of recoverable heat with the highest potential from a process and determine the maximum efficiency. The quantity or amount of available waste heat can be calculated using the following equation:

$$Q = V \times \rho \times C_p \times \Delta T$$

where, Q [J] is the amount of heat, V is the volumetric flowrate [m^3/s], ρ is the density of the fluid [kg/m^3], C_p is the specific heat of the substance [J/kg·K] and ΔT is the difference in temperature (in K) between the final highest temperature of the outlet (T_{out}) and the initial temperature of the inlet (T_{in}) in the system. [2]

2.2 Waste Heat Recovery Systems

2.2.1 Thermal Waste Heat Recovery

Technology

Regenerative and recuperative burners use heat exchanger surfaces to harness the heat from hot flue gas from combustion processes. **Regenerative WHR units** consist of two burners with separate control valves. The burners are connected to a furnace that changes flow path direction depending on the need to heat the combustion air entering the furnace. Exhaust gases from the furnace are directed to either of two cases that contain a refractory material (e.g. aluminum oxide). The refractory material is heated, recovers the heat energy and serves as the storing media. Once fully heated, the direction of the flue gas is reversed, such that the heat from the media is transferred to the inlet air entering the burner, with the hot media, as it starts firing once again. The process repeats as the exhaust from the combustion air heats up the cooler media in the opposite case with refractory material. This cycle improves the efficiency of the combustion process by saving fuel that goes into heating the inlet air. [2]

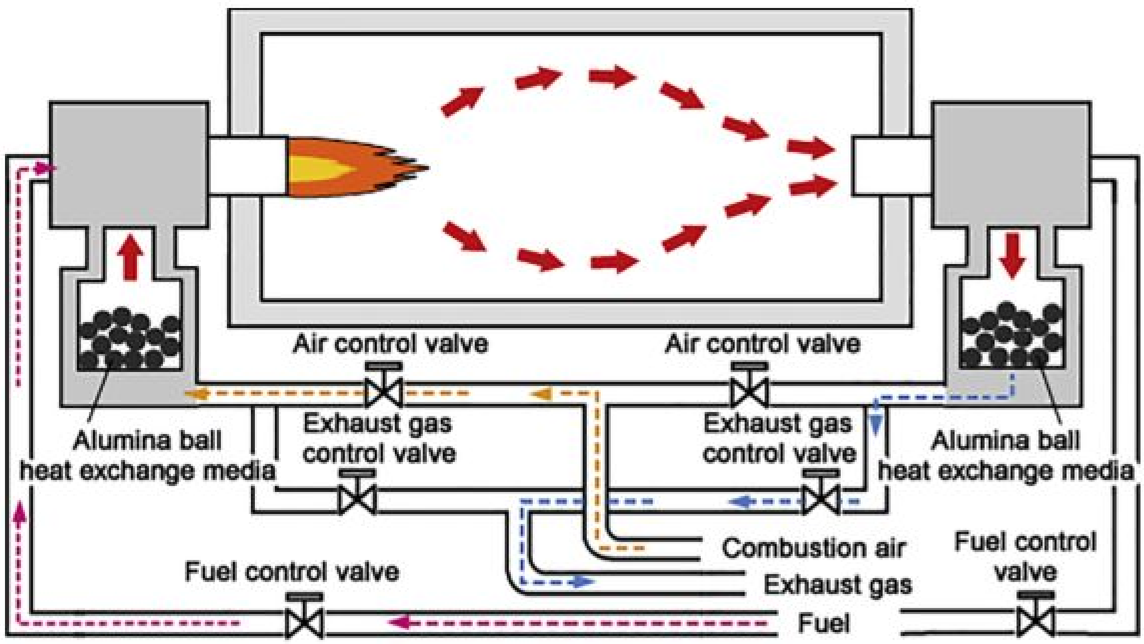

Fig 1: Regenerative burner mechanism [3]

Recuperative burners incorporate heat exchangers in their burner designs and harness the energy from the heated gas that passes through the burner. This energy from the waste exhaust gas is used to preheat the combustion air before it is mixed with the fuel. Unlike the regenerative burners, recuperative WHR units contain internal heat exchangers with features such as grooves, counter current flow, and fins in order to optimize thermal exchange between the exhaust gas and the air entering from supply lines. By capturing the waste heat from both the exhaust gas and the body of the burner nozzle, then transferring this thermal energy to the combustion air, the process is more efficient at producing additional heat at the nozzle. It is important to note that regenerative and recuperative burners are able to accomplish such efficient thermal transfer from their respective burner schemes primarily by the principle of convection with the exhaust gases. [2]

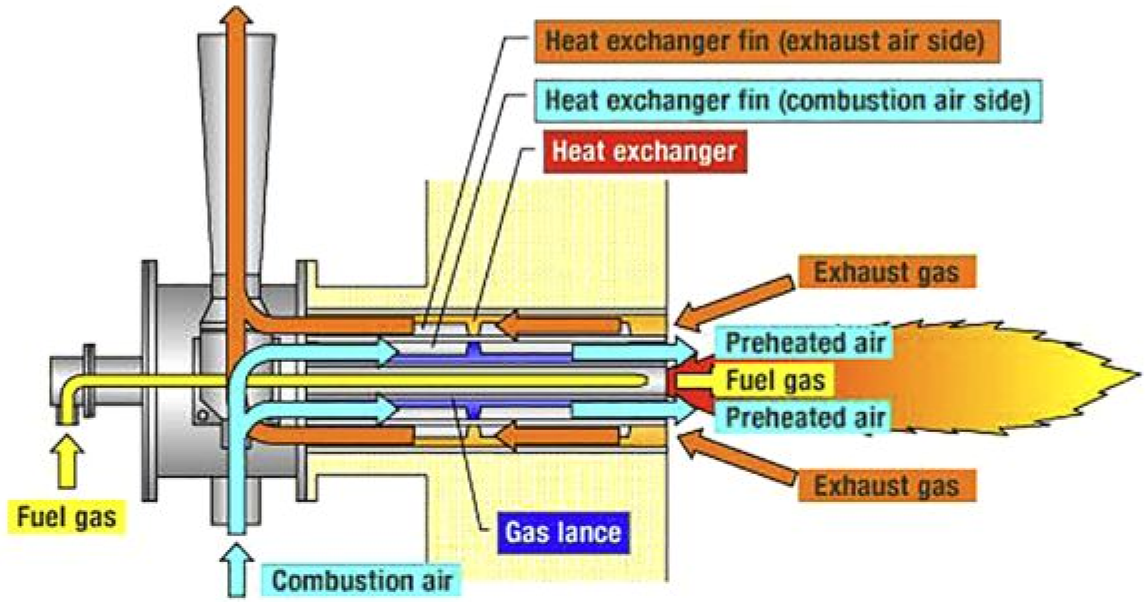

Fig. 2: Recuperative burner structure [4]

Economisers are heat exchangers with finned tube designs used in heating liquids containing waste heat of low to medium grades. The system optimizes WHR by maximizing surface area of heat absorption and heat transfer rate using tubes covered in metallic fins. The system resides in the ducts where exhaust gases are exiting and captures the waste heat from the hot gases as they pass the areas covered by fins surrounding the tubes. The working fluid, in this case a liquid, passes through the finned tubes and heat is exchanged from the fins to the liquid. Once heated, the hot liquid reenters the system and improves the thermal efficiency of the overall system. There are several types of economiser designs used for different applications such as finned tubes, coiled tubes, non-condensing and condensing configurations. From these available types of WHR units, non-condensing and condensing systems are focused for improving boiler efficiency, while the other system types are used in large thermal power plants where recovering waste heat from flue gas is a priority. Economisers recover waste heat and preheat the working fluid (i.e. feedwater in a steam engine or boiler) in these systems to minimize the energy needed to reach required boiling temperatures. Focus has now been placed on advanced materials for low-temperature WHR such as Teflon, carbon and stainless-steel tubes that can handle acidic condensate that can accumulate on the heat exchanger surfaces. Glass-tubed economisers have also permitted heat recovery from systems with gas to gas interactions in low to medium temperature applications. [2]

Waste heat boilers include a network of water tubes parallel to one another and oriented along the direction of heat leaving the system. This configuration captures heat from medium to high temperatures from exhaust gases and produces steam. The steam can then be used directly for power generation or fed back into the system. For example, in coal power plants, the heat from combustion processes reaches temperatures of 1000 ℃. The waste heat from the flue gas vaporizes the fluid flowing through the parallel tubes to produce steam, which may be used in power generation via turbines and generators. The temperature of the waste heat from the flue gas directly determines the pressure and rate of steam production. Additional burners or afterburners may be added to burner exhaust gases in the case that the flue gas does not provide the necessary waste heat to reach vaporization. Waste heat boilers may supplement WHR technologies such as afterburners, preheaters and finned tube evaporators in improving efficiency of these systems by preheating the feedwater and allowing for the production of superheated steam. [2]

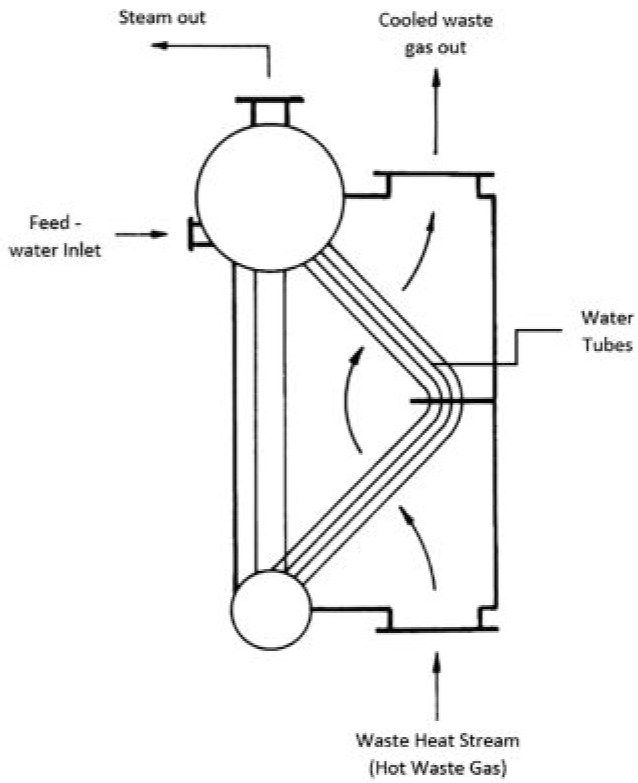

Fig. 3: Schematic of waste heat boiler incorporating parallel water tubes [2]

Air preheaters are applied from low to medium temperatures for exhaust-to-air WHR. Some examples include gas turbine exhaust and when used adjunct with furnaces, ovens, and steam boilers, cases where cross contamination must be prevented. Air preheaters come in two designs: the plate and the heat pipe. The **plate** design includes parallel plates placed perpendicular to the direction of the entering cold air inlet. Between the plates, hot exhaust is pumped in to allow for heat recovery by the plates and create hot channel areas, through which the cold air is fed. In the **heat pipe** design, sealed pipes are bundled together and placed in parallel within a container. The container is then sectioned off into cold and hot sides, depending on the inlet and outlet directions. Each pipe contains a working fluid that is heated at one end using hot waste exhaust until vaporized, which causes the gas to flow to the cold side of the pipe, where cold air passes. Convection between the passing cold air and the hot gas inside the pipe simultaneously cools the gas and heats the cool air passing over the pipes. In this cycle, heat is transferred from the cold to the hot side when the evaporated hot gas cools, flows back to the hot side, and the process repeats. The most common air preheaters that use these techniques are called regenerators and include rotary regenerators, run around coils (RAC) and recuperators.

These regenerators follow the same basic principles as air preheaters but come in different designs to be used for specific applications. [2]

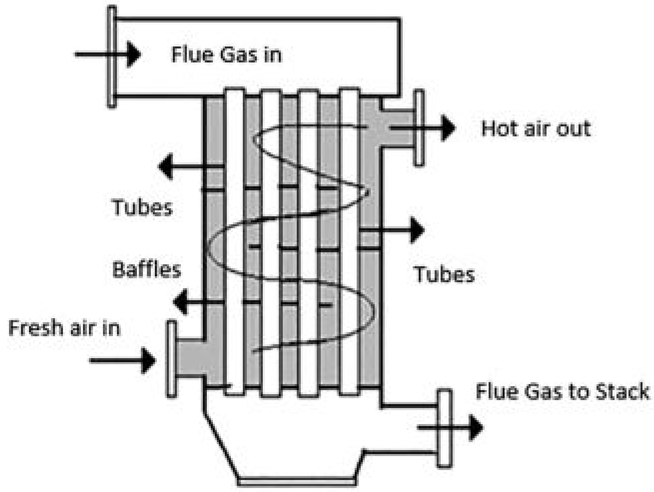

Fig. 4: Schematic of air preheater layout demonstrating air movement [2]

Recuperators are heat exchanger units made of metallic or ceramic materials. Depending on the material, they are often applied to WHR of exhaust gases with low to medium or only high temperature grades, respectively. Recuperator technology functions by feeding hot exhaust gases through a network of metal tubes or ducts before allowing the inlet air from the atmosphere to enter the network. The preheated inlet air is fed back into the system, and in this way, the fuel necessary to provide this initial heating is salvaged. This, in turn, reduces energy demand from the overall system and keeps production costs low. Heat in these configurations is transferred through convection, radiation or a combination of both of these modes of heat transfer. In a radiation recuperator, the design consists of metallic tubes surrounding an inner shelf, through which hot exhaust gases flow. As the cold incoming air is fed through these tubes, heat is radiated to the walls of the tubes from the inner shelf, heating the air before exiting to furnace burners. A convective recuperator allows hot exhaust gases to flow through small diameter tubes placed within a larger shelf. Unlike in the radiation case, the cold air is fed through the shelf and heat is transferred from the small, heated tubes to the air moving past. By combining the technologies of radiant and convective recuperators, a new design may be forged. This design consists of a larger self that splits into small diameter tubes, all through which the hot exhaust is fed. Cold air is then allowed to flow into and around the integrated shelf, which results in maximizing the heat transfer effectiveness. [2]

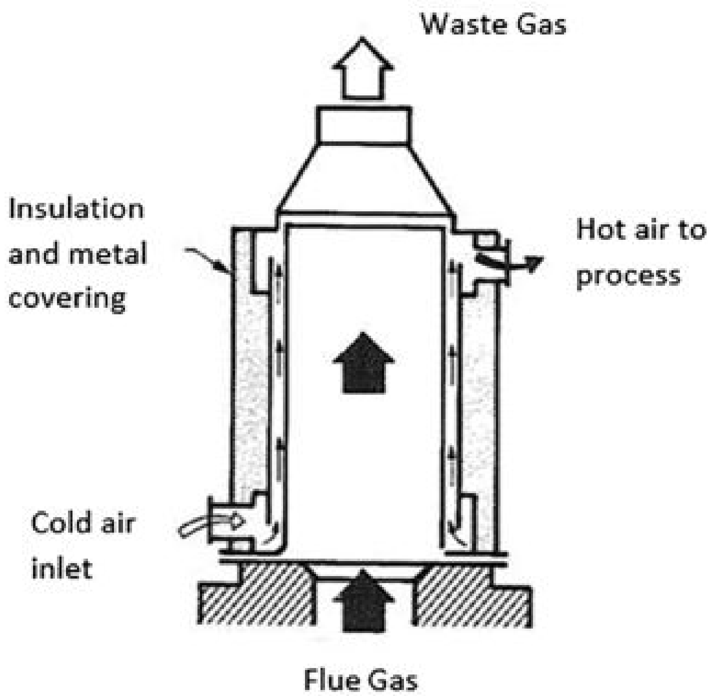

Fig. 5: Diagram of metallic recuperator [5]

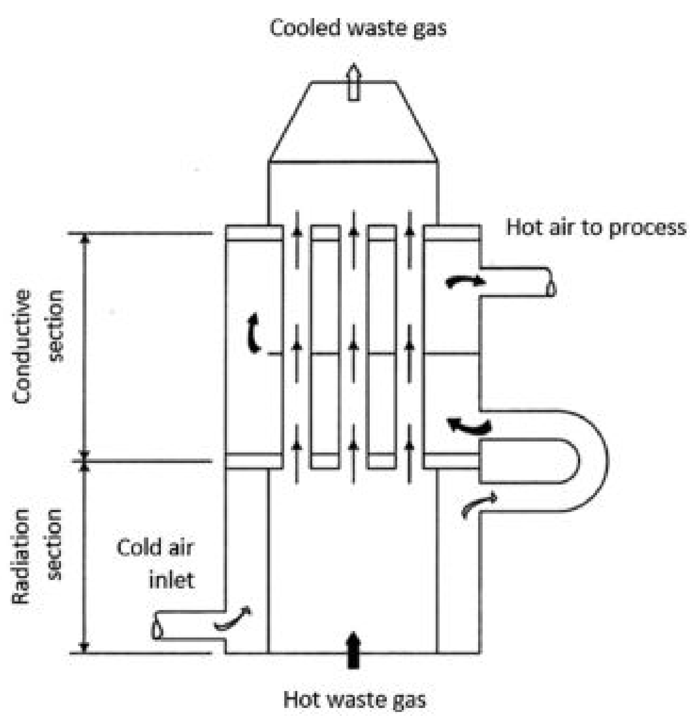

Fig. 6: Diagram of combined radiation and convective type recuperator [6]

Regenerators operate under high temperature applications and take advantage of materials with high heat capacities in order to achieve heat transfer between hot and cold gas ducts. At the core of this technology is the transfer chamber, which allows heat to be transferred from the hot side into a storage medium and then delivered to the cold side when needed. As we saw with regenerative burners, hot exhaust gases from combustion processes are passed through one of two brick chambers, where hot and cold air exchange heat. The resulting preheated air from this process, which is fed back into the system, allows for a reduction in the amount of energy needed by the system to heat the incoming air. The double-chamber design allows for the process to cycle the flow of air between the chamber preheating the air and the other that is absorbing heat from hot exhaust gases. This eventually allows the process to reach constant heat transfer. Regenerators are quite versatile in that they may operate in situations involving dirty exhausts and can come in large sizes, but this also accrues high capital costs and can serve as a disadvantage, depending on the application. [2]

A subset of the fixed regenerator is the **rotary regenerator**, intended for low to medium temperature applications. The design is focused around a porous thermal wheel, made of a high thermal capacity material, that transfers heat between hot and cold flows. The system consists of two parallel ducts with hot or cold flows placed across a rotary disk or heat wheel. The heat wheel absorbs and stores the heat from the hot stream, rotates and then transfers the heat to the cold stream. This results in a relatively high heat transfer efficiency. It is important to consider that at high temperatures, ceramic materials must be employed to deal with the structural stresses and large deformations attributed to the high temperature differences between the streams. Lastly, due to the nature of porous materials, cross-contamination between the two streams cannot be prevented, which must be considered when deciding applications. [2]

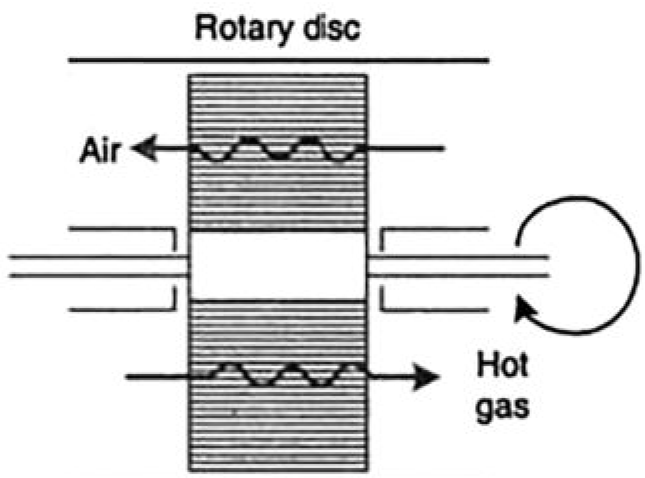

Fig. 7: Schematic of heat wheel showing air movement [6]

A **run around coil** (RAC) is typically filled with a fluid, such as water, glycol or a mixture, and serves to connect coiled heat exchangers over a distance. The waste heat captured by the primary recuperator from the exhaust of a process is transferred via the liquid to a secondary recuperator where the heat is transferred to another fluid. This heat transfer is possible due to the pumped pipework of the coil system. This system is commonly used when the source of heat is far enough to prevent the use of direct recuperators or when cross-contamination between two streams must be prevented. Considering that a pump is necessary to operate this system, additional energy and maintenance is required, which lowers the effectiveness of this process. The efficiency may be improved if an additional heat source is used. [2]

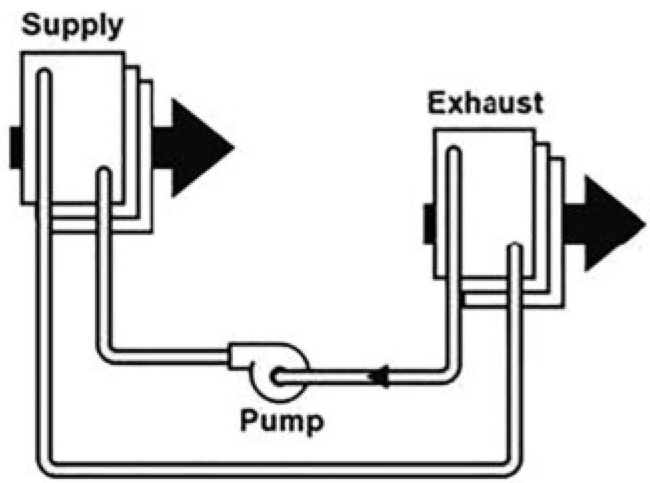

Fig. 8: Schematic of run around coil system [7]

A **plate heat exchanger** consists of several thin metal plates that are stacked or brazed in parallel to form a hollow metallic shell. Each plate is designed with pressed patterns and covered in gaskets to both control fluid flow and cause turbulence, which improves heat transfer. The gaskets are placed such as to allow one type of fluid to flow through one gap, while the other flows through the adjacent gap. This configuration allows for the hot and cold streams to flow across the plane of the plates on opposite sides and transfer heat from one fluid to another while avoiding cross-contamination. The advantage of this design over shell and tube heat exchangers is that the hot and cold streams are exposed to a larger surface area per unit volume, resulting in a larger heat transfer coefficient. [2]

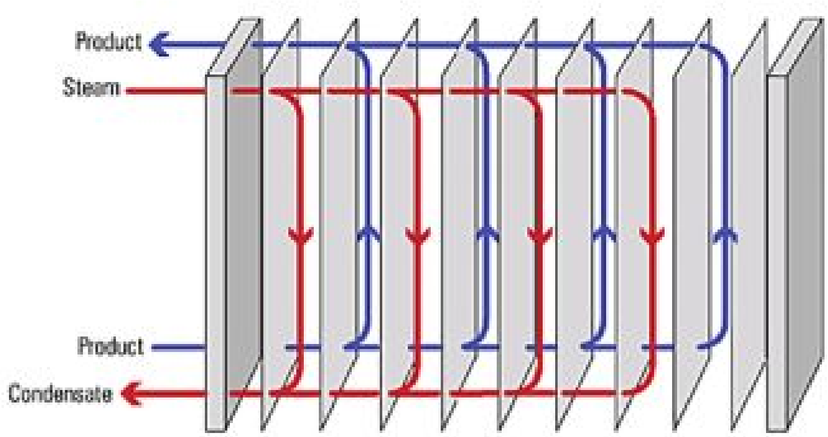

Fig. 9: Schematic of a plate heat exchanger [8]

The plates of plate heat exchangers may be gasketed, brazed or welded together in either single-pass or multi-pass configurations. A gasket heat exchanger consists of gaskets commonly made out of polymer materials and are arranged between the plates to serve as both a seal and a spacer. These plate heat exchangers are designed to be placed between two pressure plates and tightened with bolts in order to clamp the plates together in a single frame. This modular design allows for ease of dismantling for cleaning or for maximizing capacity by simply adding or removing plates. The use of gaskets gives the pack flexibility by allowing for resistance to thermal fatigue and pressure variations, which makes it ideal for applications where thermal cycling is involved. Gasket plate heat exchangers may achieve a recovery rate of up to 90% due to their efficient and effective heat transfer capabilities. The operating temperature and pressure requirements of the gaskets are their limiting factor. Brazed plate heat exchangers are created when the plates are placed in a vacuum furnace and brazed together using copper or nickel. This allows for a configuration that is much more resistant to higher pressure and temperature ranges. However, due to the nature of brazing, the plates cannot be dismantled which may create challenges when cleaning and prevents modifications to the design. The more rigid design also makes it vulnerable to thermal stresses and variations in temperature or loading that may lead to fatigue and the structure to fail. In this case, brazed plate heat exchangers are best applied where there is low temperature variation and thermal expansion is gradual (e.g. thermal oils). Welded plate heat exchangers are created using laser welding techniques that bond the plates together with weld seams. This design allows for higher temperature and pressure operating limits that are best applied in heavy duty applications. Like the brazed plate heat exchanger, however, these plate heat exchangers cannot be dismantled or modified. [2]

Heat pipe systems consist of a sealed tube, a wick, and a small amount of a working fluid (e.g. water, acetone, methanol, ammonia or sodium) that may reach equilibrium with it's own vapor. These components are subdivided into three sections including the evaporator, the adiabatic transport and condenser sections. The device is able to transfer heat from one section to another by means of vaporization and subsequent condensation of the working fluid. The process begins when, by conduction, heat is transferred from one end of the pipe, through the pipe wall and to the wick where the working fluid is evaporated. The resulting vapor pressure causes the vapor to travel through the adiabatic transport section to the other side of the pipe. Here, the vapor condenses after transferring the latent heat of vaporization back into external heat that is absorbed by a heat sink. Once a liquid, by capillary pressure, the fluid travels back through the wick to the hot end where the cycle is repeated. Heat pipes have high effective thermal conductivities, ranging from 5000 to 200,000 W/m.K, while, in comparison, solid conductors (e.g. aluminium, copper, graphite, diamond) have ranges of 250 to 1500 W/m.K.

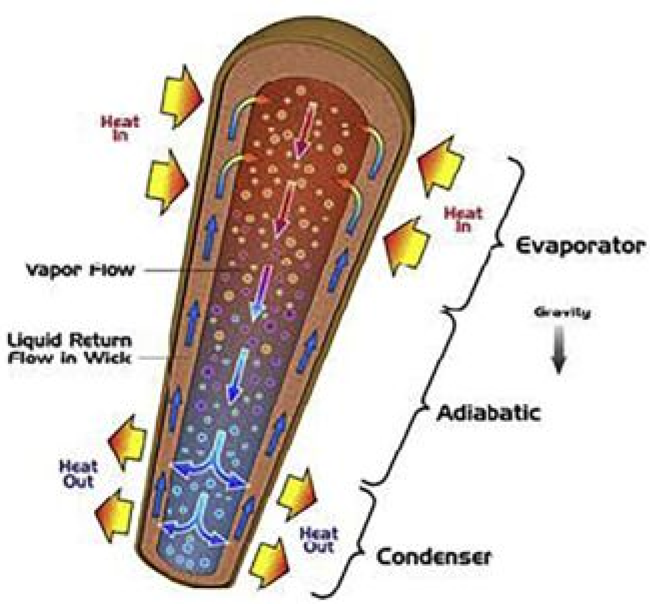

Fig. 10: Schematic of a heat pipe [9]

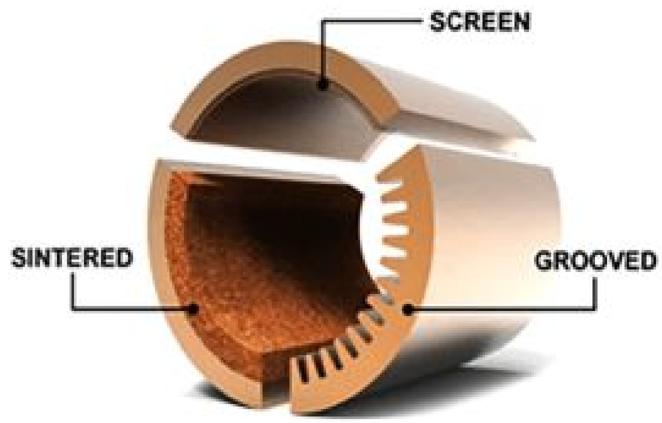

Fig. 11: Common wick types of a heat pipe [10]

When constructing a heat pipe, the choice of material will depend on the temperature range of application as well as the compatibility of the material with the chosen working fluid. Some materials typically used include aluminium, copper, titanium, monel, inconel, stainless steel and tungsten. The wick that aids the working fluid transport during the heat exchanging cycle are most commonly constructed with groove, screen (or woven) and sintered powder metal structures. Screen mesh structure wicks are commonly made of copper or stainless materials and their form is created when expanded against the pipe wall. These types of wick structures may operate in both the horizontal and vertical positions, as well as against gravity at a slight angle from the horizontal orientation. Grooved wick structures are made of extruded or threaded raised dents created perpendicular to the pipe surface and most commonly out of copper or aluminium. Like their screen mesh counterparts, these wick structures may operate both vertically and horizontally as well as against gravity but only at slight angles to the horizontal position. Sintered powder wick structures, most commonly made of fused copper powder particles, can operate both vertically and horizontally as well as against gravity with little to no limitations in any orientation. An alternative to the heat pipe is the thermosyphon, which requires no wick structure and works only with gravity. However, unlike the heat pipe which may operate in both horizontal and vertical orientations, the thermosyphon must be placed vertically to function.

A working fluid for a heat pipe system will be chosen according to the temperature range the heat pipe will be used in. In lower temperature applications, with a range of 200 to 500 K, ammonia, acetate, freon refrigerants and water are most commonly used. Water is often preferred for it's low cost, desirable thermo-physical properties and it's low chemical volatility. Heat pipes are often chosen as preferred heat exchangers because of their high thermal conductivity, which allows transferring of thermal energy over long distances with little temperature drop. They also require no maintenance, allowing for long life cycles, and their lack of moving parts due to passive operation allow for low operation costs. [2]

Pulsating heat pipes (PHP) are passive closed two-phase heat transferring units that may exchange and transport heat without requiring additional power. The design consists of a narrow, winding long tube with a working fluid inside. The PHP can be open-loop or closed-loop and functions via the oscillatory flow of liquid slugs (i.e. discrete volumes of fluid) and vapor plugs (i.e. bubbles) traveling through the long tube. In the closed-loop form, both ends of the tube are connected. In the open-loop form, one end is welded and pinched shut, while the open end is connected to a charging valve. The difference between this heat pipe and the conventional configuration is the lack of a wick structure to deliver the condensate and heat transfer is completely achieved via the oscillatory flow of the two-phase fluids. Incorporating a sintered copper wick structure into the PHP design improved the distribution of the working fluid and a reduction in local temperature fluctuations. [2]

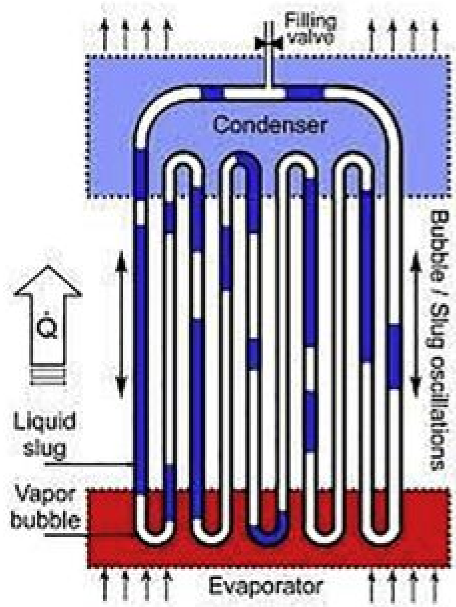

Fig. 12: Schematic of a pulsating heat pipe [11]

Thermoelectric Power Generation

Thermoelectric devices are constructed from semiconductor materials, which produce an electric current when a temperature differential is introduced between two surfaces connected with electrical leads. The Seeback effect (1821), discovered by Thomas Johann Seebeck, is the driving principle behind this phenomenon. It is defined as the generation of electrical current (I) between two semiconductors when the materials are subject to a hot (T_H) and cold (T_C) source. Although having a measured efficiency as low as 2 to 5%, advances in nanotechnology have improved this value to around 15% or higher. Studies have shown that with proper thermoelectric configurations, electricity may be produced and energy savings increased via the waste heat recovered from medium to high temperature grade processes, such as those found in glass or metal furnaces. The limiting factors creating the challenges currently faced by researchers from making this technology widespread is the need to maintain high temperature differences and high heat transfer rates between the two thin surfaces of the device. Advances in current heat transfer systems and materials are necessary to further the feasibility of this technology in WHR applications. One such experiment has attempted to combine heat pipes and thermoelectric devices for power generation from industrial processes. By modeling a prototype of a thermoelectric generator and combining it with a counterflow air duct heat exchanger, an increase in ratio of mass flow rate between upper and lower duct activity was found. This higher mass flow rate demonstrated a higher power output and an increase in system performance. [2]

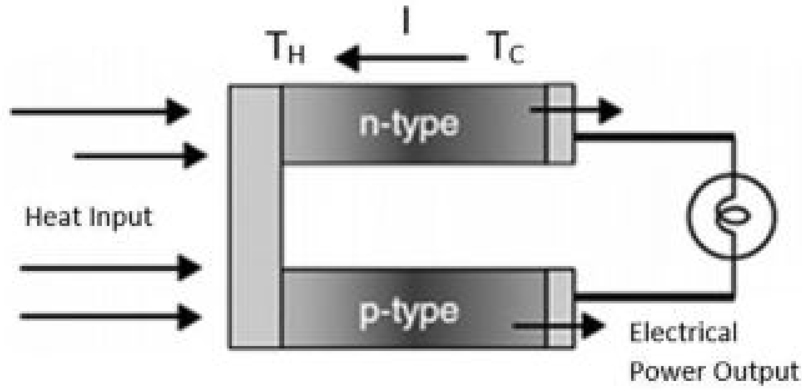

Fig. 13: Principle of the Seeback effect [12]

Piezoelectric Power Generation

Piezoelectric devices are made out of thin-film membranes and operate by converting ambient vibrations, such as those found in oscillatory gas expansion, into electricity. Piezoelectric power generation (PEPG) is able to convert low temperature grade heat directly into electricity. The challenges faced with using these devices for WHR stem from their low efficiency, high thermal impedance, high durability constraints and high costs of manufacturing. More importantly, the need for intense design work to allow for power generation, reliability and stability currently outweigh the benefits provided by this technology. [2]

Thermionic Power Generation

Thermionic devices operate by thermionic emission, similar to thermoelectric materials, and produce electric current via a temperature difference between two media and without any moving parts. During this process, a temperature difference between a hot cathode (the emitter) and a cold anode (the collector) initiates electrons to flow between a metal and metal oxide surface inside of a vacuum to produce electricity. These devices are limited by their use in primarily high temperatures applications and are generally inefficient systems. [2]

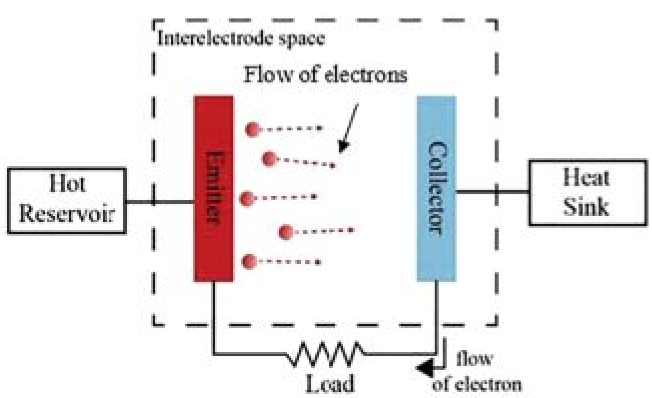

Fig. 14: Schematic of a thermionic device [13]

Thermophotovoltaic Power Generation

Thermophotovoltaic (TPV) devices directly convert radiant energy into electricity, similar to the governing principle of solar panels. The TPV system consists of an emitter, a radiation filter and a photovoltaic (PV) cell, which produces electricity from a heat source. The emitter works by emitting electromagnetic radiation when heated. The spectral filter allows only radiation waves with the wavelength matching the PV cell specifications so the PV cell may convert the radiation into electricity. Efficiency for a TPV device falls between 1 and 20% depending on the type of radiation, the amount of heat transferred by the emitter radiation and the configuration of the system. These devices are limited by specific operating temperature ranges required by PV cells and decreased efficiency at higher temperatures. The alternative is high efficiency PV cells, which may operate at higher temperatures, but increase costs. [2]

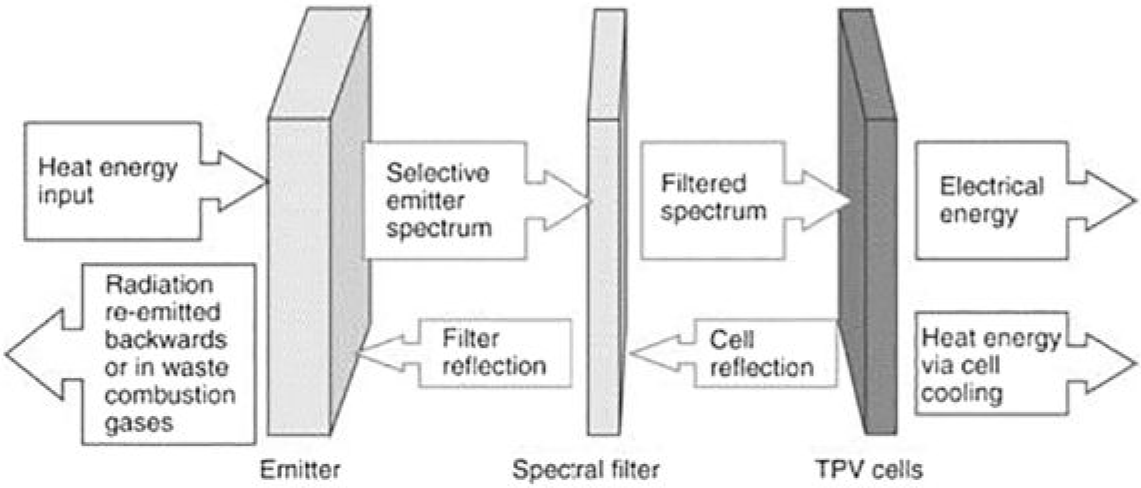

Fig. 15: Schematic of operating principles of a TPV device [14]

2.2.2 Mechanical Waste Heat Recovery

Steam Turbine

A steam turbine is a device that converts pressurized steam delivered from thermal processes into mechanical work by turning a rotating output shaft. First designed by Sir Charles Parsons in 1884, the Parson turbine uses several stages in series, allowing for the expansion of steam in the process and extracting the greatest amount of kinetic energy from the system. [15] This turbine design is the motivation for most modern day steam turbines found in industrial processes. The Parson turbine utilizes stationary blades that direct incoming steam onto moving blades. Upon receiving high-pressure steam from steam mains, the steam passes through the stationary blades where it expands and increases in velocity. The steam continues on to the moving blades, expanding again. This alternate configuration of stationary and moving blades surrounding a drum, or rotor, repeats in discrete puffs of steam until overload capacity is reached and a continuous stream of steam allows for synchronized rotation of the output shaft. [16] As a result, the rotary motion produced by a steam turbine is best used with a generator to convert the thermal energy of steam into useful mechanical work.

2.2.3 Thermoacoustic Waste Heat Recovery

Thermoacoustic Heat Engine

A thermoacoustic heat engine is a device that converts thermal energy and acoustic vibrations into useful work. One of the earliest forms of this heat engine appeared in 1859 in an article written by P.L. Rijke. In his experiment, Rijke used a glass tube, open at both ends, and placed a wire gauze made of iron inside the tube, offset from one of the edges. After heating the gauze over an open flame while maintaining a vertical orientation, the tube produced an audible sound close to the natural frequency of the tube, or resonator. The acoustic power generated from the inputted thermal energy is attributed to the expansion and compression of the air inside the resonator due to the rapid cooling from natural convective heat transfer. Therefore, most important to the operation of this system is the temperature difference between the hot air rising through the tube and the temperature of the heated wire gauze. [17] More advanced technologies have been developed since, which incorporate carefully designed tuned acoustic ducts, electronically monitored power generators, and specialized heat exchangers. These systems allow for the heat transfer from exhaust gases at different temperatures to be regulated and optimized for specialized WHR. [18]

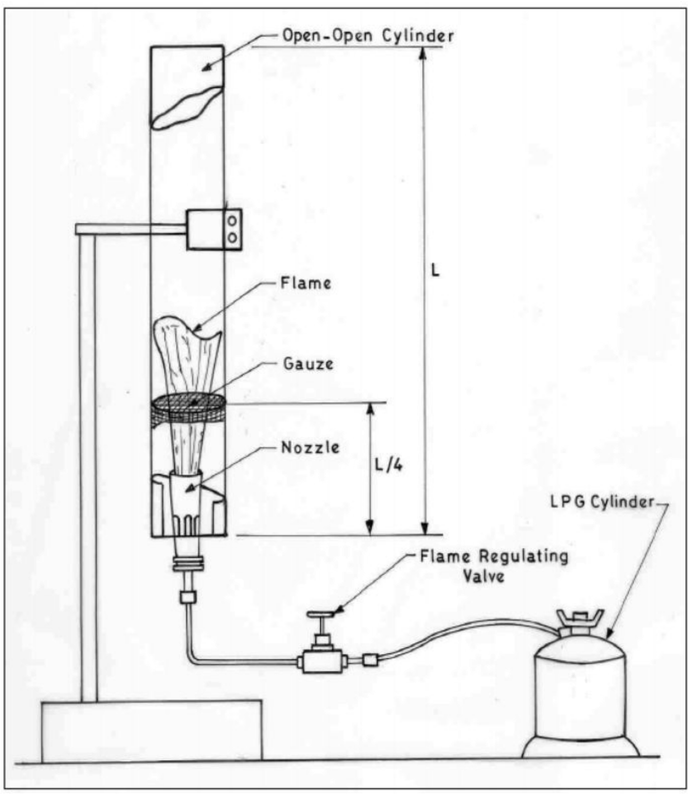

Fig. 16: Schematic of Rijke tube experimental set-up [19]

3. Design and Analysis

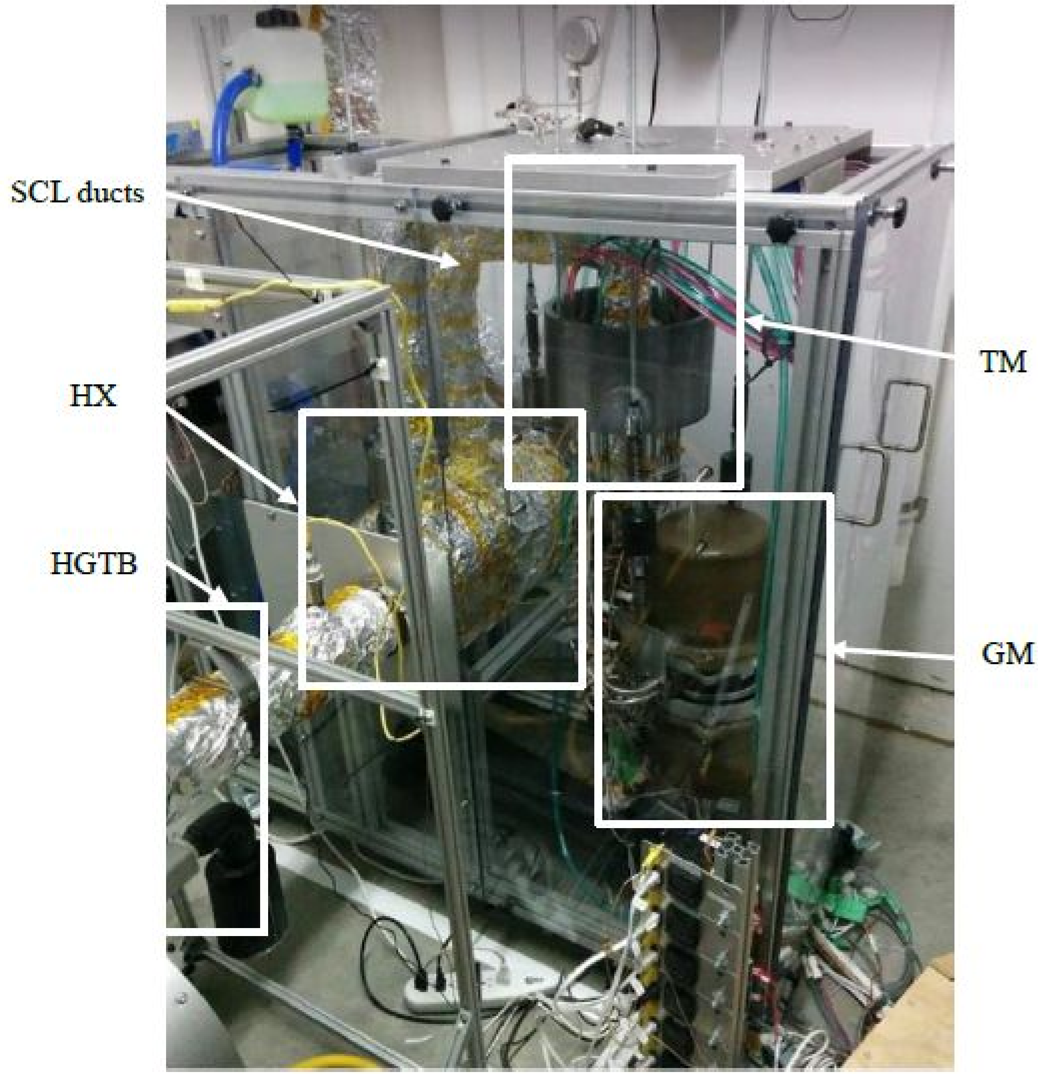

Fig. 16: Thermoacoustic converter (TAC) in a test cell with major components denoted [18]

3.1 Thermoacoustic Converter (TAC)

A proof of concept of a thermoacoustic converter (TAC) modeling the exhaust being produced from a light duty truck under highway driving conditions and the resulting WHR was created and tested by Maarten Elferink and Thomas Steiner. According to the manuscript submitted to the Acoustical Society of America, a specialized thermoacoustic engine they had designed and built by connecting an acoustic amplifier thermal module (TM) and an acoustic power to electrical power converting generator module (GM) using tuned acoustic ducts demonstrated the ability to transfer acoustic power successfully. A specialized external heat exchanger (HX) specially built in the Pacific Northwest National Laboratory by Greg Whyatt was used to convert the high temperature burner exhaust from a hot gas test bench (HGTB) to a low temperature waste heat stream delivered to the TAC via a self-circulating loop (SCL). The entire system was primed and filled with helium, the working fluid, pressurized to 12 MPa.

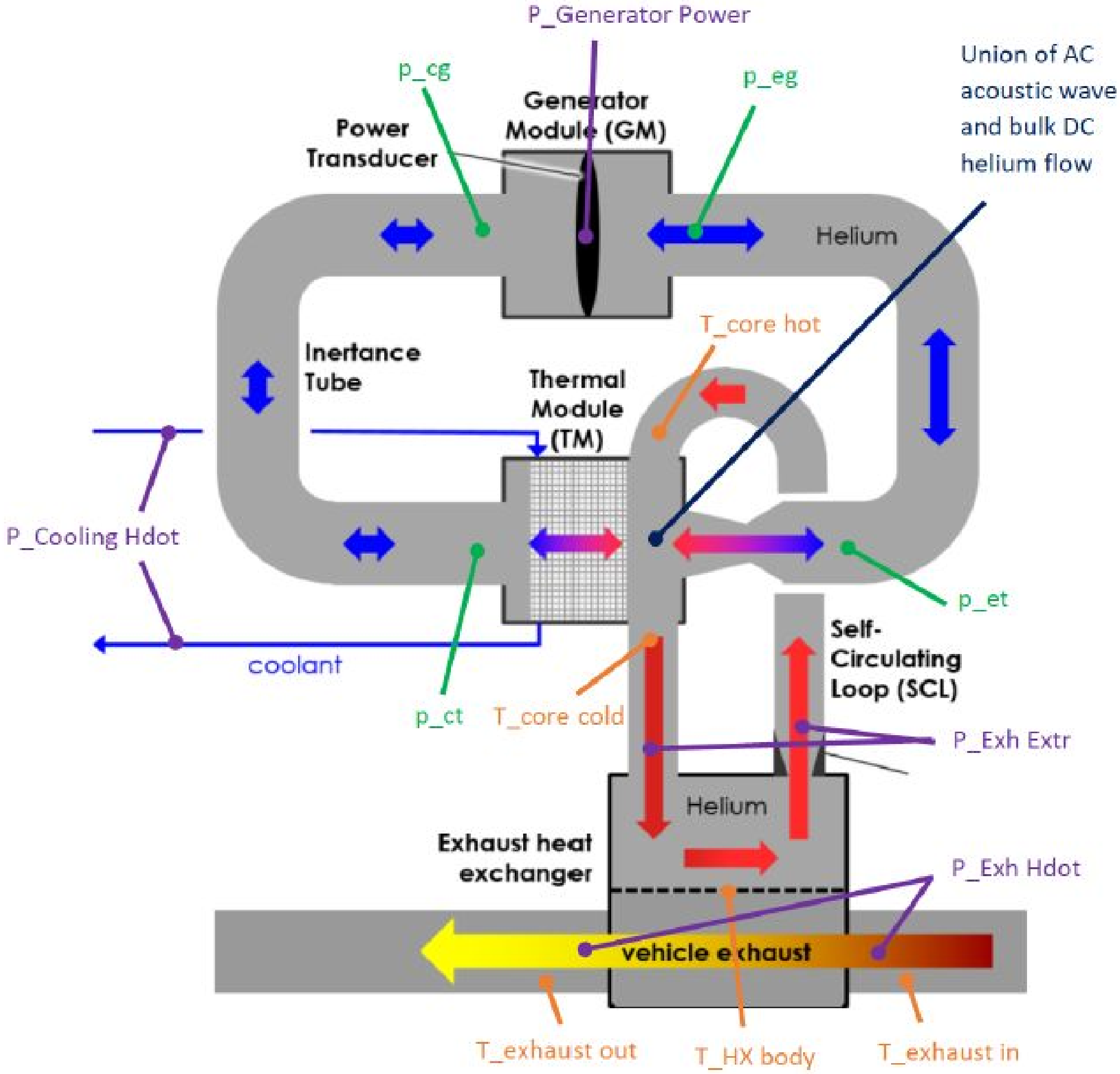

Fig. 17: Schematic of WHR system designed and built by Maarten Elferink and Thomas Steiner; micro-channel external heat exchanger designed and built by Greg Whyatt [18]

The acoustic power in the system travels in a counterclockwise direction and is amplified by the TM using a regenerator. The thermal gradient is maintained by extracting heat from the cold side of the regenerator by pumping coolant through a heat exchanger and then allowing the cooling fluid to discharge the heat to the environment with a radiator. On the hot side of the regenerator, the steady flow of hot helium coming from the SCL and running past it's surface maintains a temperature gradient. The acoustic pressure oscillations in the single, interconnected pressurized volume allows for the steady flow of helium throughout the device. The SCL works to power the acoustic amplification delivered in the TM by transferring heat from the micro-channel counter flow heat exchanger to the regenerator. An acoustic Venturi drive method uses the acoustic oscillating flow of the system to drive the steady flow of helium by superimposing the oscillatory and fluid flows to one another. This in turn lowers acoustic power dissipation and allows a wider range of exhaust temperatures.

In order to compare the experimental results of the prototype with a thermacoustic simulation model, temperature values and other pertinent measurements were made to understand the underlying thermodynamics. Temperatures for the inlet and outlet of the external heat exchanger as well as those for the helium at the TAC core were recorded. A thermocouple, placed on the external HX wall halfway along the flow direction, and an air mass flow sensor, to measure air flow, were used to calculate the enthalpy of the exhaust flow from the burner. A fluid reservoir with anti-freeze coolant, a fluid pump and a radiator (with a radiator fan) were used in the cooling loop system on the cold side of the regenerator. Therefore, it was important to control the fluid loop temperature with the radiator fan and maintain a temperature range of 50 to 85℃. The cooling fluid inlet (before entering the heat exchanger) and outlet (at the radiator) temperature and fluid flow were measured in order to calculate the thermal energy extracted by the cooling loop. By insulating the TAC core, it is hypothesized that approximately all heat loss by the core is transferred to the coolant rather than lost to the environment. Static pressure sensors measured the helium charge pressure while dynamic pressure sensors were used to measure the dynamic acoustic pressure swings at four locations along the acoustic loop. The voltage and current output of the GM were measured using a power meter and were used to calculate the electrical power output. A pair of accelerometers mounted on the reciprocators of the GM measured the device's stroke. To determine the amplitude and phase at operating frequency, Fourier transforms were applied to the dynamic signals captured during the data taking process. In order to calculate the heat delivered to the core, our previous calculation for heat loss attributed to the cooling loop and the mechanical power derived from the GM, found using the electrical power measurement and conversion efficiency (~88%), were applied to conservation of energy to infer the resulting value. [18]

3.2 Component Analysis

In determining the effectiveness of the experimental results and the thermodynamic model, it is necessary to run a pure acoustic test without a temperature difference applied to the heat exchangers. The reliance of the thermoacoustic process on steady helium circulation in order to deliver the necessary heat to drive the system leads to the notion that helium outlet temperature must be less than helium inlet temperature. To determine TAC performance for the pure acoustic case, core (helium) outlet temperature was set to the external heat exchanger inlet temperature. Furthermore, the minimum helium temperature cannot be higher than the temperature measured from the exhaust exiting the external heat exchanger. The higher the temperature difference between the inlet and outlet of the exhaust temperature, the more heat has been extracted from the burner exhaust into the device. According to the data logged by Steiner and Elferink, the exhaust temperature must remain above a minimum of 300 ℃ in order to extract useful energy.

As a preliminary check, the amount of heat leakage from the external exhaust heat exchanger, the core, SCL and acoustic ducting was determined by heating the system to it's operating temperature. The system was then placed in a “run down” sequence, where both the burner fuel and air flow from the HGTB were shut off and the GM kept inactive so that, besides inherent heat losses, only thermoacoustic activity would be recorded. In order to calculate heat storage of the system above ambient temperature, the following equation was utilized:

$$Q = m_s \times C_s \times (T - T_{amb})$$

where m_s is the mass of the component, C_s is the heat capacity of the component, T is the temperature above ambient, and T_{amb} is the ambient temperature of the system. We may use this equation to determine the expected decay of the measured temperature decay as follows:

$$\frac{dQ}{dt} = m_s \times C_s \times \frac{dT}{dt}$$

The divergence of the data for the TAC from the expected exponential decay may be attributed to the proximity of the TAC core to the external exhaust heat exchanger in the current test cell configuration, which resulted in sudden increased heat transfer by natural convection. Considering this statistical noise, a leakage of 125 W to the ambient was calculated. The external exhaust heat exchanger also displayed a deviation from the data, but these may be attributed to a combination of the high thermal heat capacity and natural convection to the core. The measurements from the thermocouple placed inside the external exhaust heat exchanger confirmed these deviations after a period long after the initial shut off, on the order of fifteen minutes. These observations allowed for the heat leakage from this heat exchanger to be around 400 W. A full power run analysis of the TAC was used to confirm the thermal behavior of the device. A final 4 kW of heat was confirmed to be extracted with 3 kW attributed to the cooling loop and 1 kW to heat leakage losses. A maximum power value of 570 W was extracted by the GM from the prototype power response. The input enthalpy rate provided by the burner was calculated using the following equation:

$$\frac{dH}{dt} = \frac{dm}{dt} \times C_p \times (T_{out} - T_{in})$$

where dm/dt is the exhaust mass flow, C_p is the exhaust heat capacity, and T_{out},T_{in} are the outlet and inlet exhaust temperatures respectively. The enthalpy from the burner was calculated to be 17 kW. By taking the max achievable power output of 570 W over the 17 kW provided by the burner, an efficiency of 3.4 % for heat converted to usable electricity was calculated. [18]

From this experimental analysis and the availability of several WHR technologies, for both commercial and research applications, it was concluded that improvements could be made to the overall system to address some pitfalls. In order to take advantage of the naturally convective heat transfer apparent in the system, it would be optimal to reconfigure the layout of the device. Space management is a priority, especially in commercial applications where systems are often refitted to already space limited environments. Therefore, the addition of low-profile and space-efficient heat pipes throughout these empty spaces would not only provide a method of WHR to shield components from unwanted effects of natural convection, a short of "heat shield", but also improve the efficiency of the system by using this heat leaked to the environment. In this way, using the same amount of fuel, more heat could be extracted that is already being produced by the system and fed back in with a device that requires low maintenance and maintains a long life cycle.

The recurring mention and observation of the high thermal heat capacity of the external exhaust micro-channel heat exchanger is a point of concern and has the potential for improvement. By introducing a high temperature difference using the high temperature exhaust produced by the natural gas operated burner, the method optimized the maximum heat recoverable given the available system components and configuration. In order to improve the efficiency of this technique, an air preheater designed and built around the operating principle of the combined radiant and convective recuperator may be utilized. This device, applied to high temperature grade applications by using ceramic material, could maximize the surface area for optimal heat transfer effectiveness if used with the already existing natural gas burner. If a low to medium temperature application was employed using metallic material, this device could be employed directly with the exhaust hypothesized from a light duty truck or commercial vehicle with similar exhaust temperature.

4. Discussion

The thermoacoustic converter is a WHR unit that shows great promise with future iterations and application of advanced technologies. It is operated by clear thermodynamic principles and takes advantage of ingenious new methods of using acoustic vibrations for both transfer and exchange of thermal energy. A reimagining of the experimental set-up and the layout of the experiment would have the potential to increase efficiency and make this technology more competitive.

As discussed before, the parasitic heat loss pathways that arise from thermal conduction and convection from both the external exhaust heat exchanger, the connecting acoustic ducts, and the TAC core were ignored and numerically filtered. However, there is great potential to harness these deviations as sources of recoverable waste heat. The underlying understanding that the prototype, as is usually the case, was designed and built for quick and easy improvements of optimal duct operating frequency or the test cell configuration was decided by space limitations, may be extended to an overhaul of individual components. The specially designed and built external exhaust micro-channel heat exchanger demonstrated a large thermal capacity. This material property not only made it difficult to achieve true steady state, but directly impacted the resulting response of the prototype in both thermal and power data analysis. Rethinking the materials chosen for such a device by using ceramic materials rather than metals would take advantage of low thermal conductivity of ceramics in order to decrease the possibility of unwanted natural convection from the surface of the heat exchanger and allow for use with high temperature grades despite a high heat capacity.

Considering TAC performance improvements as a function of increasing power output is the most direct method to increase the efficiency of the overall system. By increasing the amount of helium pumped into the system, the heat carried superimposed on the acoustic pressure oscillations would naturally increase the transfer of thermal energy. In order to ensure this does not overload pumping power requirements, the SCL duct diameters may be increased, which would decrease viscous losses at steady flow. To further reduce viscous and thermal relaxation losses, the performance of the regenerators used in the TM may also be improved. The felt regenerators in place would be replaced with high performance regenerators that could improve power output by 30%. [18] The greatest challenge, but most potentially rewarding advancement, would be in obtaining more power by increasing amplifier stages. Increasing the power gain of the overall system would require a focus on the hot to cold temperature difference of every stage. Low temperature grades provide low power gains, but by using amplifier stages in series, these small, incremental gains may be summed to create substantial power increases to generate useful work. This type of advancement would allow a wider application to drive cycles at low power states, where exhaust temperatures are low, and the use of several stages would increase the stream of processes at different temperatures offering recoverable heat pathways.

To determine maximum efficiency of energy conversion throughout this process, it is important to determine a robust and precise method to evaluate all possible heat loss, leakage and dissipation. When evaluating thermal and power values from experimental results, heat transfers such as conduction and convection from the heat exchangers were determined to be negligible.

The acoustic dissipation in the acoustic ducts, which heated the ducts and contributed to the thermal leakage, was taken as negligible because of the small surface areas and a crucial assumption that the insulation was adequate enough for the conditions. However, in calculating efficiency, every percentage is vital, and in commercial practices, is often directly related to the determination of cost-effectiveness. It is important to utilize sensors of higher precision and determine these measurements with a greater degree of accuracy in order to evaluate these heat losses. This would provide assurances that all possible origins of heat waste are being considered and subsequently recovered for true optimization.

5. Conclusion

The world is being faced by several challenges. As engineers, we have the ability to effect real change in how we manage and use our resources. Our focus now is no longer only on how to utilize raw resources but, more importantly, on how we use those resources in every form they appear. Waste heat recovery provides an opportunity to challenge the way we see our resources by reimagining waste heat as another resource available to us. Using fundamental principles of thermodynamics, understanding material properties, and applying conversion technologies, we may harness additional energy from a seemingly unused pool of potential.

Thermoacoustics, a new player in the waste heat recovery field, is full of potential to inspire a new understanding of waste heat. Acoustic power, previously perceived as an often negligible source of energy, has shown promise as yet another unharnessed part of a developing technology. While maintaining a passive profile, thermoacoustic waste heat recovery can be amplified using existing and complementary waste heat technologies that extract useful work in a previously unnoticed place.

More research and quantitative analysis must be done to further the feasibility of thermoacoustic waste heat recovery technology. In comparing the advantages and disadvantages of each waste heat recovery unit, it is apparent that no single device reigns superior over the rest. Rather, to determine optimal performance for any application, it is vital to first determine temperature grades of available waste heat from a system and determine the types of heat transfers governing these losses. Gaining a more clear picture of the underlying thermodynamics and operation of the system will allow us, as engineers, to develop solutions that create interdependent devices that take advantage of inherent deficiencies to maximize power output and efficiency.

6. References

[1] "Waste Heat Recovery: Technology and Opportunities in U.S. Industry," p. 112.

[2] "Waste Heat Recovery Technologies and Applications - ScienceDirect" [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2451904918300015. [Accessed: 13-Feb-2020].

[3] "Regenerative Burner Mechanism:Tipton Corp." [Online]. Available: https://www.tipton.co.jp/english/sc/sc02.html. [Accessed: 22-May-2020].

[4] "Recuperative Burner (Recupeburner) /By Technology Classification|Technology|OSAKA GAS" [Online]. Available: https://www.osakagas.co.jp/en/rd/technical/1198941_6995.html. [Accessed: 22-May-2020].

[5] "B17_52_A Guide to Heat Exchangers for Industrial Heat Recovery_State of New York.Pdf."

[6] 2005, *Energy in Minerals and Metallurgical Industries*, Allied Publishers.
[7] “HK EE NET - Air Conditioning System Air-Side System/Equipment” [Online]. Available: https://ee.emsd.gov.hk/english/air/air_technology/air_tech_air.html. [Accessed: 22-May-2020].
[8] “Heat Exchangers,” IPIECA [Online]. Available: https://www.ipieca.org/resources/energy-efficiency-solutions/efficient-use-of-heat/heat-exchangers/. [Accessed: 22-May-2020].
[9] “Heat Pipes & Heat Exchangers” [Online]. Available: https://www.jhcss.com.au/products-1/thermal-management/heat-pipes-heat-exchangers. [Accessed: 22-May-2020].
[10] “Heat Sink Manufacturer | Heat Pipes & Vapor Chambers,” Celsia [Online]. Available: https://celsiainc.com/. [Accessed: 22-May-2020].
[11] Khodami, R., Abbas Nejad, A., and Ali Khabbaz, M. R., 2016, “Experimental Investigation of Energy and Exergy Efficiency of a Pulsating Heat Pipe for Chimney Heat Recovery,” Sustain. Energy Technol. Assess., **16**, pp. 11–17.
[12] In, B. D., and Lee, K. H., 2015, “A Study of a Thermoelectric Generator Applied to a Diesel Engine:,” Proc. Inst. Mech. Eng. Part J. Automob. Eng.
[13] Abdul Khalid, K. A., Leong, T. J., and Mohamed, K., 2016, “Review on Thermionic Energy Converters,” IEEE Trans. Electron Devices, **63**(6), pp. 2231–2241.
[14] Nicholas, R. J., and Tuley, R. S., 2012, “4 - Thermophotovoltaic (TPV) Devices: Introduction and Modelling,” *Functional Materials for Sustainable Energy Applications*, J.A. Kilner, S.J. Skinner, S.J.C. Irvine, and P.P. Edwards, eds., Woodhead Publishing, pp. 67–90.
[15] “Sir Charles Algernon Parsons | British Engineer,” Encycl. Br. [Online]. Available: https://www.britannica.com/biography/Charles-Algernon-Parsons. [Accessed: 21-May-2020].
[16] Allen, J. R., 1910, *Heat Engines:Steam--Gas--Steam Turbines--and Their Auxiliaries,* New York [etc.].
[17] 1859, *The London, Edinburgh and Dublin Philosophical Magazine and Journal of Science*, Taylor & Francis.
[18] Elferink, M., and Steiner, T., 2018, “Thermoacoustic Waste Heat Recovery Engine: Comparison of Simulation and Experiment,” Victoria, Canada, p. 065002.
[19] Sarpotdar, S., Ananthkrishnan, N., and Sharma, S. D., 2003, “The Rijke Tube — A Thermo-Acoustic Device,” Resonance, **8**, pp. 59–71.