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Waste heat recovery technologies and applications

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ABSTRACT

Industrial waste heat is the energy that is generated in industrial processes which is not put into any practical use and is lost, wasted and dumped into the environment. Recovering the waste heat can be conducted through various waste heat recovery technologies to provide valuable energy sources and reduce the overall energy consumption. In this paper, a comprehensive review is made of waste heat recovery methodologies and state of the art technologies used for industrial processes. By considering the heat recovery opportunities for energy optimisation in the steel and iron, food, and ceramic industries, a revision of the current practices and procedures is assessed. The research is conducted on the operation and performance of the commonly used technologies such as recuperators, regenerators, including furnace regenerators and rotary regenerators or heat wheels, passive air preheaters, regenerative and recuperative burners, plate heat exchangers and economisers and units such as waste heat boilers and run around coil (RAC). Techniques are considered such as direct contact condensation recovery, indirect contact condensation recovery, transport membrane condensation and the use of units such as heat pumps, heat recovery steam generators (HRSGs), heat pipe systems, Organic Rankine cycles, including the Kalina cycle, that recover and exchange waste heat with potential energy content. Furthermore, the uses of new emerging technologies for direct heat to power conversion such as thermoelectric, piezoelectric, thermionic, and thermo photo voltaic (TPV) power generation techniques are also explored and reviewed. In this regard, the functionality of all technologies and usage of each technique with respect to their advantages and disadvantages is evaluated and described.

1. Introduction

With the growing trend of increases in fuel prices over the past decades as well the rising concern regarding global warming, engineering industries are challenged with the task of reducing greenhouse gas emissions and improving the efficiency of their sites.

In this regard, the use of waste heat recovery systems in industrial processes has been key as one of the major areas of research to reduce fuel consumption, lower harmful emissions and improve production efficiency.

Industrial waste heat is the energy that is generated in industrial processes which is not put into any practical use and is wasted or dumped into the environment. Sources of waste heat mostly include heat loss transferred through conduction, convection and radiation from industrial products, equipment and processes and heat discharged from combustion processes [1]. Heat loss can be classified into high temperature, medium temperature and low temperature grades. Waste Heat Recovery (WHR) systems are introduced for each range of waste heat to allow the most optimum efficiency of waste heat recovery to be obtained.

High temperature WHR consists of recovering waste heat at temperatures greater than 400 °C, the medium temperature range is 100–400 °C and the low temperature range is for temperatures less than 100 °C [2]. Usually most of the waste heat in the high temperature range comes from direct combustion processes, in the medium range from the exhaust of combustion units and in the low temperature range from parts, products and the equipment of process units [2].

It is estimated that the UK industrial sector consumes as much as 17% of the overall UK economy's energy consumption and generates about 32% of the UK's heat-related CO_2 emissions. From this value and as can be seen from Fig. 1, 72% of the UK industrial demand is from industrial thermal processes of which 31% is classified as low temperature process heat [3] and almost 20% of that or 40 TWh/yr is estimated to have potential for industrial waste heat recovery [4]. It is found that the most energy consuming industries in the UK are cement, ceramic, iron and steel, refineries, glassmaking, chemicals, paper and pulp and food and drink. These industries together contribute about £50 bn/yr to the UK's economy [4]. This indicates that improving

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Nomenclature

Symbols

Cp	specific heat (J/kg.K)
h	specific enthalpy (J/kg)
Q	heat content (J)
q	heat (J)
s	specific entropy (kJ/kg.K)
T	temperature (K)
V	flow rate (m^3/s)
w	work (J)
ρ	density (kg/m^3)

Acronyms

BOF	Basic Oxygen Furnace
CHP	Combined Heat and Power
CRC	Clausius-Rankine Cycle
HRSG	Heat Recovery Steam Generator
IC	Internal Combustion
ORC	Organic Rankine Cycle
RCA	Spinning Disk Atomiser
SDA	Rotating Cup Atomiser
WHR	Waste Heat Recovery
RAC	run around coil

Subscripts and superscripts

CO	carbon monoxide
CO_2	carbon dioxide
CP	*Critical Pressure*
H_2	Molecular Hydrogen
Fe	pig iron
FeO	iron oxide
Tb	Average Temperature
Tc	Temperature Cold
ΔT	Temperature Difference

energy efficiency through waste heat recovery models can help UK businesses to reduce the operating costs of their businesses, improve the energy efficiency of their sites and reduce the UK's industrial CO_2 emissions.

2. Waste heat recovery systems

Waste heat recovery methods include capturing and transferring the waste heat from a process with a gas or liquid back to the system as an extra energy source [5]. The energy source can be used to create additional heat or to generate electrical and mechanical power [6].

Waste heat can be rejected at any temperature; conventionally, the higher the temperature, the higher the quality of the waste heat and the easier optimisation of the waste heat recovery process. It is therefore important to discover the maximum amount of recoverable heat of the highest potential from a process and to ensure the achievement of the maximum efficiency from a waste heat recovery system [7].

The quantity or the amount of available waste heat can be calculated using the equation shown below.

$$Q = V \times \rho \times C_P \times \Delta T \tag{1}$$

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

Depending on the type and source of waste heat and in order to justify which waste heat recovery system can be used, it is essential to investigate the amount and grade of heat recoverable from the process.

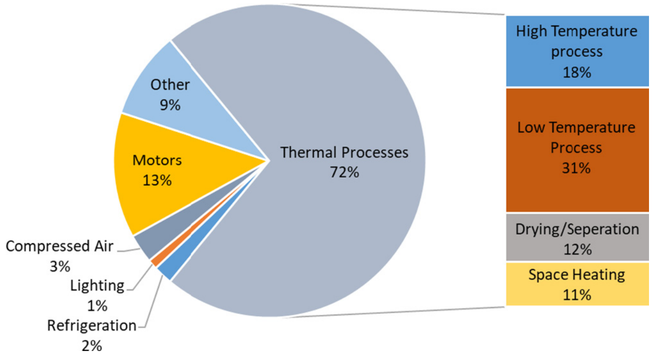


Fig. 1. Energy consumption in the UK manufacturing industry [3].

There are many different heat recovery technologies available which are used for capturing and recovering the waste heat and they mainly consist of energy recovery heat exchangers in the form of a waste heat recovery unit. These units mainly comprise common waste heat recovery systems such as air preheaters including recuperators, regenerators, including furnace regenerators and rotary regenerators or heat wheels and run around coil, regenerative and recuperative burners, heat pipe heat exchangers, plate heat exchangers, economisers, waste heat boilers and direct electrical conversion devices. These units all work by the same principle to capture, recover and exchange heat with a potential energy content in a process.

2.1. Regenerative and recuperative burners

Regenerative and recuperative burners optimise energy efficiency by incorporating heat exchanger surfaces to capture and use the waste heat from the hot flue gas from the combustion process [8]. Typically, regenerative devices consist of two burners with separate control valves, which are connected to the furnace and alternately heat the combustion air entering the furnace. The system works by guiding the exhaust gases from the furnace into a case which contains refractory material such as aluminium oxide [9]. The exhaust gas heats up the aluminium oxide media and the heat energy from the exhaust is recovered and stored. When the media is fully heated, the direction of the flue gas is reversed, with the stored heat being transferred to the inlet air entering the burner and the burner with hot media starts firing. Combustion air from the hot media then heats up the cooler media and the process starts again. Through this technique, the regenerative burner can save the fuel needed to heat the air and this improves the efficiency of combustion [10] (see Fig. 2).

Burners that incorporate recuperative systems are also used commercially. A recuperative burner has heat exchanger surfaces as part of the burner design, which capture energy from the heated gas that passes through the body of the burner [12]. The burner uses the energy of waste gas from the exhaust to preheat the combustion air before it gets mixed with the fuel. The burners consist of an internal heat exchanger with various features such as grooves, counter current flow and fins, which are used to establish thermal contact between the waste exhaust gases and the combustion air coming from the supply pipe [13]. The design works by collecting the both the exhaust gas and waste heat from the body of the burner nozzle, and using them both to transfer heat into the combustion air. This air preheating results in an improved efficiency of combustion and thus more heat from the nozzle.

It should be noted that the burner and the nozzle are inserted into

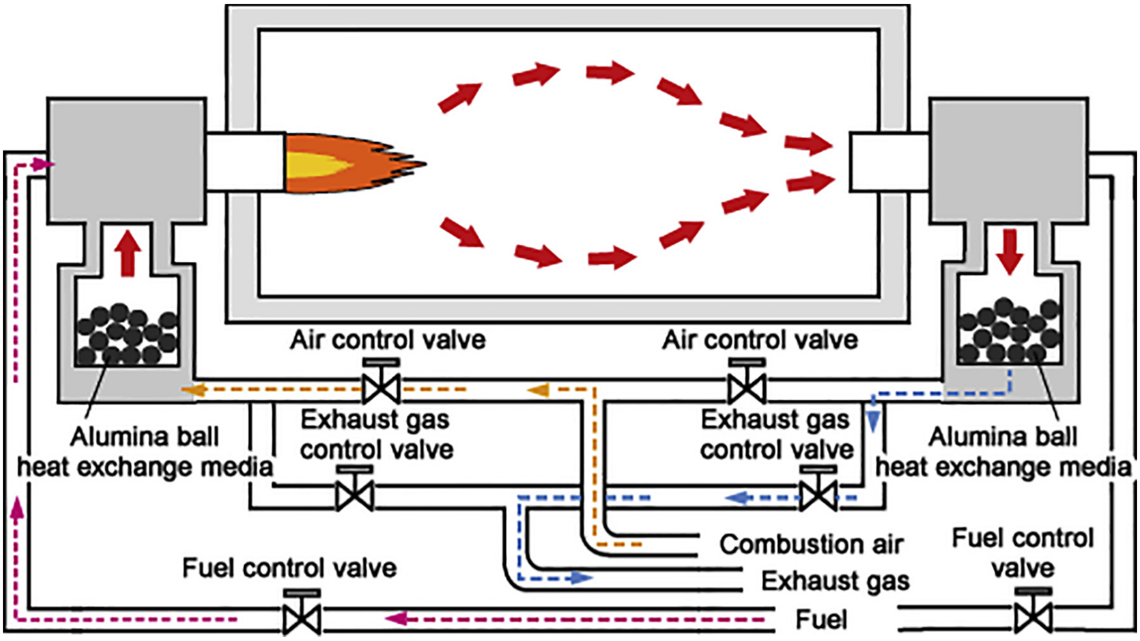


Fig. 2. Regenerative burner mechanism [11].

the furnace body and the waste heat is transferred to the burner by convection from the exhaust gases. *Osaka Gas* [14] demonstrates that for a furnace with a temperature of 1000 °C the air can be preheated to at least 500 °C, indicating a considerable improvement of thermal efficiency (see Fig. 3).

2.2. Economisers

Economisers or finned tube heat exchangers that recover low – medium waste heat are mainly used for heating liquids. The system consists of tubes that is covered by metallic fins to maximise the surface area of heat absorption and the heat transfer rate [15].

The system is located in the duct carrying the exiting exhaust gases and it absorbs the waste heat by letting the hot gases pass through different sections covered by the finned tubes. Liquid is passed through the tubes and it captures heat from the finned tubes. The hot liquid is then fed back to the system, maximising and improving the thermal efficiency [16]. Based on a study conducted by *Spirax Sarco* [17], it is shown that if an economiser is used for a boiler system, it can increase the efficiency by 1% for every 5 °C reduction of flue gas temperature. This indicates that the fuel consumption of the system can be reduced by 5–10% with a payback period of less than 2 years [18]. Economisers recover the waste heat and improve the efficiency of a system by preheating the fluid in the system such as the feedwater in a steam generator or a boiler, so less energy is required to achieve the boiling temperature. In another study by *Maxxtec* [19], it is noted that regardless of the design of the system, if the temperature of the flue gas is reduced by 140 °C, the fuel consumption can be reduced by 7%.

It is investigated that several different types of economisers are available for different applications but they have the same functionality [20]. These designs include finned tubes, coiled tubes, non-condensing and condensing economisers. The condensing and non-condensing

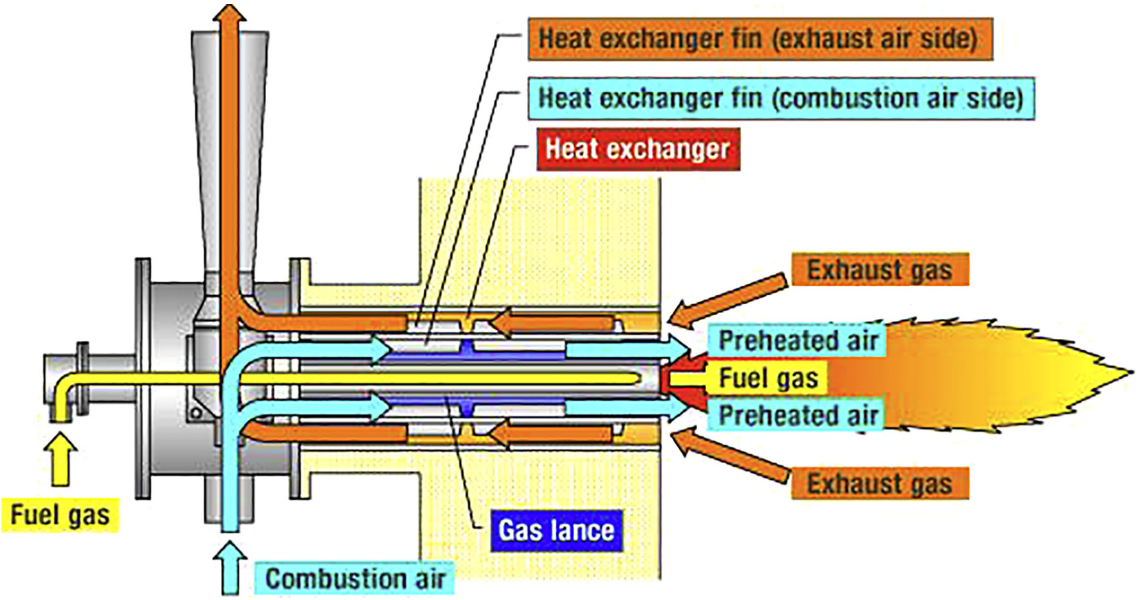


Fig. 3. Recuperative burner structure [14].

types are mainly used to improve the efficiency of boiler systems, whereas the other types are commonly used in thermal power plants and large processing units to recover waste heat from the flue gas.

Having mentioned that, *Vandagriff* [21] investigates, economisers that are used for low-temperature heat recovery namely as deep economisers are also available that are made out of advanced materials such as Teflon, carbon and stainless-steel tubes and can withstand the acidic condensate deposition on the surface of the heat exchanger. Glass-tubed economisers are on the hand used for gas to gas heat recovery and for low to medium temperature applications [22].

2.3. Waste heat boilers

Waste heat boilers consists of several water tubes that are placed in parallel to each other and in the direction of the heat leaving the system. The system is suitable to recover heat from medium – high temperature exhaust gases and is used to generate steam as an output. The steam can then be used for power generation or directed back to the system for energy recovery [23].

For example, as *J* + *G* [24] reports, in a coal power plant the heat generated from the combustion process after leaving the combustion chamber has a temperature of up to 1000 °C. The use of a waste heat boiler in this case allows the recovery and utilisation of the heat of the flue gas to vaporise a fluid and produce steam that can be used for energy generation through turbines and generators.

The pressure and the rate of steam production mainly depends on the temperature of the waste heat. If the waste heat is not sufficient for the system to produce the required amount of steam, an auxiliary burner unit or an after burner in the exhaust gases can be added to the system to compensate for that [25].

As *Turner* [26] reports, waste heat boilers can also be coupled with other waste heat recovery equipment such as afterburners, preheaters and finned-tubed evaporators to improve efficiency by preheating the feed water and produce superheated steam if required (see Fig. 4).

2.4. Air preheaters

Air preheaters are mainly used for exhaust-to-air heat recovery and for low to medium temperature applications. This system is particularly useful where cross contamination in the process must be prevented. Such applications can include gas turbine exhausts and heat recovery from furnaces, ovens, and steam boilers [27].

Air preheating can be based on two different designs, the plate type and the heat pipe type. The plate type consists of parallel plates that are placed perpendicular towards the incoming cold air inlet. Hot exhaust air is fed into the channels between the plates, transferring heat to the plates and creating hot channels, through which the cold air is passed.

The heat pipe type on the other hand consists of a bundle of several sealed pipes placed in parallel to each other in a container. The container is split into two sections accommodating cold and hot air, inlet and outlet. The pipes inside the container accommodate a working fluid which when faced with the hot waste gas at one end of the pipes, evaporates and moves towards the other end of the pipe where cold air is passing [28]. This results in heat being absorbed at the hot section of the pipe, which is transferred to the cold section, heating the cold moving air over the pipes. The working fluid then condenses and moves towards the hot section of the pipe, repeating the cycle [29].

As *Nicholson* [30] explain, there are mainly three commonly used types of air preheaters which are classified as regenerators, including rotary regenerators, run around coil, and recuperative. These technologies all function with the same principle as air preheaters, however, have different configurations and used for different purposes (see Fig. 5).

2.4.1. Recuperators

Recuperators are a form of heat exchanger units that are usually made out of metallic or ceramic materials, depending on their application, and they are used to recover waste exhaust gases at medium to high temperature [32].

In this technology, the hot exhaust gases are passed through a series of metal tubes or ducts that carry the inlet air from atmosphere. This result in the recuperator preheating the inlet gas which then re-enters the system. The energy that is now available in the system can therefore be described as the energy which does not have to be supplied by the fuel, meaning that a decrease in energy demand and production costs is achieved [33].

Metallic recuperators are used for applications with low – medium temperatures, while heat recovery in high temperature application is better suited to ceramic recuperators. Recuperators can be said to mainly transfer heat to the inlet gas based on convection, radiation or a combination of radiation and convection. A radiation recuperator consists of metallic tubes around the inner shelf where hot exhaust gases pass through. The cold incoming air is then fed to the tubes around the hot shelf and heat is radiated to the wall of the tubes (see Fig. 6).

The tubes transfer the heat to the cold air, which is then delivered to the furnace burners. On the other hand, the convective recuperator exchanges heat by passing hot exhaust gases through relatively small diameter tubes that are placed in a larger shelf. The cold air is passed through the large shelf, picking up heat from the small hot tubes inside the shelf that is heated by the waste gas.

A combination of radiant and convective recuperators provides another possibility which can maximise heat transfer effectiveness. In this technology, hot exhaust gas is fed into a larger shelf and then split into smaller diameter tubes. Cold air is fed into and around the shelf, and this results in a quantitative improvement in heat transfer [35] (see Fig. 7).

2.4.2. Regenerators

Regenerators transfer heat from the hot gas duct to the cold gas duct through storing the waste heat in a high heat capacity material. The

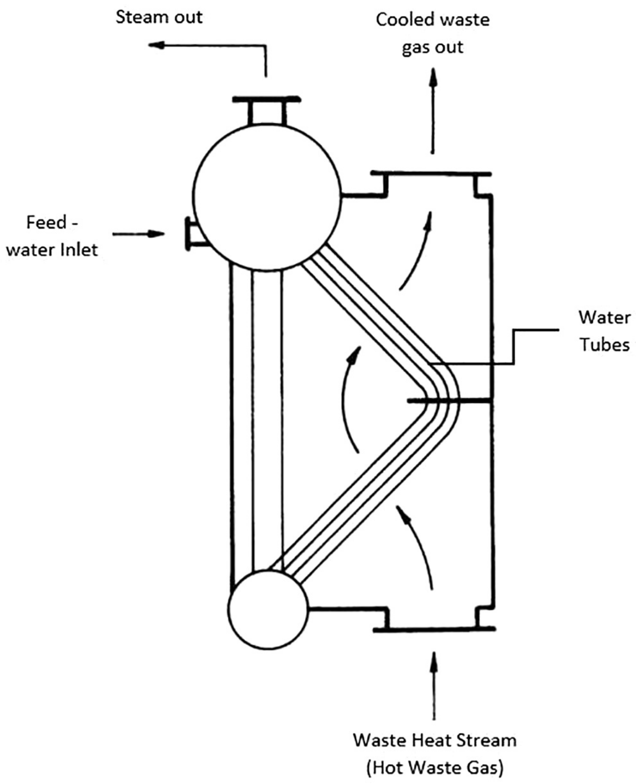


Fig. 4. Schematic of a waste heat boiler incorporating parallel water tubes [26].

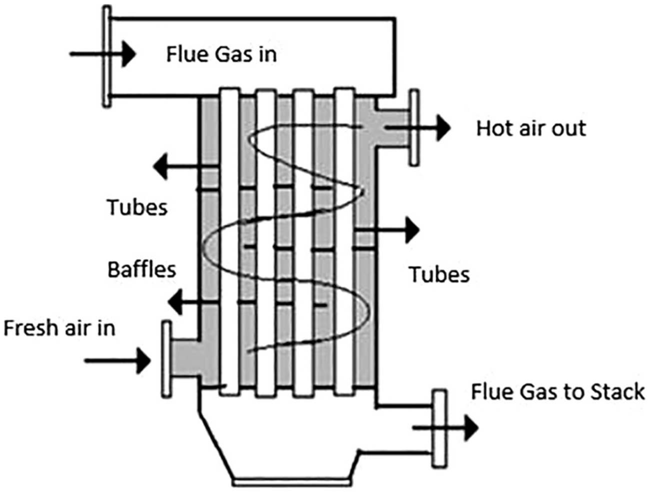


Fig. 5. Air preheater layout showing air movement [31].

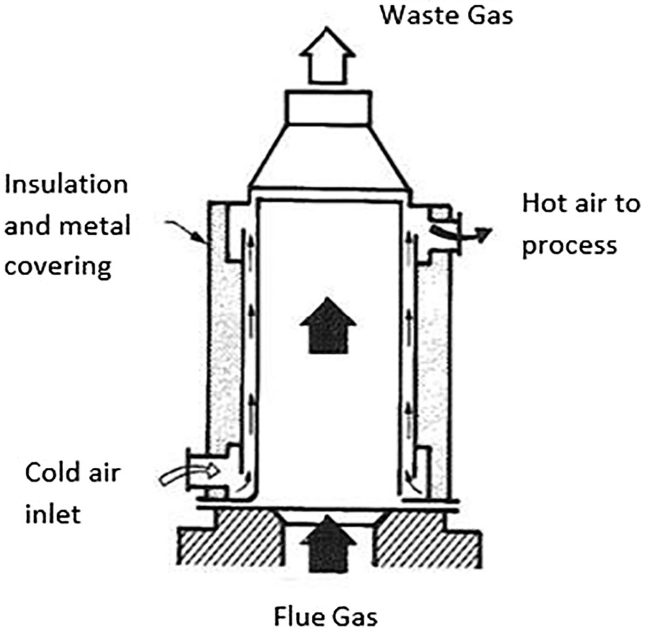


Fig. 6. Diagram of metallic recuperator [34].

system consists of a chamber which is used as a link between the hot air duct and the cold air duct that takes the heat energy from the hot side, stores and delivers it to the cold side. For instance, regenerative furnaces consist of two brick chambers through which hot and cold air exchange heat. As hot combustion gases pass through the brick chamber, heat from the hot flue gas is absorbed, stored and delivered to the cold airflow when it is passed through the chamber. The flow of the preheated gas is then injected into the flow going to the combustion chamber, decreasing the amount of energy needed to heat the system.

Two chambers are used so that, one is transferring heat to the flow entering the system, the other one is absorbing heat. The direction of inlet flow is changed frequently to allow a constant heat transfer rate to be obtained [36].

Regenerators are suitable for high temperature applications such as glass furnaces and coke ovens and they have been historically used with open-hearth steel furnaces. Regenerators are particularly suitable for applications with dirty exhausts, however, they can be very large in size and have very high capital costs, which is a disadvantage with this technology [37].

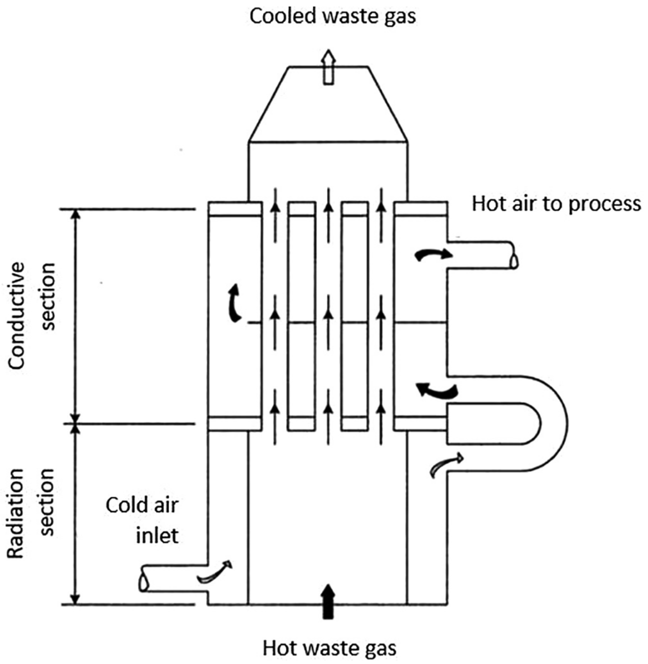


Fig. 7. Combined radiation and convective type recuperator [33].

2.4.3. *Rotary regenerators*

Rotary regenerators work in a similar manner to fixed regenerators, however, in this technology, heat is transferred through a porous thermal wheel between the hot and cold flows. In this system, two parallel ducts containing hot and cold flows are placed across a rotary disk or heat wheel which is made out of a high thermal capacity material. The heat wheel takes and stores heat from the flow coming through the hot duct, rotates and delivers it to the flow coming through the cold duct. Rotary regenerators are used for low – medium temperature applications and could potentially offer a very high overall heat transfer efficiency [38] (see Fig. 8).

The reason heat wheels are not suitable for high temperature applications is due to the structural stresses and the possibility of large expansion and deformations that can be caused by high temperature differences between the two ducts [39]. Having said that, heat wheels made out of ceramic materials can be used for high temperature applications.

As heat wheels are mainly made out of porous material, cross contamination therefore be cannot prevented. This can be a major

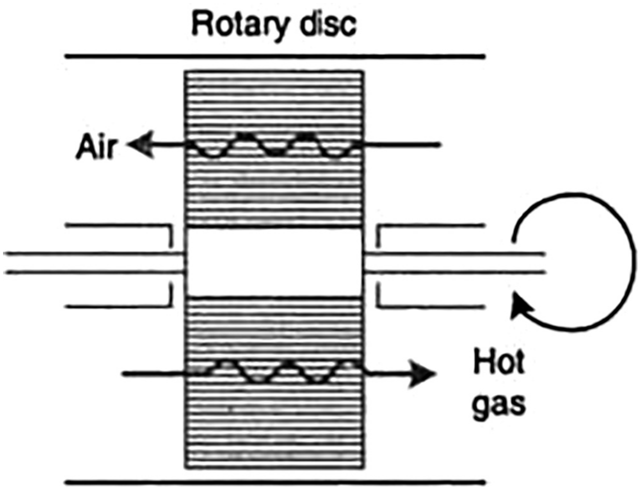


Fig. 8. Schematic diagram of heat wheel [33].

disadvantage especially when cross contamination between the two ducts must be prevented. However, this is shown to be advantageous for applications where recovering humidity and moisture from the outlet duct is required [38].

2.4.4. Run around coil (RAC)

This system as can be seen from Fig. 9 and according to *Toolan* [40], consists of a pair of coiled heat exchangers that are connected to each other by a run around coil that is filled with a fluid such as a water or glycol or a mixture of both [41]. The liquid in the coil takes the waste heat that is captured by the primary recuperator from the exhaust gas of a process and transports it to the secondary recuperator where it would be mixed with the supply air. The possibility of exchanging heat between the two air streams is due to the liquid round coil system, which are connected to each other by a pumped pipework.

This unit is used when the sources of heat are too far from each other to use a direct recuperator and when cross contamination between the two flow sources due to moister, corrosive gases, toxic and biological contaminates needs to be prevented. This system is found to have a very low effectiveness when compared to a direct recuperator and needs a pump to operate, which requires additional energy input and maintenance [43]. Having said that and as *Carbon Trust* [44] discovers, the effectiveness and efficiency of this technology can be improved by using a secondary heat source as shown in Fig. 10.

2.5. Plate heat exchanger

Plate heat exchangers are used to transfer heat from one fluid to another when cross contamination needs to be avoided. A plate heat exchanger is made out of several thin metal plates that are stacked or brazed in parallel to each other and formed into a hollow metallic shell. Each plate usually consists of different pressed patterns that are surrounded with gaskets to control the fluid flow and produce turbulence for better heat transfer [45]. The gaskets are arranged in such a way that allows only one type of fluid to flow through one gap, while the other fluid gets directed through the adjacent gap [46]. As can be seen from Fig. 11, between every two consecutive plates a space or passage has been implemented that makes the hot and cold fluids flow along and through the plane of the plates.

This way, the hot and cold fluids pass through each section of the heat exchanger passing over the front and back of plates alternatively, exchanging heat and not getting contaminated with each other. The other advantage plate heat exchangers offer in comparison with similar types of heat exchanger such as the conventional shell and tube heat exchangers is the fact the hot and cold fluids are exposed to a larger surface area per unit volume and a larger heat transfer coefficient [48].

It is reported that there are mainly three types of plate heat exchanger, arranged in either single-pass or multi-pass arrangements, as shown in Figs. 12 and 13 [49,50]. The plates of plate heat exchangers can either be gasketed, brazed or be welded together [51,52]. In a gasket plate heat exchanger, a gasket usually made out of a polymer material is placed between the plates that works as a seal and separator around the edges of the plates [53]. The plates are placed and clamped together in a frame with the use of tightening bolts and two thicker pressure plates on each side.

The design therefore allows the heat exchanger to be dismantled for cleaning or be optimised to have a bigger or smaller capacity by removing or adding additional plates [54]. The use of gaskets with this design brings the advantage of resistance to thermal fatigue and sudden pressure variation as it gives flexibility to the plate pack. This is ideal for applications that constantly go through thermal cycling by being exposed to variations of temperature [55]. Having said that, the use of gaskets is restricted by the operating temperature and pressure of the cycle which is a disadvantage [56]. Gasket plate heat exchangers are nonetheless proven to give efficient and effective heat transfer with a recovery rate of up to 90% [57].

In a brazed plate heat exchanger, all the plates are brazed together by using copper or Nickel in a vacuum furnace [59]. The design unlike the gasket heat exchanger offers more resistance to higher pressure and temperature ranges and is relatively cheap to maintain [60]. However, as it is brazed, it cannot be dismantled which means issues can be raised when cleaning or modifying the size is required. As the design also has a more rigid construction than the gasket type, it is more susceptible to thermal stress and any sudden or frequent variation in temperature and load can lead to fatigue and the failure of the structure. *IITD* [61] concludes therefore, that brazed heat exchangers are mainly used for applications where temperature variation is slow and applications where thermal expansion is gradual, such as with thermal oils.

Welded plate heat exchangers are reported to have more flexibility and resistance when it comes to thermal cycling and pressure variations as compared to brazed heat exchangers [55]. This advantage is achieved through the use of laser welding techniques that hold the plate pack together by welded seams [62]. This type of heat exchanger is shown to have higher temperature and pressure operating limits and because of this they are found to be suitable for heavy duty applications [63]. Nonetheless, similar to the brazed heat exchangers, they cannot be dismantled and modified in size.

With the use of a plate heat exchanger in an experiment, *Cipollone* [64] demonstrated that the performance of an evaporator used for a heat recovery steam generator can be improved when a plate heat exchanger is used as the component to superheat the working fluid of the system.

2.6. Heat pipe systems

As can be seen from Fig. 14, a heat pipe is a device which can transfer heat from one place to another with the help of condensation and vaporisation of a working fluid. A heat pipe consists of a sealed container, a wick structure, and a small amount of working fluid such as water, acetone, methanol, ammonia or sodium that is in equilibrium with its own vapour [65]. A heat pipe can be divided into three different sections: the evaporator section, the adiabatic transport section and the condenser section.

When heat is applied to one end of the pipe, it is conducted through the pipe wall and wick structure and the working fluid inside the pipe evaporates. As a result, a vapour pressure is generated which drives the vapour through the adiabatic transport section to the other end of the pipe. The vapour then condenses by losing the latent heat of vaporisation through the wick structure and wall of the pipe to the heat sink. The vapour flow then turns into liquid and is absorbed by the wick structure. The capillary pressure that is created by the menisci in the wick structure drives the liquid back to the hot end of the pipe and the

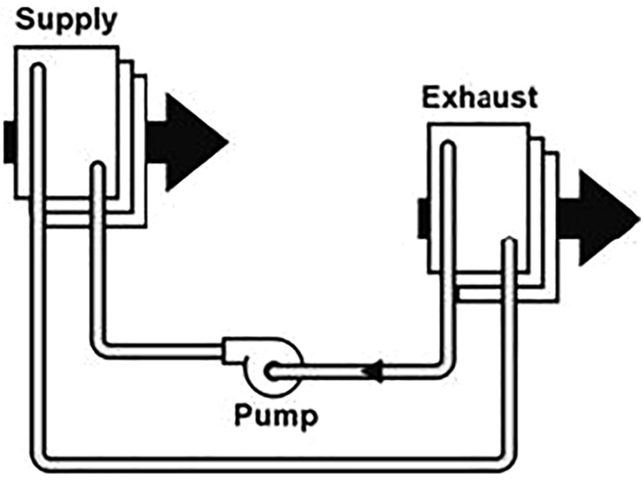


Fig. 9. Schematic of run around coil system [42].

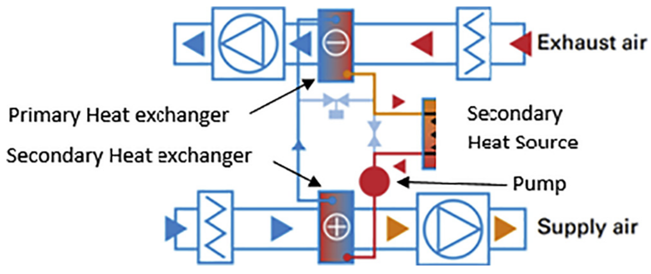


Fig. 10. Run around coil system compromising a secondary heat source [44].

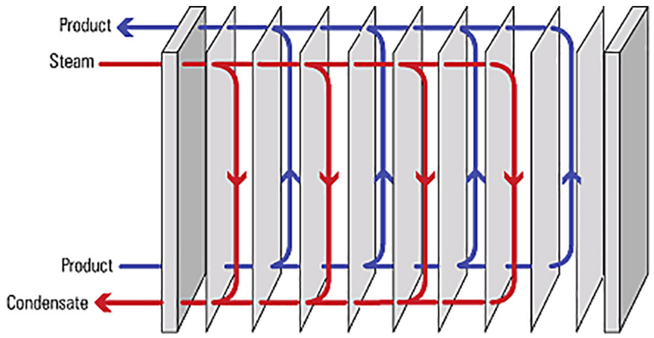


Fig. 11. Schematic of a plate heat exchanger [47].

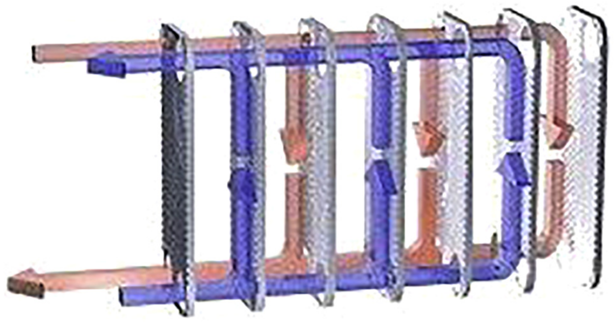


Fig. 12. Single-pass configuration plate heat exchanger [58].

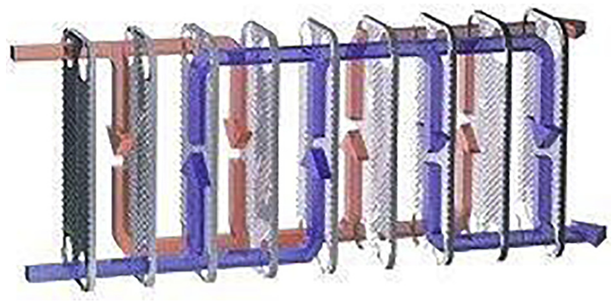


Fig. 13. Multi-pass configuration plate heat exchanger [58].

cycle repeats [66].

It can be shown that heat pipes have very high effective thermal conductivities. Solid conductors such as aluminium, copper, graphite, and diamond have thermal conductivities ranging from 250 to 1500 W/m K whereas heat pipes have effective thermal conductivities in the range from 5000–200,000 W/m K [67].

Heat pipes are constructed from a range of different materials such as aluminium, copper, titanium, Monel, stainless steel, Inconel and tungsten. The choice of the material used for heat pipes largely depends on the application temperature range and the compatibility of the material with the working fluid [68].

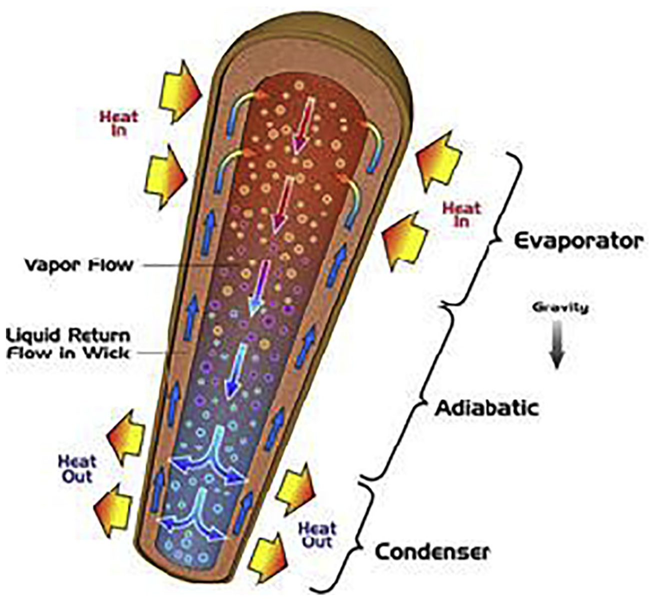


Fig. 14. Schematic of a heat pipe [69].

As mentioned earlier, the heat pipe wick structure aids the transport of the working liquid from the condenser back to the evaporator. Various materials and techniques are used to construct the heat pipe wick structure, however as *PSC* [70] reports, groove, screen/woven and sintered powder metal structures are the most common. It is also reported that heat pipes referred to as thermosyphons are also available; they have no wick structure and work only with the aid of gravity. These heat pipes cannot be used in a horizontal orientation and should be placed vertically. Having mentioned this, heat pipes with a wick structure can operate in both horizontal and vertical orientations and do not have such a limitation.

As shown in Fig. 15, screen mesh structure wicks are usually made out of copper or stainless materials and are expanded against the pipe wall to form the wick structure. Heat pipes made with this structure are capable of transporting the working fluid both horizontally and vertically and also against gravity at a very slight angle from the horizontal [70]. Grooved wick structures on the other hand consist of raised dents that are made perpendicular to the pipe surface by extrusion or threading processes commonly out of copper or aluminium materials. Heat pipes made with this type of structure can operate in gravity aided and horizontal orientations and similar to screen wick structures can transport liquid at a slight angle from horizontal [71]. In contrast, as *ATS* [72] showed in the conducted experiments, sintered copper powder structures are capable of transporting the working fluid against gravity vertically and also horizontally with not much limitation. This type of wick structure is made usually from copper powder particles that are fused together to form a sintered wick structure.

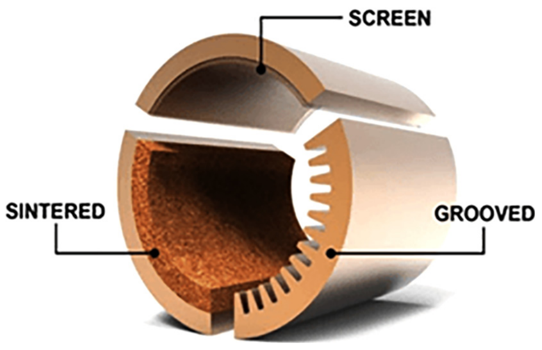


Fig. 15. Common wick types of a heat pipe [73].

The type of working fluid used in a heat pipe largely depends on the temperature range of the application for which the heat pipe is being used. For example, as explained by *Faghri* [65] and *ACT* [74], for low temperature applications in the temperature range of 200–550 K, ammonia, acetone, "Freon" refrigerants and water are used. Most applications of heat pipes usually fall within this temperature range and water is reported to be the mostly used fluid as it is cheap, has good thermo-physical properties and also is safe to handle [75]. Heat pipes in general have a high thermal conductivity, which results in a minimal temperature drop for transferring heat over long distances, long life that requires no maintenance, as they incorporate passive operation and no moving parts which can wear out and they have lower operation costs when compared to the other types of heat exchangers [76].

2.6.1. *Pulsating heat pipes*

Pulsating heat pipes or PHPs are passive closed two-phase heat transfer devices that are similar to conventional heat pipes and are capable of transporting heat without the requirement of any additional power input. As shown in Fig. 16, the system consists of a narrow meandering long tube that is filled with a working fluid. The PHP can be in the form of either open-loop or closed-loop configuration and operate by the oscillatory flow of liquid slugs and vapour plugs. As can be seen from Fig. 16, in the closed-loop configuration, both ends of the tube are connected to each other, whereas, for the open-loop configuration, one end of the tube is welded and pinched off, while the other end is open and connected to a charging valve [77,78]. The main difference between PHPs and heat pipes is the fact that there is no wick structure to deliver the condensate to the condenser and heat transfer is entirely achieved by the oscillatory flow [79]. *Holley and Faghri* [80] developed a PHP with a sintered copper wick structure and demonstrated that the working fluid is better distributed throughout the pipe which results in more nucleation sites for boiling and as a result the fluctuation in local temperature is reduced.

For instance in an experiment, [82] investigated and proved that with the use of closed-loop oscillating heat pipe, the quantity of using fuel in pottery kilns can be reduced and energy thrift can be achieved. In this experiment, a closed-loop oscillating heat pipe that was made out of copper capillary tube and filled with R123 and water was used as a heat exchanger to recover the waste heat from pottery kilns.

2.7. *Heat recovery steam generator (HRSG)*

The heat recovery steam generator (HRSG) is a complex system used to recover the waste heat from the exhaust of a power generation plant. It consists of several heat recovery sections such as an evaporator, super heater, economiser and steam drum, which are very large in size. By looking at the configuration of a HRSG in Fig. 17, it can be pointed out that the superheater is placed in the path of the hottest gas upstream of the evaporator and the economiser is placed downstream of the evaporator in coolest gas.

Typically, HRSGs comprise a triple pressure system, this being high pressure, reheat or intermediate pressure and low pressure [84]. The system can also recover the waste heat from the exhaust of manufacturing processes to improve overall efficiencies by generating steam that can be used for process heating in the factory or for driving a steam turbine to generate electricity. It is reported that with the use of HRSG for steam production, a system efficiency of as high as 75–85% can be achieved [85].

The system contains an evaporator section and a steam drum for converting water to steam. The steam is then superheated as its temperature is increased beyond the saturation point. As can be seen from Fig. 18, the evaporator is located between the economiser and the superheater with the steam drum on top of it.

In the evaporator, the steam for the turbine is generated which is then delivered to the steam drum and the superheater. As shown in Fig. 18, in the steam drum the steam and water mixture is separated from the saturated steam as the feedwater is delivered to the evaporator.

The steam is separated in two steps through a combination of gravity and mechanical work before it gets delivered to the superheater. This heats the steam beyond the saturation temperature, i.e. generating superheated steam. The economiser on the other hand, preheats the feedwater to the evaporator, thus improving the efficiency of steam generation. The steam generated in the process is then sent to a thermodynamic cycle such to generate power and improve the efficiency of the plant.

2.8. *Thermodynamic cycles used for waste heat recovery*

As *Costiuc et al.* [87] explain, through the use of thermodynamic cycles, heat recovery from waste sources can be directly conducted to obtain electrical energy and improve energy efficiency of a process. In this regard, *Nemati et al.* [88] through a comparative thermodynamic analysis of Organic Rankine Cycle and Kalina Cycle suggested that the use of thermodynamic cycles that employ organic working fluids enables a cost effective and promising way of energy recovery from moderate grades of waste heat sources. In this chapter therefore, the usage and functionality of the mentioned thermodynamic cycles for WHR will be reviewed.

2.8.1. *Organic Rankine cycle*

The Organic Rankine Cycle works on the principle of the Clausius-Rankine cycle, however, the system uses organic substances with low boiling points and high vapour pressures as the working fluid to generate power instead of water or steam [89]. It has been shown that the use of an organic fluid as the working fluid makes the system suitable for utilising low grade waste heat and for power generation using energy sources such as geothermal [90], biomass [91], and solar applications [92].

The Clausius-Rankine Cycle or CRC is introduced as the ideal vapour power cycle and is described as the elementary operating cycle for all power plants that use an operating fluid such as water to generate electricity [93]. A typical Rankine cycle consists of a pump, a condenser, an evaporator and a generator. Fuel is burned in the evaporator and the water as the working fluid is heated to generate superheated steam. This is then directed to the turbine to generate power and then passed through the condenser, losing heat and turning back into its

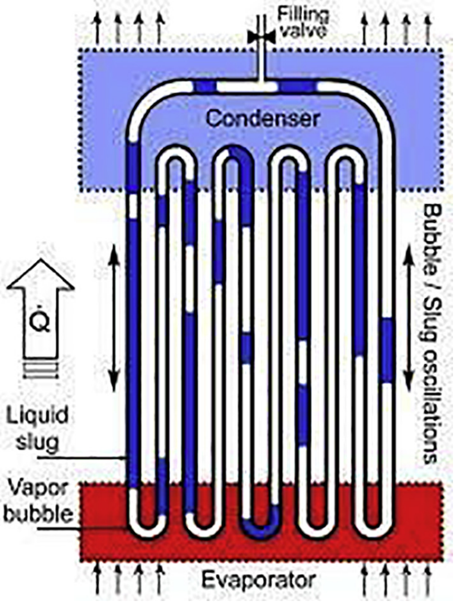


Fig. 16. Schematic of a pulsating heat pipe [81].

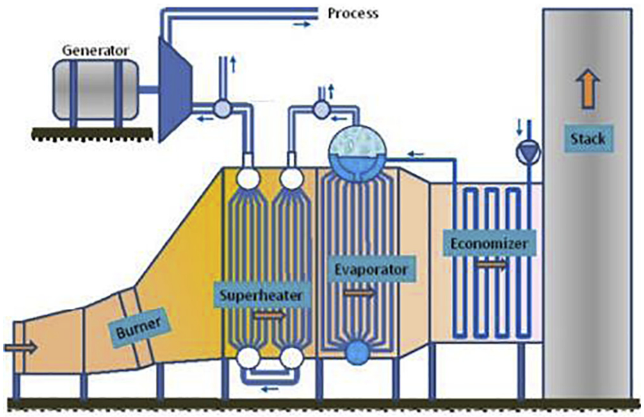


Fig. 17. Heat Recovery Steam Generator (HRSG) [83].

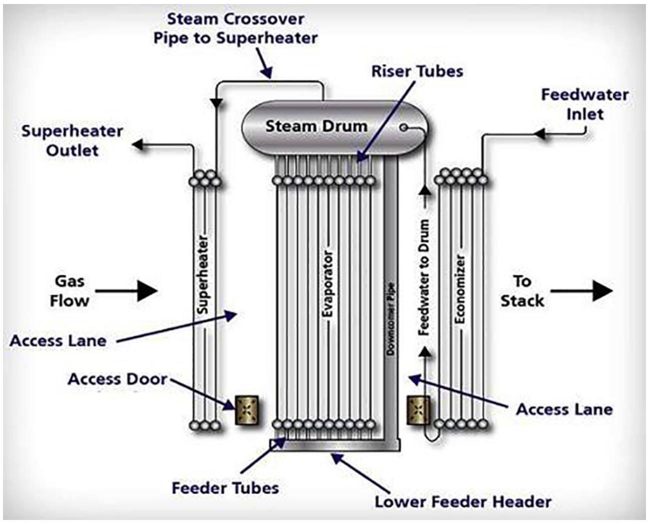


Fig. 18. Typical heat recovery steam generator components [86].

liquid state. The liquid water is then pumped into to the evaporator and the cycle is repeated.

When compared to the CRC, typically an Organic Rankine cycle (ORC) system consists of a heat exchanger which is connected to an evaporator and a preheater in a cycle, and a recuperator that is linked to a condenser [94]. This way, when waste heat travels from the source and passes over the heat exchanger, the heat exchanger will heat the intermediate fluid which then cycles through the evaporator and preheater. The organic fluid is then heated by intermediate fluid causing it to vaporise and becomes superheated vapour.

The vaporised organic fluid then passes with high enthalpy through the turbine and the vapour expands causing the turbine to spin and generate electricity [95]. The vapour then exits the turbine and passes over the recuperator to reduce the temperature and preheat the organic fluid at a later stage.

At the condenser, air or water from a cooling tower or the environment condenses the organic vapour back into a fluid. Once the fluid reaches the pump, the system is pressurised to the required level and the fluid will then pass again to the recuperator where it is reheated and the cycle restarts [96] (see Fig. 19).

Mamun [98] showed an ORC offers many advantages when compared to conventional steam turbine for waste heat recovery. *Stefanou et al.* [99] demonstrated that with the use of an ORC along with a waste heat recovery steam generator unit in a steel mill, a net efficiency of almost 22% can be achieved.

The design and performance of an ORC system nonetheless depends on the selection of the working fluid and its specifications in terms of thermodynamics and environmental and safety criteria [100]. This therefore indicates that the selection of the optimum working fluid is an important task when considering the use of ORC for waste heat recovery processes. For instance, *Douvartzides and Karmalis* [101] considered 37 different working fluid substances and demonstrated that by appropriately selecting the working fluid and the operation for the cycle, the overall efficiency of a plant can be increased by almost 6% and the fuel consumption can be reduced by 13%.

2.8.2. Kalina cycle

Similar to Organic Rankine cycle, the Kalina cycle is a variant of Rankine cycle that uses the working fluid in a closed cycle to generate electricity. This system however, commonly uses a mixture of water and ammonia as the working fluid [102] in a process that usually consists of a recuperator and separator in addition to other components of a Rankine cycle to generate steam and power (see Fig. 20).

The difference between the Kalina cycle and cycles that use a single fluid to operate is in the fact that the temperature does not remain constant during boiling and this is shown to result in a greater efficiency for the cycle [104]. In a single-fluid cycle, the working fluid is uniformly heated to the evaporating temperature at which a constant supercritical or superheated steam is generated. However, for a binary mixture working fluid such as in the Kalina cycle, the temperature of each fluid is increased separately during evaporation as a result of each fluid having a different boiling point. This will result in a better thermal matching with the evaporator and condenser as the source of the cooling medium does not need to satisfy a particular working fluid in the process [105] (see Fig. 21).

This can be also clearly illustrated in the T, s diagrams shown below which indicates that for the Kalina cycle, the average hear rejection temperature (Tc) is lower and the average heat addition temperature (Tb) is higher when compared to a Rankine cycle. This and according to Eq. (2) derived for Carnot efficiency (η_{Carnot}), will result in a higher thermal efficiency [106].

$$\eta_{Carnot} = 1 - T_c/T_b \tag{2}$$

Based on above explanation, *Wang* [107] by developing a mathematical model from the waste heat recovered through a waste heat boiler demonstrated that the Kalina cycle system shows a better performance when compared to ORC.

On the other hand, *Milewski* [108] studied the concept of WHR based on the ORC and Kalina cycle in the steel industry and discovered that the Kalina cycle offers a better result when the recovered heat is of medium-high grade nature. In this study, the ORC was a competitor to the Kalina cycle when the recovered heat was below 200 °C.

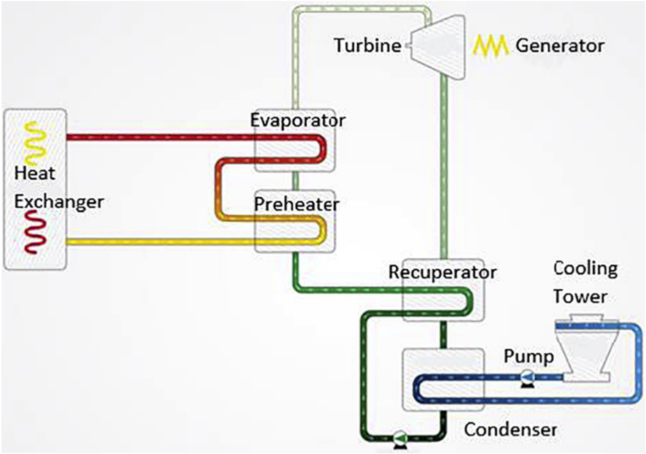


Fig. 19. Schematic of a Typical Organic Rankine cycle [97].

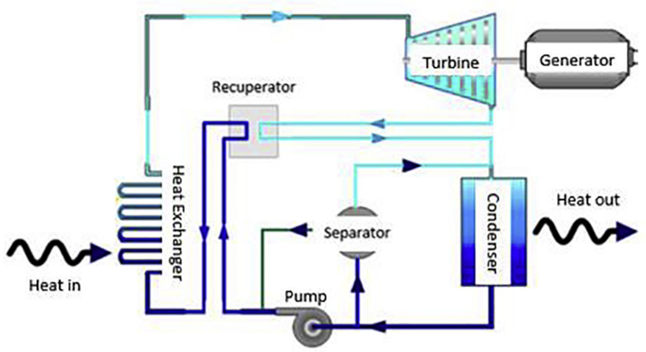


Fig. 20. Configuration of a Kalina cycle consisting a Recuperator and Separator [103].

2.9. Heat pumps

A heat pump is a thermodynamic device which takes and transfers heat from a heat source and to a heat sink using a small amount of energy [109]. Heat pumps collect heat from air, water, or ground and are categorised as air-to-air, water source and geothermal heat pumps. Heat pumps can be used as an efficient alternative to furnaces and air conditioners to cool or heat an environment [110]. Having mention that, *Chua* [111] explains that heat pump systems can also be used to offer economical and efficient alternative of recovering heat from various sources to improve overall energy efficiency. In this sight and as *McMullan* [112] describes the heat pump has become an important component in the context of WHR and energy efficient processes.

A heat pump works with the same principle as refrigerators and air-conditioners, however, employs a refrigerant cycle to produce hot air and/or water by extracting heat from a heat source and passing that to an evaporator to heat the refrigerant at low pressure. This is then delivered to a compressor to produce high pressure and temperature gas that can be delivered to a heat exchanger (condenser) [113] (see Fig. 22).

Baradey [115] discusses that heat pump in particular are good for low-temperature WHR, as they give the capability to upgrade waste heat to a higher temperature and quality. This was for instance demonstrated in a study, where, from a heat source of 45–60 °C, the heat pump delivered almost 2.5–11 times more useful energy comparing to other WHR systems used for the equal heat input [116].

Through reclaiming waste heat that is dissipated into the environment and upgrading it by the means of a heat pump, a resulting useful heat can be generated and used directly for the process to reduce the energy intake and improve the overall efficiency of the system (see Fig. 23).

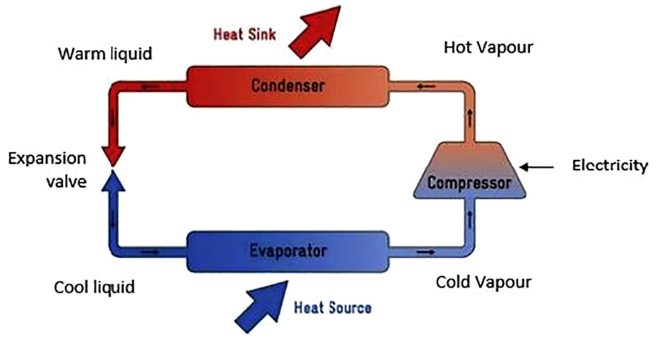


Fig. 22. Heat pump working diagram [114].

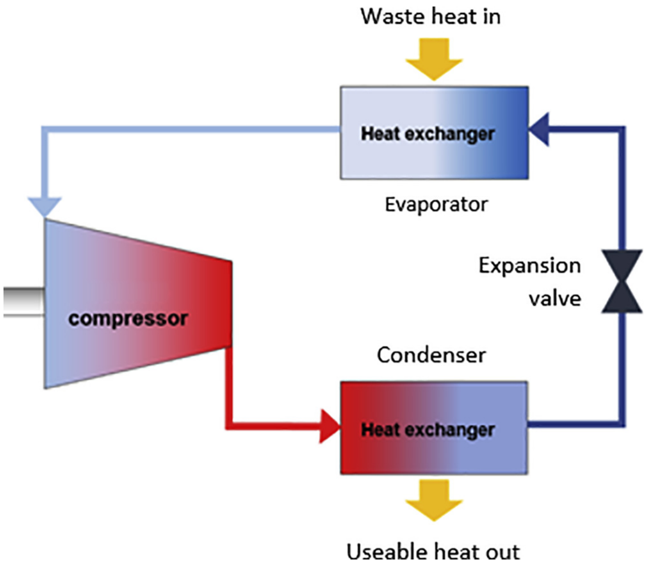
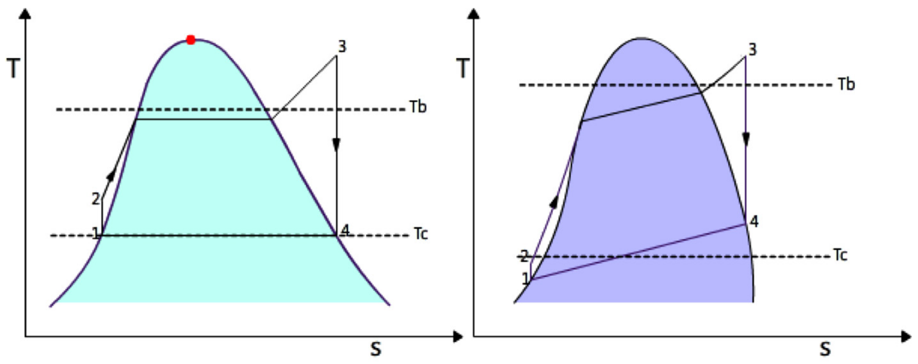


Fig. 23. Heat pump diagram in the context of WHR [117].

2.10. Direct electrical conversion devices

Systems are also available that produce electricity directly from waste heat and eliminate the need for converting heat to mechanical energy to produce electrical energy. These technologies include the use of thermoelectric, piezoelectric, thermionic, and thermo photo voltaic (TPV) devices for electricity generation [118]. *Khalid et al.* [119] mentions that these technologies are not widely used in industry, however, a few have undergone prototype testing and have offered promising results. Below the technologies that were mentioned as direct electrical devices are explained.



(a) T-s Diagram of Rankine cycle.

(b) T-s Diagram of Kalina cycle.

Fig. 21. Comparison of Rankine and Kalina cycles [106].

2.10.1. Thermoelectric generation

Thermoelectric devices are made out of semiconductor materials that generate electrical current when they face a temperature differential between two surfaces [120]. Discovered in 1821 by Thomas Johann Seebeck, the system works based on a principle called Seeback effect, which as can be seen from Fig. 24, is described as the generation of electrical current *(I)* between two semiconductors when the materials are subject to a hot (T_H) and cold source (T_C) [121]. The system has a very low efficiency of 2–5%, however, as *Caillat et al.* [122] reports, recent advances in nanotechnology have allowed electrical generation efficiencies of 15% or greater to be achieved. Based on a study conducted by *Hendricks and Choate*, [123], it is explained that advanced thermoelectric packages can appropriately be used to produce electricity and obtain major energy savings from the waste heat dissipated from medium-high temperature range applications, for instance glass or metal furnaces [124,125]. Nonetheless, *Hendricks and Choate* [123] reports that maintaining a large temperature difference and obtaining high heat transfer rates across the two rather thin surfaces of the device are issues and challenges at present which require advances in heat transfer systems and materials. Having mentioned that, *Remeli et al.* [126] in an experiment demonstrated that using the combination of heat pipes and thermo-electric generators can lead to further utilising power generation for industrial processes. In their project, a bench type containing thermoelectric generators was modelled and fabricated which through testing with a counter flow air duct heat exchanger, indicated an increase in the ratio of mass flow rate of the upper duct to lower duct. A higher mass flow rate ratio proved a higher power output from the system and an increase of the overall system performance.

2.10.2. Piezoelectric power generation

Piezoelectric Power Generation (PEPG) is a process of converting low temperature heat energy directly to electricity [128]. Piezoelectric devices for heat recovery are made out of thin-film membranes and they work by converting ambient vibration such as oscillatory gas expansion into electricity [129–131]. There are technical challenges and disadvantages associated with these devices that limit their use for heat recovery, namely, low efficiency, high internal impedance, the need for long term durability and very high cost [123,132]. Having mentioned that, the main issue with the use of PEPG devices are associated with the high cost of manufacturing these devices as well as the way the systems must be designed to enable power generation, reliability and stability [133].

2.10.3. Thermionic generator

Thermionic devices operate in a similar manner to thermoelectric devices in the sense that they produce electric current through temperature difference between two media without the use of any moving objects, however, they operate through thermionic emission [134]. In this technology and as can be seen from Fig. 25, a temperature difference between a hot cathode (Emitter) and a cooler anode (Collector) generates a flow of electrons between metal and metal oxide surfaces through a vacuum in an interelectrode space to generate electricity [135]. The functionality of this technology is shown to be limited to high temperature applications and be inefficient, however, several attempts have been made to improve their efficiency and enable their use for low temperature applications [136] (see Fig. 26).

2.10.4. Thermo photo voltaic (TPV) generator

These devices are used to directly convert radiant energy into electricity similar to the functionality of solar panels [138]. These systems are shown to potentially enable a new method of waste heat recovery and they use an emitter, a radiation filter and a Photo Voltaic (PV) cell to produce electricity from a heat source [139]. The system employs an emitter which, when heated by the heat source, emits electromagnetic radiation. The PV cell then converts the radiation to electrical energy and the spectral filter ensures that only the radiation waves with the correct wavelength matching the PV cell pass through. The efficiency of a TPV device is investigated to range from 1% to 20%, depending on the radiation and heat transfer radiated from the emitter and the arrangement of the generator [140,141].

For instance, in a study *Utla and Onal* [142] demonstrated that by applying TPV cells systems with an efficiency of 7.3% as a WHR method in an iron and steel production plant, the energy efficiency of the plant can be improved by almost 189971 MJ annually. Nonetheless, it has been found that PV cells have a limited operating temperature range and their efficiency decreases as the cell temperature increases [143]. Having said that, high efficiency PV cells that can withstand high temperature ranges are also available, however, they are expensive and increase system costs [140,141].

3. Low-temperature waste heat recovery challenges and opportunities

Recovering waste heat is more feasible and easier when temperatures are in the medium – high range [6]. Having said that, there are vast opportunities for recovering waste heat in the low temperature range as most industrial waste heat is in this category, as demonstrated by *Haddad et al.* [145] and shown in Fig. 27.

Nevertheless, recovering low temperature waste heat is found to be more challenging than medium – high temperature waste heat. The reason for this is mainly because of the problems associated with the method of collecting the waste heat [146].

For instance, water vapour exists in low temperature exhaust gases and it tends to cool down, mix with other particles and deposit corrosive solids onto heat exchanger surfaces [25]. Heat exchanger surfaces therefore have to be cleaned or replaced on a regular basis to maintain the functionality of the heat exchanger, which can be uneconomical. The use of advanced materials that minimise corrosion and reduce the need for regular maintenance in this regard should therefore be considered [147].

In addition, as the heat transfer rate is low when recovering low-temperature waste heat, large heat exchangers may be required to achieve optimum heat transfer. This is mainly because convective heat transfer rates are a function of temperature difference between two locations and the area through which heat is transferred [148]. Having said this, the cost of equipment used to recover heat for low temperature applications may be less as lower waste heat temperatures allow the use of less expensive materials [149].

Nonetheless, the main challenge with the low temperature waste heat recovery can be finding a use for the recovered heat. Potential uses for low temperature waste heat can include using a heat pump to improve and increase heat to a higher temperature and the use of the waste heat to produce domestic hot water, space heating and process heating [147,150].

The method of recovering low-temperature waste heat include cooling exhaust gases below dew point temperatures. The dew point temperature is the temperature at which a moist gas mixture begins to

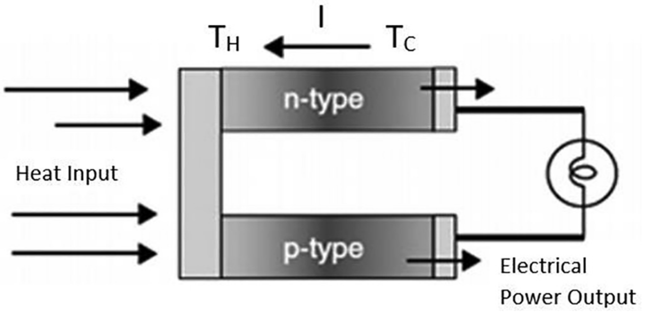


Fig. 24. Principle of the thermoelectric generation [127].

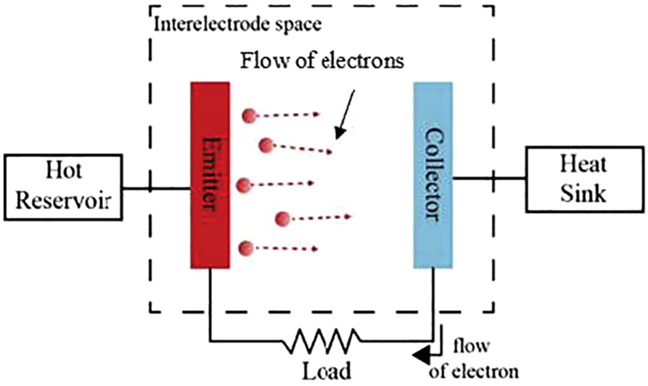


Fig. 25. Schematic of a thermionic generator [137].

condense and becomes saturated as it is cooled down at a constant pressure [151]. This way, the waste heat from a low temperature process is captured, transferred through a heat exchanger and used to preheat a process or for low-temperature power generation. In addition to the technologies introduced in the previous chapter, techniques that employ units such as transport membrane condensers, direct and indirect contact condensation recovery are also describe to be used for low-temperature WHR [152].

3.1. Direct and indirect contact condensation recovery

A direct contact condensation recovery unit works by mixing the waste exhaust gas with cooled water to produce hot water for domestic and preheating uses. As can be seen from Fig. 28, the system uses a direct mixture heat exchanger which includes a water dispenser, exhaust inlet, exhaust outlet and hot water outlet. The flue exhaust gas and water move in counter-flow directions from the bottom and the top of the heat exchanger, respectively. This results in waste heat being transferred to the cool water, which is then stored at the bottom of the heat exchanger. The hot water can then be fed and provide heat to an external system [153]. The heat exchanger can also be used to transfer heat from immiscible liquid – liquid and solid – liquid or solid-gas [150]. A disadvantage with this system due to absence of a separating wall is the fact that particles from the flue gas can be mixed with the water, which may require filtering before exiting the heat exchanger [150,154].

Indirect contact condensation recovery on the other hand, consists of a shell and tube heat exchanger made from advanced materials such as Teflon, glass and stainless steel to minimise corrosion from acidic

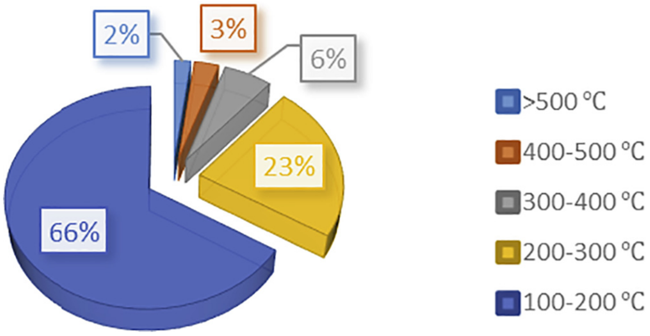


Fig. 27. Low-temperature categories.

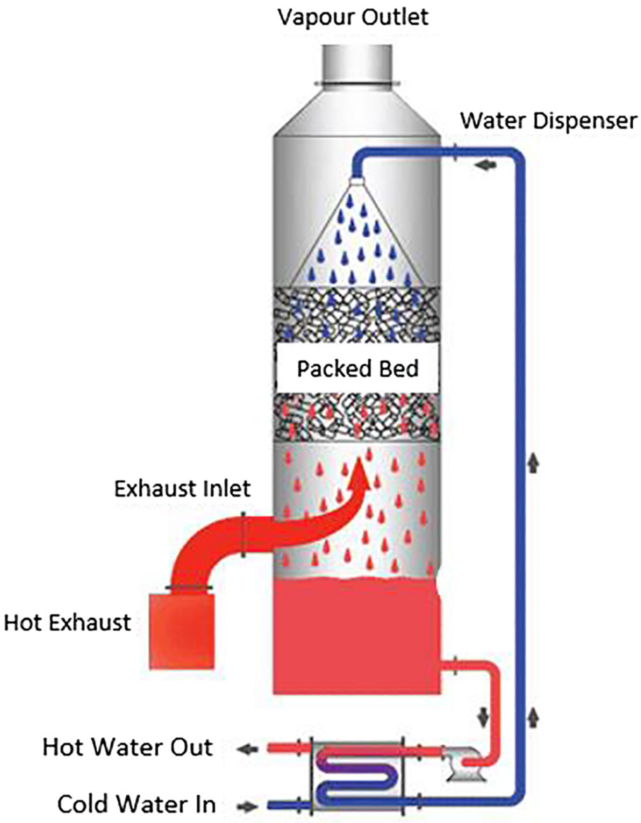


Fig. 28. Schematic of a direct contact condensation recovery unit [155].

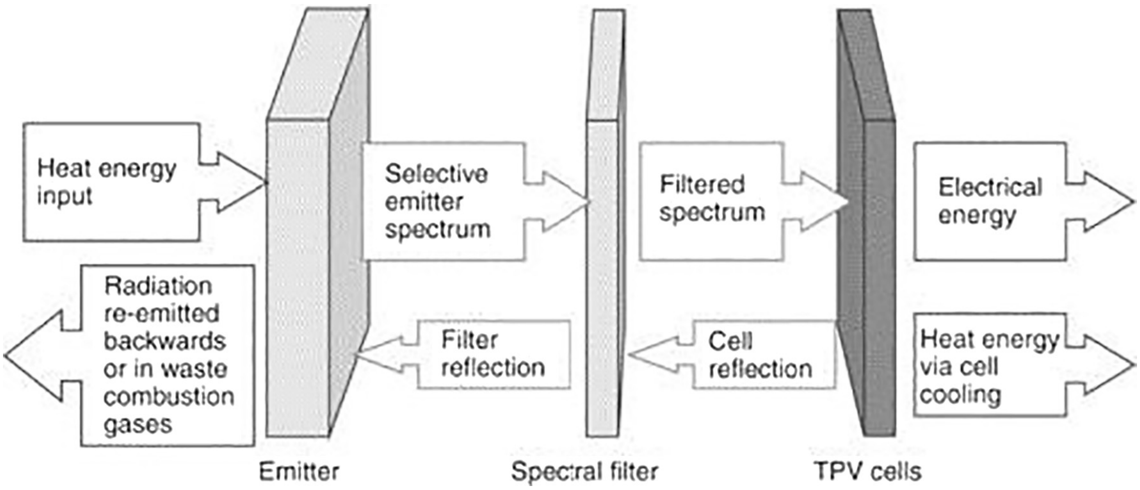


Fig. 26. Operating principle of a TPV device [144].

condensate deposition. The system transfers heat from the exhaust gases to the cool water that is flowing through the pipes of the heat exchanger. This system provides the advantage of eliminating cross contamination of the flue gas and water and can be designed to work as a filter of a process [26].

3.2. Transport membrane condenser

Similar to direct contact condensation recovery systems, transport membrane condenser units produce hot water from water vapour from flue gas streams. As can be seen from Fig. 29, the system works by extracting and delivering the hot water back into the system feed water directly from the exhaust gas at a temperature above the dew point through a capillary condensation channel [146]. This way, unlike direct contact condensation recovery systems, the water is extracted through a membrane channel rather than directly from the flue gas and so the recovered water is not contaminated and does not require filtering.

4. Summary table

The table below shows a summary of all the technologies investigated in this paper including their temperature range, benefits and limitations:

5. Waste heat recovery opportunities in industry

Different industrial processes consume different amounts of energy and produce different quantities and qualities of waste heat. To take advantage of the potential of industrial waste heat, it is therefore essential to look into and analyse the industrial processes used in large energy consuming industries and to investigate what suitable waste heat recovery methods can be applied to the systems of each sector.

As mentioned before and indicated by *McKenna and Norman* [157], the largest amounts of industrial waste heat in the UK are mainly associated with cement, ceramics, iron and steel, refineries, glassmaking, chemicals, paper and pulp, and food and drink industries. When considering waste heat recovery options for industrial processes, it is important to examine the source and the usefulness of the waste heat produced and discover which waste heat recovery method is the most suitable.

In this paper, the iron and steel, ceramic and food industries were selected to investigate how optimising energy management through the use of waste heat recovery systems could be achieved in each sector. The reason for selecting the mentioned industries to conduct further investigations for the application of WHR is give an indication how and what WHR technologies can be applied to different industrial and production processes that demonstrate all waste heat temperature ranges (low-high).

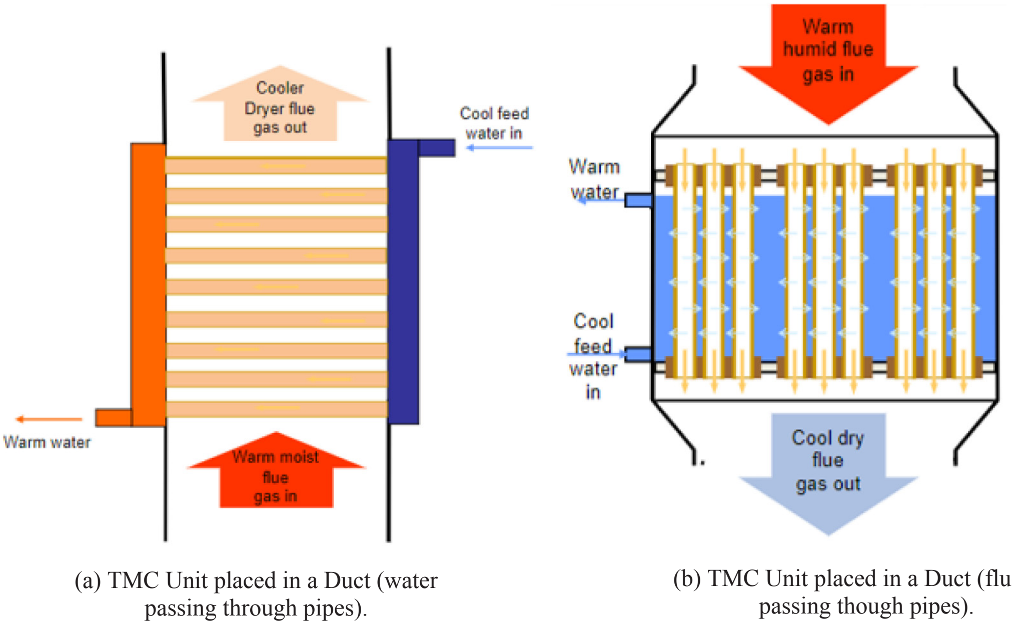
5.1. Waste heat in iron and steel industry

Iron and steel production is a resource and energy intensive process which involves extensive amounts of heat and raw material. Waste heat recovery in the iron and steel industry includes recovering heat dissipated from high-temperature sources such as furnaces used for sinter, coke, iron, and steel production, which is investigated to account for roughly 8% of the overall industrial energy consumption in the UK [4].

A common method of waste heat recovery in the iron and steel industry is from clean streams of gases from production processes. For instance, *Jouhara et al.* [158] in an experiment demonstrated that for a heat source of 450 °C, the use of a Flat Heat Pipe (FHP) in the wire cooling line of a steel production facility can offer a recovery of heat up to 15.6 (kW). In this experiment, an innovative FHP model was constructed at the dimensions of 1 m height × 1 m width and tested at the hottest point of the cooling zone of the production line. The model was charged with water at a flow rate of 0.38 kg/s and hot gases dispersing from the process impacted on a flat heat pipe panel which was inclined at an angle to the horizontal.

In another study demonstrated by [159] and with the use of waste heat boiler, a waste heat recovery system was produced that can recover sensible heat from hot air emitted by the cooling process of sinter coolers located downstream of sinter machines. The system generated approximately 280 MW of power, increasing the overall efficiency of the plant by almost 6%.

Heat recovery plant for contaminated and dirty exhaust gases from coke ovens, blast furnaces, oxygen furnaces and electric arc furnaces are also available, yet implemented less, due to the limitations and high capital costs of current methods [160]. For instance, *Mandil* [161] reports that the procedure for producing coke in coke ovens extracts gas with high quality waste heat from the exit of the coke oven and the



(a) TMC Unit placed in a Duct (water passing through pipes).

(b) TMC Unit placed in a Duct (flue gas passing though pipes).

Fig. 29. Shows different transport membrane condenser units [156].

Table 1
Summary table of WHR technologies.

Technologies	Temperature Range Used	Benefits	Limitations
Regenerative Burners	High	Saving fuel by preheating the combustion air and improving the efficiency of combustion.	The system requires additional components such as a pair of heat exchange media and several control valves to function, which can be complex.
Recuperative Burners	High	Both the exhaust gas and waste heat from the body of the burner nozzle are capture and more heat from the nozzle is generated.	The burner and the nozzle needs to be inserted into the furnace body, which may require installation and modification of the furnace.
Economisers	Low – Medium	The system maximises the thermal efficiency of a system by recovering low-medium temperature heat from the waste flue gas for heating/preheating liquids entering a system.	The system may need to be made out of advanced materials to withstand the acidic condensate deposition, which can be expensive.
Waste Heat Boilers	Medium – High	The system is suitable to recover heat from medium – high temperature exhaust gases and is used to generate steam as an output.	An additional unit such as an auxiliary burner or an after burner might be needed in the system if the waste heat is not sufficient to produce the required amount of steam.
Recuperators	Low – High	The technology is used for applications with low – high temperatures and is used to decrease energy demand by preheating the inlet air into a system.	To maximise heat transfer effectiveness of the system, designs that are more complicated may need to be developed.
Regenerators	Medium – High	The technology is suitable to recover waste heat from high temperature applications such as furnaces and coke ovens and for applications with dirty exhausts.	The system can be very large in size and have very high capital costs.
Rotary Regenerators	Low – Medium	Rotary regenerators are used for low – medium temperature applications and could potentially offer a very high overall heat transfer efficiency.	The system is not suitable for high temperature applications due to the structural stresses and the possibility of deformations that can be caused by high temperature
Run around coil (RAC)	Medium – High	This unit is used when the sources of heat are too far from each other to use a direct recuperator and when cross contamination between the two flow sources needs to be prevented	This system is found to have a very low effectiveness when compared to a direct recuperator and needs a pump to operate, which requires additional energy input and maintenance
Heat Recovery Steam Generator (HRSG)	High	The system can be used to recover the waste heat from the exhaust of a power generation or manufacturing plant to significantly improve overall efficiencies by generating steam that can be used for process heating in the factory or power generation.	The system requires several components to function and may require an additional burner to improve the quality of the recovered waste heat. On the other hand, the system is very bulky and require on site construction.
Plate Heat Exchanger	Medium – High	Plate heat exchangers have high temperature and pressure operating limits and are used to transfer heat from one fluid to another when cross contamination needs to be avoided.	Parameters such as frequent variation in temperature and load must be studied and based on that suitable heat exchanger design must be chosen to avoid failure of the structure of the heat exchanger for the application
Heat Pipe Systems	Medium – High	Heat pipes have very high effective thermal conductivities, which results in a minimal temperature drop for transferring heat over long distances and long life that requires no maintenance, as they incorporate passive operation. They have lower operation costs when compared to the other types of heat exchangers.	To achieve an optimum performance from the heat exchanger, appropriate design, material, working fluid and wick type based on the application and temperature range of the waste heat must be studied and chosen.
Thermoelectric Generation	Medium – High	The system produces electricity directly from waste heat and eliminate the need for converting heat to mechanical energy to produce electrical energy.	The system has a very low efficiency of 2–5%, however, recent advances in nanotechnology have allowed electrical generation efficiencies of 15% or greater to be achieved
Piezoelectric Power Generation	Low	The system can be used for low-temperature waste heat recovery and works by converting ambient vibration such as oscillatory gas expansion directly into electricity.	The system are found to have a low efficiency, high internal impedance, need for long term durability and very high cost.
Thermionic Generator	High	The device is used for high temperature waste heat recovery and works by producing electric current through temperature difference between two media without the use of any moving objects	The functionality of this technology is shown to be limited to high temperature applications and be inefficient, however, several attempts have been made to improve their efficiency and enable their use for low temperature applications
Thermo Photo Voltaic (TPV) Generator	Low – High	These devices are used to directly convert radiant energy into electricity and offer a better efficiency when compared to other direct electrical conversion devices.	The device is found to have a limited operating temperature range and their efficiency decreases as the temperature increases. Having said that, high efficiency PV cells that can withstand high temperature ranges are also available, however, they are expensive and increase system costs.
Heat Pump	Low – Medium	Heat pumps transfers heat from a heat source to a heat sink using a small amount of energy and can be used to offer economical and efficient alternative of recovering heat from various sources to improve overall energy efficiency. Heat pumps in particular are good for low-temperature WHR, as they give the capability to upgrade waste heat to a higher temperature and quality.	In order to use this system, the method of capturing the waste heat based on its source and grade must firstly be analysed and in that respect, appropriate heat exchanger and system installation needs to be set up.
Direct Contact Condensation Recovery	Medium – High	the system uses a direct mixture heat exchanger without a separating wall and can be used to transfer heat from immiscible liquid – liquid and solid – liquid or solid-gas.	Due to absence of a separating wall in this heat exchanger, particles from the flue gas can be mixed with the water, which may require filtering before exiting the heat exchanger.
Inirect Contact Condensation Recovery	Medium – High	The system provides the advantage of eliminating cross contamination of the flue gas and water and can be designed to work as a filter of a process.	The system consists of a heat exchanger which in order to minimise corrosion from acidic condensate should be made from advanced materials and can be expensive.
Transport Membrane Condenser	Medium – High	The system works by extracting and delivering the hot water back into the system feed water directly from the exhaust gas through a capillary condensation channel. This way, the water is extracted through a membrane channel rather than directly from the flue gas and so the recovered water is not contaminated and does not require filtering.	The system employs a capillary condensation channel, which in order to minimise corrosion from acidic condensate, may need to be made from advanced materials and can be expensive.

oven chamber. The heat content of the waste gas extracted from the exit of the oven chamber is not usually recovered and goes to waste as it contains a high level of tars and other materials that if not filtered will deposit on the heat exchanger surfaces used for waste heat recovery.

Therefore, various technologies are employed to filter coke oven exhaust particles from the oven chamber outlet so that the waste heat can be recovered and used. The processes include filtering and removing tars and other materials from the coke oven gas and using the remaining recycled (clean) gas to generate an additional heat source and preheat the coke oven using regenerators investigated in Section 2.4.2 [162]. Having said that, the hot gas that is extracted from the oven flue can also provide a good heat source and can be further recovered with the use of heat pipes [163].

Blast furnaces on the other hand contain several auxiliary blast stoves that provide heat through flue gases to convert iron oxide (FeO) into pig iron (Fe) [164]. In blast furnaces, waste heat is mainly recovered from the combustion exhausts and is transferred to regenerators to be reused in the system for reheating the blast furnace and preheating the combustion air.

The pig iron purification process is usually conducted in the basic oxygen furnace (BOF) where oxygen is injected to the hot metal and scrap and fluxes added to control metal erosion. The main waste heat recovery methods used for this process include semi wet and wet open combustion and supressed combustion techniques. The open combustion system includes the use of a waste heat boiler to recover waste heat that is produced as a result of the reaction of oxygen in the furnace gas duct. On the other hand, in the supressed combustion technique, the combustion gas is collected to be used as fuel through reducing air infiltration and inhibit combustion of the CO and by adding a skirt to the outlet converter mouth [165,166].

According to *Quader et al.* [167], approximately 30% of steel is produced through the electric arc furnace route (EAF) by melting recycled steel scrap. Similar to the supressed combustion technique, the waste heat recovery method used in electric arc furnaces aims to capture and collect flammable by-product gases such as CO to provide additional heat for the system. The electric smelting technique used in electric arc furnaces is reported to be one of the most common manufacturing methods in steel production from recycled scrap. In this method, electric arc furnaces that employ carbon electrodes are used to melt recyclable steel scrap and cut-offs from product manufacture and consumers. During furnace operation in this system, several emission gases and pollutants are released with a temperature ranging between 1300 and 1900 °C [168]. These waste gases can be recovered and be used to preheat the scrap materials that are placed in the furnace. Using preheaters in this method results in the carbon electrodes requiring less energy to melt the scrap and allows reduced electricity consumption for the plant.

Heat recovery from solid product streams such as slags, hot cokes, cast steels and hot steels is also demonstrated to have significant potential. For instance, the waste heat from a coke oven can be recovered through coke dry quenching and wet quenching. The process of coke dry quenching involves catching the hot incandescent coke in a cooling

Table 2
Comparison of different WHR methods.

Author	Process	Description	Observations and Remarks
[173,174]	Solid slag impingement process	In this process, the stream of liquid slag is fragmented and turned into granules and particles through striking the stream into previously solidified particles. The recycled particles with the slag granules are then fed to a fluidised bed, where heat recovery is conducted.	The heat is recovered through adjusting the product temperature to 500–800 °C by controlling the ratio of recycled to liquid slag in the fluidised bed. This process generated steam with a temperature up to 250 °C and a heat recovery rate up to about 65%.
[175–177]	Mechanical stirring process	This process includes striking and crushing the molten slag with the use of rotating blades or moving sticks. Through this action, heat is recovered in a container by radiation and conduction to water pipes. Then the crushed particles are discharged into a fluidised bed to recover additional energy.	With the use of a waste heat boiler in the final stage of the process a recovery efficiency of up to 59% through this method can be achieved.
[176–179]	Rotating drum process	Through this process, a stream of molten slag is broken up into particles as it is poured onto a rotating drum. The particles are then fed into a fluidised bed where heat is recovered.	This process has been tested in full scale and has been proven to recover 50–60% of the slag heat into a hot airflow.
[180–183]	Air blast method	In this method, the slag is heated to obtain the optimum viscosity and flow rate which is then delivered to a channel where a high pressure air nozzle breaks down the slag stream into particles. The system uses two waste heat boilers for recovery to generate steam.	The first boiler recovers heat through radiation and convection from the slag flying droplets, whereas the second boiler which is located at the bottom of the unit recovers heat from cooler slag granules. An energy balance study has shown that about 41% of heat is recovered by steam and another 39% could potentially be recovered from the exhaust stream at 500 °C
[184,185]	Rotating cup atomiser (RCA) process	The process contains a high speed rotating cup which generates a centrifugal force and surface tension that can cause the breakup of the high temperature slag into particles. In this process, high temperature slag is gradually poured into the rotating cup and at the same time air is blown to recover heat from the hot particles.	The process produces hot air and solid granules which are then dropped into a fluidised bed for further heat recovery. This process has been tested commercially and has proven to recover 59% of the slag heat and cool down the slag particles to 250 °C
[172,186,187]	Spinning disk (SDA) atomiser processes	The spinning disk (SDA) atomiser works with the same principle as the rotating cup atomiser (RCA) process but with the difference that the slag flow is poured onto a high speed rotating disk rather than a cup. The slag particles are then dropped into a collection fluidised or packed bed where further heat recovery is obtained.	Through blowing an air flow onto the slag particles, primary heat recovery is achieved which is then further improved at the second recovery stage. The heat generated from these operations is indicated to be at a temperature above 600 °C which can be used for steam generation or process preheating.
[171,188,189]	Methane reforming reaction process	In this process, reactive gases are employed to cool down the molten slag particles and transfer the waste heat into chemical energy. This in return will conduct an intensive heat exchange from the molten slag to the gas mixture and produce H_2 and CO, which can be used as fuel. This means that the high temperature from the slag is stored as chemical energy	Through a proposed process design, hot slag is poured onto a rotating cup and then deposited into a packed bed where a mixture of methane and water are injected and CO + H_2 is generated. The system is estimated to cool down the slag temperature to 150 °C and recover 51% of the slag heat. Heat from the slag deposit can be further recovered at the bottom of the unit to improve the total recovery to almost 83%
[190,191]	Direct use for making high value-added product	In this process the sensible heat from the slag is converted though several chemical processes and into high value added mineral wool which can be used for thermal insulation.	The heat from the slag was used as a heat source and the recovery rate was discovered to be up to 70%.

chamber and by passing an inert gas over the coke to recover and deliver the waste heat loss to a waste heat boiler [169]. This process can also be conducted through wet quenching where heat is transferred to cool water that is sprayed over the hot coke. Wet quenching is also used to recover waste heat from hot slag, however as *Shan et al.* [170] reports, this process is found to be an inefficient method of waste heat recovery as it consumes a large amount of water, fails to recover the sensible heat and is less environmental friendly. Having said that, it is reported that other technologies that employ chemical techniques have also been developed that offer more efficient waste heat recovery.

As *Sun* [171] explains, the recovery from slag is possible in three different forms: recovery as hot air or from steam, conversion of the waste heat to fuel through chemical reaction, and the use of thermoelectric power generation. In regard to thermal energy recovery, *Zhang* [172] explains that recovery is conducted through dry granulation including mechanical crushing methods such as the solid slag impingement process, the mechanical stirring process and the rotating drum process. Other techniques such as the air blast method, the centrifugal granulated method such as the spinning disk (SDA) and Rotating cup (RCA) atomiser processes are also available and have been studied as shown in Table 1 below. Chemical methods on the other hand include the use of the methane reforming reaction process and direct use for making high value-added products (see Table 2).

5.2. Waste heat in food industry

The food industry is estimated to account for about 26% of the EU's total energy consumption and to be the UK's fourth highest industrial energy user [192,193]. Most of the waste heat produced in the food industry is classified as low-medium temperature [194]. Having said that, the amount of available waste heat in the food industry depends largely on the type of process in question and widely varies from sector to sector. This is mainly due to the fact that different industries use different processes for production and this indicates that the actual amount of useful waste heat can only be determined by conducting a comprehensive audit for the energy usage of processes. Based on the study conducted by *Feldman* [39], it is claimed that there are, however, general opportunities for waste heat recovery in the food industry that can be discussed in this paper.

It is estimated that depending on the process, energy wastage is between 10% and 45%. Potentially, the main sources of the waste heat are associated with heating and refrigeration systems, hot streams of water or air used in production and heat from processing operations [195].

In the red meat processing industry, for example, the source of waste heat can be classified into recovery from refrigeration systems, meat processing and by-product rendering [196]. For instance, in a slaughter house, the refrigeration of carcasses is the most energy intensive process. On the other hand, if by-product rendering takes place, this can be a major energy user. The clean-up operation that uses large amount of hot water can also be nominated as a major energy consumer and also processes such as scalding, singeing and hair removal can use an extensive amount of energy [197].

For instance, in hog singeing operations where heat is used to dry out the hog carcasses, the majority of heat is released into the atmosphere. Waste heat recovery can be used largely for this operation to provide a more efficient production by supplying the energy requirement for the dehairing and scalding processes. For instance, based on the study conducted by *Ashrafi et al.* [198] and *Environment Agency* [199] it is explained that singeing operations produce a waste flue gas of up to 800 °C that through the use of waste heat recovery equipment such as economisers can be utilised for boilers and to pre-heat the feedwater to produce hot water. On the other hand, recovery of heat from overflow hot water from the hot scalding process with the use of automatically operated scalding chambers is also achievable [197,200].

The production of processed meat is more energy demanding than slaughtering meat as it involves operations such as cooking, cooling, smoking, etc. As *Fritzson and Berntsson* [201] reports, the majority of heat loss in food processing operations is associated with refrigeration and curing of the product. Based on the type of operation, waste heat sources can include heat from condensers, waste water, smoking vents and cooker exhaust [202]. Again, recovery from these sources must be studied based on individual cases as for some waste heat sources, such as waste water and cooker exhaust, recovery may be difficult and not economical because of the grease and food waste products in the exhaust.

On the other hand, it has been shown that in poultry processing, where bird meat is prepared and processed, the largest quantity of energy and energy loss is associated with the scalding, cooling and freezing processes. *Shupe and Whitehead* [203] reports that, for instance, when overflow from scalders and chillers occur, heat recovery can easily be conducted by collecting and returning the energy back to the scalder or chiller systems. Heat can be recovered from refrigeration condenser systems and be used to preheat the boiler that is used for processing wash water [204]. The operation of obtaining heat from a refrigerant condenser can be conducted through the use of a de-superheater, which can be installed between the compressor and condenser to recover heat in a temperature range of 60–90 °C [205].

Heat rejected by the pasteurisation process and refrigeration condensers on the other hand are the main source of waste heat in dairy processing plants [206,207]. Nevertheless, the waste heat from the dryer exhaust can also be a potential waste heat source that can be used to preheat supply air for the spray dryers [208]. Having mentioned that, the heat from the pasteurisation and milk cooling processes can be recovered and be used to preheat cold milk in the regenerator through the use of heat exchangers such as economisers or CO_2 heat pumps [209]. The heat from refrigeration condensers is used to produce hot water for clean-up, preheat boiler feed water, or heat culture tanks for some operations [207,209]. *Singh and Dasgupta* [209] showed that with the use of a heat pump with an internal heat exchanger for combined heat recovery and hot water generation, the total fuel cost for production can be reduced by nearly 46% with a payback period of approximately 40 months.

In another study conducted by *Bowater* [210] and with the use of heat pumps, the energy efficiency of a large meat production plant was improved. In this study, heat pumps were used to recover heat from the refrigeration condensers of the plant to produce heating and hot water to a temperature of 65 °C, indicating a possible daily energy saving of up to £530.

Similar to the dairy industry, in the egg processing industry waste heat can be recovered from the pasteurisation process and can be used through a regenerator to preheat the cold egg product. The waste heat from the refrigeration systems, hot waste water from egg washing and exhaust air from egg drying process can also be recovered to preheat boiler feed water, heat egg wash water and preheat the dryer air [211]. In freezing and canning processes the main operations are conducted in fruit and vegetable processing [39]. In freezing operations, the major waste heat is dissipated from the refrigeration system condenser. The waste heat is derived from hot refrigerant and is easily recoverable [212]. On the other hand, in canning operations the major waste heat is reported to come from wastewater and retort vents. Waste heat recovered from these operations in fruit and vegetable processing can be used for water heating, can washing, blancher makeup water, plant clean up and boiler feed water [195].

In biscuit manufacture and bakeries the major waste heat sources are from flue gases coming from the cooking ovens, fryers, pan washers and boilers. Hot water can then be produced from the recovered waste heat for use in clean-up. The recovery of heat from the cooking oven exhausts is also a possibility for other uses [207,208]. For instance, [213] used a thermo-acoustic heat engine (TAHE) to recover the low grade waste heat that is dissipated from the exhaust gas of cooking ovens in biscuit manufacture. The technology works with a prime mover that does not have any mechanical parts and the engine consists of two heat exchangers and a stack of parallel plates that are contained in a cylindrical casing and it converts thermal energy to acoustic energy. The investigation concluded that by recovering waste heat with a temperature of 150 °C, an output of 1030 W of acoustic power with a thermal engine efficiency of 5.4% can be obtained.

In another study *Mukherjee et al.* [214]demonstrated that with the use of air-preheaters, 4% savings can be achieved in the oven fuel consumption. In an experiment, heat was recovered from the exhaust flow of an industrial baking oven and the primary air supply of the burner was increased to 105 °C. This study indicated that the increase in the primary air temperature can result to a saving of at least £4,200 of running cost.

5.3. Waste heat in the ceramic industry

The ceramic industry is one of the most energy-intensive industries in the UK [215]. As stated by the British Ceramic Confederation Energy Policy, ceramic manufacturers should be concerned about the environmental and economical impacts of their businesses and take steps in that regard to protect the world's resources and reduce their carbon footprint [216]. With respect to this, the use of waste heat recovery units in the ceramic industry has been identified as an effective way of achieving this goal and improving industrial energy efficiency [217].

In order to discover the waste heat potential and identify how the recovered waste heat can be used, it is important to identify the sources of available heat in the production process and investigate the effectiveness of waste heat recovery technologies with these sources [215]. As *UNIDO & ECC* [218] reports, electrical energy and chemical energy in the form of fuel are the main types of energy used in the ceramic industry. The electrical energy is used to power the motors of the production equipment and machines and the chemical energy in the form of fuel is used to provide thermal energy to heat the kilns and furnaces. The ceramic production process typically consists of five stages. In the first stage, the raw material and additives are ground and mixed to produce material slurry. The material slurry is then then fed into a drying tower where it gets dried and converted to powder so it can be pressed to a shape and form unfired ceramic. This then passes to another drying operation through a hot chamber where controlled heat allows the product water content to be reduced before the material enters a kiln and is fired to form blank ceramic. The product is then sent to a polisher to achieve a smooth surface. As *Peng et al.* [219] explains, the two energy consuming operations producing the most emissions are the drying and firing operations. It is reported by *Delpech et al.* [220] that the firing stage is the largest consumer of energy in the ceramic production process and this contributes to almost 50% of energy loss through the flue gas and the cooling gas exhaust.

In this stage of production, the ceramic structural integrity such as mechanical strength, abrasion resistance, dimensional stability and resistance to water, chemical and heat is increased by heating up the product to a temperature between 750 °C and 1800 °C. The chart below illustrates a breakdown of the main thermal energy consumption in ceramic manufacture [221] (see Fig. 30).

Many different waste heat recovery technologies in this regard have been investigated and introduced to accommodate and recover heat from the drying and firing processes. For instance, as *Delpech et al.* [220] explains, the best available techniques for recovery in the ceramic industry include recovery of excess heat from roller kilns by the use of cogeneration (or combined heat and power), Organic Rankine Cycles to generate electricity and the use of heat pipe systems.

5.3.1. Recovery of excess heat from roller kilns

It is investigate that for the recovery of excess heat from roller kilns, some processes employ heat exchangers to recover heat from the kiln exhaust and preheat the combustion air entering the system [222]. Nonetheless, it is noted that because the combustion gases, possible corrosion problems for the heat exchanger can occur. Having said that, the heat from the cooling zones of tunnel kilns can be recovered to preheat the dryer or used through the mean of other methods mentioned such as CHP or ORC to generate heat and electricity for the process and plant.

Through this method, the generated electricity can be utilised in the oven to power the air and exhaust fans and the generated heat from the process can be used to heat equipment that dries the ceramics [223,224]. For instance in an experimental study of an ORC (Organic Rankine Cycle) for low grade waste heat recovery in a ceramic industry [225] proved that by recovering 200–300 °C from Kiln gases, the maximum cycle efficiencies can reach a gross electrical efficiency of 12.5% with a net electrical efficiency of 11%. Nonetheless, on the other hand, *Mezquita* [226] demonstrated in a study that through the recovery and diluting the flue gas stacks by using an oxidiser with ambient air, the working fluid temperature can be raised to 105 °C, estimating a potential energy savings up to 17.3%. The technique was discovered to lead to an energy saving of 685 kW and annual cost savings of more than 190 k€ without the requirement of any special investment.

Nevertheless it is argued that transporting the heat from the source to use may be a challenge and in this regard suitable heat insulation maybe required. Having mentioned that, significant energy savings have been achieved with the use of new technologies such as the use of thermal oil to transfer heat from the afterburner to the dryer [227] (see Fig. 31).

6. Conclusion

In conclusion, industrial waste heat is the energy lost in industrial processes to the environment. Waste heat recovery in industry covers methods of collection and re-use of the lost heat of industrial processes that can then be used to provide useful energy and reduce the overall energy consumption. Heat loss is mainly classified into high temperature, medium temperature and low temperature grades and waste heat recovery systems are correspondingly introduced for each range of waste heat. The selection of heat recovery methods and techniques largely depends on key factors such as the quality, quantity and the nature of heat source in terms of suitability and effectiveness. The identification of the waste sources is an important aspect when looking into waste heat recovery methods for industrial processes in order to achieve optimum results and efficiency. In this regard, a comprehensive review is presented for waste heat recovery methodologies and state of the art technologies used in industrial processes.

It was investigated that, there are many different heat recovery technologies available for capturing the waste heat and they mainly consist of energy recovery heat exchangers in the form of a waste heat recovery unit. These units mainly comprise common waste heat recovery systems and all work by the same principle to capture, recover and exchange heat with a potential energy content in a process.

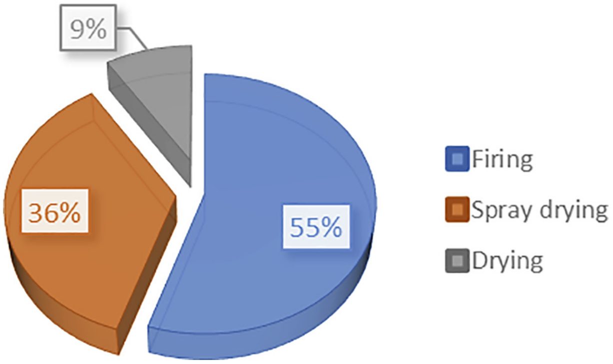


Fig. 30. Thermal energy sources in ceramic industry.

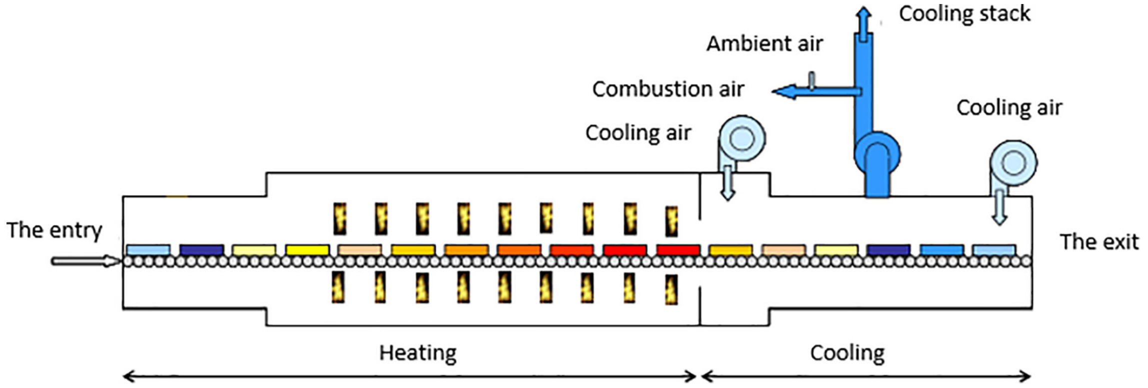


Fig. 31. Schematic of a Ceramic Kiln [228].

It was discovered that major heat recovery equipment are mainly categorised based on the temperature range and the type of fluid being recovered in the process and each has a different usage. For instance, it was studied, regenerative and recuperative burners optimise energy efficiency by incorporating heat exchanger surfaces to capture and use the waste heat from the hot flue gas from the combustion process, whereas, economisers recover low – medium waste heat and are mainly used for heating liquids. On the other hand, it was explored that waste heat boilers are suitable to recover heat from medium – high temperature exhaust gases and are mainly used to generate steam for power generation or energy recovery.

Systems such as air preheaters were found to be useful for exhaust-to-air heat recovery and for low to medium temperature applications. This system was revealed to be particularly useful where cross contamination in the process must be prevented. Nonetheless systems that incorporate several heat recovery systems such as the heat recovery steam generator was also reviewed and it was discovered that this complex system recovers the waste heat and employs a thermodynamic cycle to generate power and improve the efficiency of a power or manufacturing plant.

The working principles of thermodynamic cycles that are mainly used for waste heat recovery such as the Organic Rankine Cycle and the Kalina cycle were also studied and it was determined that the Kalina cycle offers a better result when the recovered heat is the medium-high grade. However, the ORC was a competitor when the recovered heat was in the low-medium range. Nevertheless, the functionality of plate heat exchanger and heat pipe systems were also looked at and it was learned that these heat exchangers can be used to transfer heat from any temperature range and from one source to another when cross contamination needs to be avoided.

The functionalities of direct electrical conversion devices were also explored and it was discovered that these systems produce electricity directly from waste heat and eliminate the need for converting heat to mechanical energy to produce electrical energy. Nonetheless, due to the limitations these technologies offer, they are not widely used in industry. The working principles of heat pumps were also studies and it was learned that this technology is in particular good for low-temperature waste heat recovery, as it gives the capability to upgrade waste heat to a higher temperature and quality.

By considering the heat recovery opportunities for energy optimisation in the steel and iron, food, and ceramic industries, current practices and procedures were assessed and reviewed. For instance, by looking into the waste heat recovery potential for the iron and steel industry, it was revealed that the sources of waste heat are mainly within the range of medium-high temperature but challenges and limitations related to recovery methods exist due to the presence of dirty and low quality waste heat. In this regard, new and innovative technologies and techniques are employed to recover the waste heat from different sources in iron and steel production processes.

The investigated technologies and techniques include, the use of Heat Pipes to recover heat from the cooling line; regenerators to recover the waste heat from the exits of coke ovens, oven chambers, and blast furnaces; semi wet and wet open combustion and supressed combustion techniques for recovery from the basic oxygen furnaces; capturing and using flammable by-product gases and waste heat through preheaters in electrical arc furnaces; heat recovery through coke dry quenching and wet quenching and recovery as hot air steam or conversion of the waste heat to fuel through chemical reactions from hot slag.

Waste heat recovery opportunities in food industry were also investigated and it was discovered that the potential sources of waste heat in this industry are mainly associated with heating and refrigeration systems, hot streams of water or air and heat from processing operations. Heat recovery from these sources must be studied on an individual case basis as some waste heat sources such as waste water and cooker exhaust recovery may be difficult and uneconomical to utilise because of grease and food waste products in the exhaust.

Having said that, technologies such as thermoacoustic heat engines (TAHEs), economisers, automatic scalding chambers, heat pumps and de-superheaters are considered to be alternative methods of optimising energy management in the processes of the food industry.

In the ceramics industry, the primary sources of available waste heat come from kilns and furnaces mainly through the drying and firing operations. The available techniques for waste heat recovery in this industry include recovery of excess heat from roller kilns though co-generation or combined heat and power, the Organic Rankine Cycles to generate electricity and heat pipe systems.

The functionality of each system has been analysed and it has been shown that recovery of excess heat from roller kilns can be carried out by accumulating the waste heat from the cooling zones of the kiln tunnel and using that as a heat source to preheat the dryer or through the means of other mentioned methods such as CHP or ORC to generate heat and electricity for the plant.

To sum up, this paper indicates that improving energy efficiency by utilising waste heat recovery in industrial processes is achievable based on different approaches and with the use of different state of the art technologies. However, in order to obtain the most optimum efficiency for a system through waste heat recovery, the type of process in question should be always examined and analysed and then a method of waste heat recovery for optimising energy efficiency should be assigned.

Conflict of interest

None.

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