**Unit 6 Waste Heat Recovery**

**Objectives:** At the end of this chapter the reader would be able to describe what waste heat recovery is, what are its different forms, how waste heat can be utilised through different methods, what are the commercially available waste heat recovery options and what are the factors upon which the design of a waste heat recovery system is based.

**Pre-requisites:** Understanding of basic thermodynamic and heat transfer principles, basic understanding of fluid mechanics.

**6.1 Classifications and Applications**

Some amount of heat energy generated in industrial processes cannot be put to practical use. This energy is known as waste heat. Waste heat is generally generated from hot combustion gases discharged to the atmosphere, heated products exiting industrial processes, and heat transfer from hot equipment surfaces. Waste heat recovery systems are designed to recover the unused heat to do some useful work. The mechanism to recover the unused heat depends on the temperature of the waste heat gases and the economics involved. Recovery of the waste heat helps in saving considerable amount of primary fuel. Although waste heat systems are designed to utilise the waste heat but some amount of heat is still lost.

While designing a heat recovery system the waste heat is graded in terms of its potential value as shown in Table 6.1:

TABLE 6.1 WASTE SOURCE AND QUALITY[[1]](#footnote-1)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **S.No.** | **Source** | | **Quality** | | |
| 1. | Heat in flue gases. | | The higher the temperature, the greater the potential value for heat recovery | | |
| 2. | Heat in vapour streams. | | As above but when condensed, latent heat also recoverable. | | |
| 3. | Convective and radiant heat lost from exterior of equipment | | Low grade – if collected may be used for space heating or air preheats. | | |
| 4. | Heat losses in cooling water. | | Low grade – useful gains if heat is exchanged with incoming fresh water | | |
| 5. | Heat losses in providing chilled water or in the disposal of chilled water | | a) High grade if it can be utilized to reduce demand for refrigeration. b) Low grade if refrigeration unit used as a form of heat pump. | | |
| 6. | Heat stored in products leaving the process | | Quality depends upon temperature. | | |
| 7. | Heat in gaseous and liquid effluents leaving process. | | Poor if heavily contaminated and thus requiring alloy heat exchanger. | | |
| **TABLE 6.2 TYPICAL WASTE HEAT TEMPERATURES FROM VARIOUS SOURCES[[2]](#footnote-2)** | | | | | |
|  | | | **Types of Device** | | **Temperature, °C** |
| **TYPICAL WASTE HEAT TEMPERATURE AT HIGH TEMPERATURE RANGE** | | | Nickel refining furnace | | 1370 –1650 |
| Aluminium refining furnace | | 650–760 |
| Zinc refining furnace | | 760–1100 |
| Copper refining furnace | | 760– 815 |
| Steel heating furnaces | | 925–1050 |
| Copper reverberatory furnace | | 900–1100 |
| Open hearth furnace | | 650–700 |
| Cement kiln (Dry process) | | 620– 730 |
| Glass melting furnace | | 1000–1550 |
| Hydrogen plants | | 650–1000 |
| Solid waste incinerators | | 650–1000 |
| Fume incinerators | | 650–1450 |
| **TYPICAL WASTE HEAT TEMPERATURE AT MEDIUM TEMPERATURE RANGE** | | | Steam boiler exhausts | | 230–480 |
| Gas turbine exhausts | | 370–540 |
| Reciprocating engine exhausts | | 315–600 |
| Reciprocating engine exhausts (turbo charged) | | 230–370 |
| Heat treating furnaces | | 425–650 |
| Drying and baking ovens | | 230–600 |
| Catalytic crackers | | 425–650 |
| Annealing furnace cooling systems | | 425–650 |
| **TYPICAL WASTE HEAT TEMPERATURE AT LOW TEMPERATURE RANGE** | | | Process steam condensate | | 55–88 |
| **Cooling water from:** | |  |
| Furnace doors | | 32–55 |
| Bearings | | 32–88 |
| Welding machines | | 32–88 |
| Injection moulding machines | | 32–88 |
| Annealing furnaces | | 66–230 |
| Forming dies | | 27–88 |
| Air compressors | | 27–50 |
| Pumps | | 27–88 |
| Internal combustion engines | | 66–120 |
| Air conditioning and refrigeration condensers | | 32–43 |
| Liquid still condensers | | 32–88 |
| Drying, baking and curing ovens | | 93–230 |
| Hot processed liquids | | 32–232 |
| Hot processed solids | | 93–232 |

Waste heat recovery systems are classified according to the temperature of the waste heat. Accordingly, waste heat recovery systems are classified as high temperature heat recovery, medium temperature heat recovery and low temperature heat recovery systems. Table 6.2 lists the various types of heat recovery systems and the equipment’s from which waste heat is typically recovered.

**6.2 Benefits of waste heat recovery**

Waste heat recovery increases the plant efficiency and in turn reduces the primary fuel consumption and leads to economic stability. In addition to the economic benefits of waste heat recovery for the facility, waste heat recovery is a greenhouse­gas­free source of energy.

**6.3 Commercial waste recovery systems[[3]](#footnote-3)**

Commercial methods for waste heat recovery typically include transferring heat between gases and/or liquids, transferring heat to the load entering furnaces, generating mechanical and/or electrical power or using waste heat with a heat pump for heating or cooling facilities.

**6.3.1 Transferring heat between gases and/or liquids**

Heat exchangers are most commonly used to transfer heat between gases and/or liquids. Waste heat recovery heat exchangers basically transfer heat from combustion exhaust gases to combustion air entering the furnace. This helps in reducing the primary energy consumption. Typical technologies used for air preheating include recuperators, furnace regenerators, burner regenerators, rotary regenerators, and passive air preheaters.

**6.3.1.1 Recuperator**

Recuperators are used to recover waste heat from medium to high temperature applications such as soaking or annealing ovens, melting furnaces, afterburners, gas incinerators, radiant­tube burners, and reheat furnaces. Heat recovery in case of recuperators is based on radiation, convection or combination of radiation and convection.

A simple radiation recuperator consists of two concentric lengths of ductwork. Hot waste gases pass through the inner duct and heat transfer is primarily radiated to the wall and to the cold incoming air in the outer shell as shown in figure 6.1. The preheated shell air then travels to the furnace burners.

In the convective or tube type recuperator hot gases pass through relatively small diameter tubes contained in a larger shell. The combustion air enters the shell and heated with the help of the waste gases. Baffles around the tubes helps in increasing the heat transfer rate.

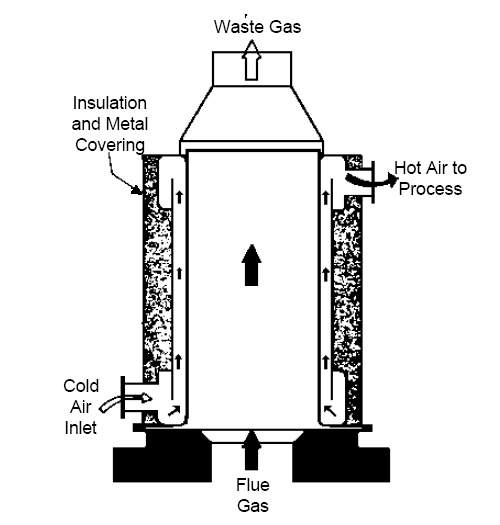


Figure 6.1Metallic Radiation Recuperator Design (Source: PG&E)

The combined radiation/convection recuperator system includes a radiation section followed by a convection section in order to maximize heat transfer effectiveness as shown in figure 6.2.

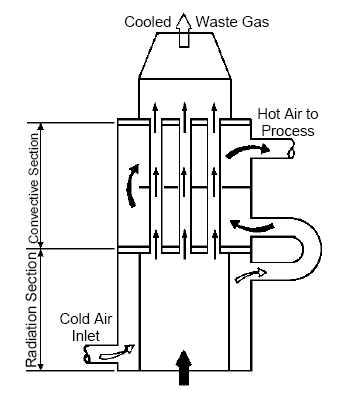


Figure 6.2 Combined Radiation/Convection Recuperator (Source: PG&E)

Recuperators are constructed out of either metallic or ceramic materials. Metallic recuperators are used in applications with temperatures below 1093ºC, while heat recovery at higher temperatures is better suited to ceramic tube recuperators. These can operate with hot side temperatures as high as 1538ºC and cold side temperatures of about 982ºC[[4]](#footnote-4).

**6.3.1.2 Regenerators**

Regenerative furnaces consist of two brick chambers through which hot and cold air flows alternately as shown in figure 6.3. As combustion exhausts pass through one chamber, the bricks absorb heat from the combustion gas and increase in temperature. The flow of air is then adjusted so that the incoming combustion air passes through the hot chamber, which transfers heat to the combustion air entering the furnace. Two chambers are used so that while one is absorbing heat from the exhaust gases, the other is transferring heat to the combustion air. The direction of airflow is altered about every 20 minutes.

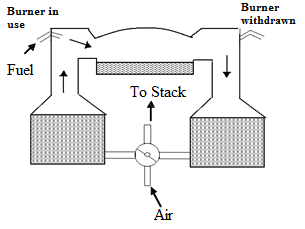
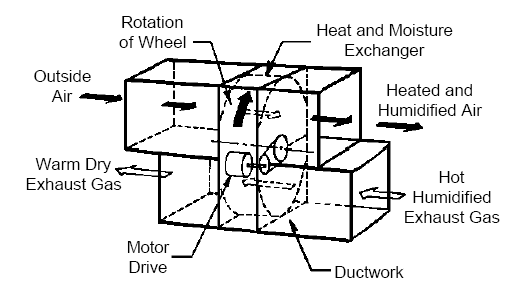
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Figure 6.3 Regenerative Furnace Diagram

Regenerators find extensive application in glass furnaces and coke ovens, and were historically used with steel open hearth furnaces, before these furnaces were replaced by more efficient designs. Regenerators are also used in iron making to preheat the hot blast provided to blast stoves. Regenerators used in blast stoves are however not a heat recovery application, but simply the means by which heat released from gas combustion is transferred to the hot blast air. Regenerator systems are especially suited for high temperature applications with dirty exhausts. Commercial use of regenerators is limited because of their large size and capital costs compared to the recuperators[[5]](#footnote-5).

The working principle of rotary regenerators is similar to that of fixed regenerators in that heat transfer is facilitated by storing heat in a porous media, and by alternating the flow of hot and cold gases through the regenerator. Rotary regenerators are sometimes also called as air preheaters and heat wheels. They basically use a rotating porous disc placed across two parallel ducts, one containing the hot waste gas, the other containing cold gas as shown in figure 6.4. The disc is made up of a high heat capacity material and it rotates between the two ducts and transfers heat from the hot gas duct to the cold gas duct. As high temperature result in thermal stresses heat wheels are generally restricted to low and medium temperature applications. The integrity of the duct wheel air seals may be compromised because of differential expansion and large deformations resulting out of large temperature differences between the two ducts. For high temperature applications ceramic wheels can be used. The porosity of the wheel may result in cross contamination between the two gas streams. Prevention of cross contamination is a major challenge.



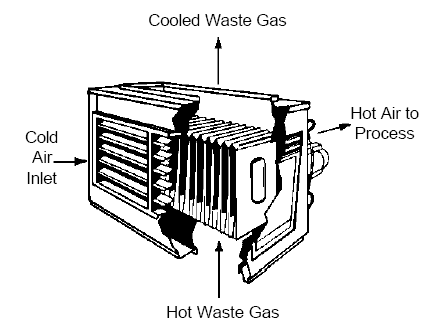
**Figure 6.4 Rotary Regenerator (Source: PG&E, 1997)**

Heat wheels when designed with hygroscopic material can be used to recover moisture as well as heat from clean gas streams. Thus heat wheels are extensively used for space heating and air conditioning systems.

**6.3.1.3 Passive Air Preheaters**

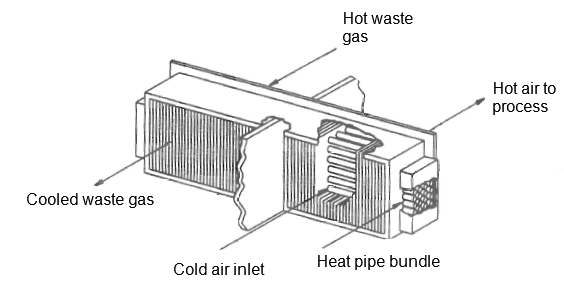
When cross contamination between gas streams is to be prevented passive air preheaters are used. They are basically gas to gas heat recovery devices for low to medium temperature applications. They are widely used in ovens, steam boilers, gas turbine exhaust, secondary recovery from furnaces, and recovery from conditioned air.

Passive preheaters can be either plate type or heat pipe type. In the plate type exchanger multiple parallel plates are used to create separate channels for hot and cold gas streams as shown in figure 6.5. The heat transfer surface area is significantly increased because the hot and cold streams flows alternate between the plates. Although these systems are less susceptible to contamination compared to heat wheels, but they are often bulkier, more costly, and more susceptible to fouling problems.



**Figure 6.5 Passive Gas to Gas Air Preheater (Source, PG & E, 1997)**

The heat pipe heat exchanger consists of several pipes with sealed ends. The movement of the working fluid between the hot and cold ends of the pipe is facilitated by the capillary wick structure in each pipe. As shown in figure 6.6 below, hot gases pass over one end of the heat pipe, causing the working fluid inside the pipe to evaporate. Pressure gradients along the pipe cause the hot vapour to move to the other end of the pipe, where the vapour condenses and transfers heat to the cold gas. The condensate then cycles back to the hot side of the pipe via capillary action.



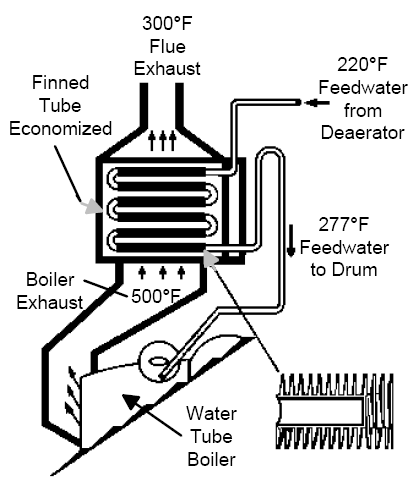
**Figure 6.6 Heat Pipe Heat Exchanger (Source: Turner, 2006)**

**6.3.1.4 Regenerative/Recuperative Burners**

Burners that incorporate regenerative or recuperative systems are commercially available. These systems provide increased energy efficiency compared to burners operating with ambient air. A self-recuperative burner incorporates heat exchange surfaces as part of the burner body design in order to capture energy from the exiting flue gas, which passes back through the body. Self-regenerative burners pass exhaust gases through the burner body into a refractory media case and operate in pairs similar in manner to a regenerative furnace. Typically, recuperative burner systems have less heat exchange area and regenerative burner systems lower mass than stand­alone units. Hence, their energy recovery is lower but their lower costs and ease of retrofitting make them an attractive option for energy recovery.

**6.3.1.5 Finned Tube Heat Exchangers/Economizers**

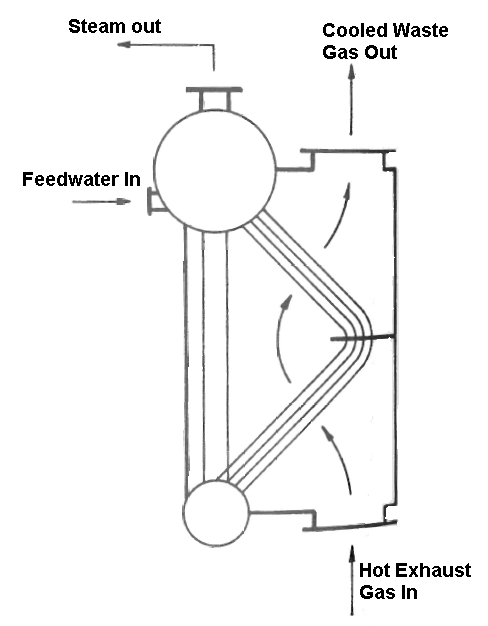
Finned tube heat exchangers are used to recover heat from low to medium temperature exhaust gases for heating liquids. Applications include boiler feed water preheating, hot process liquids, hot water for space heating or domestic hot water. The finned tube consists of a round tube with attached fins that maximize surface area and heat transfer rates. Liquid flows through the tubes and receive heat from hot gases flowing across the tubes. Figure 6.7 illustrates a finned tube exchanger where boiler exhaust gases are used for feedwater preheating, a setup commonly referred to as a boiler “economizer”.



**Figure 6.7 Finned Tube Exchanger/ Boiler Economizer (Source: PG&E 2007)**

**6.3.1.6 Waste Heat Boilers**

Waste heat boilers, such as the two pass boiler shown in Figure 6.8, are water tube boilers that use medium­ to high­ temperature exhaust gases to generate steam. Waste heat boilers are available in a variety of capacities. In cases where the waste heat is not sufficient for producing desired levels of steam, auxiliary burners or an afterburner can be added to attain higher steam output. The steam can be used for process heating or for power generation. Generation of superheated steam will require addition of an external superheater to the system.



**Figure 6.8 Waste Heat Boiler**

**6.3.2 Load Preheating**

Load preheating refers to any efforts to use waste heat leaving a system to preheat the load entering the system. The most common example is boiler feedwater preheating, where an economizer transfers heat from hot combustion exhaust gases to the water entering the boiler. Other applications utilize direct heat transfer between combustion exhaust gases and solid materials entering the furnace. For example, in the aluminum metal casting industry, stack melters can replace reverberatory furnaces to reduce energy consumption. With stack melters, ingots and scrap are charged through the top of the furnace and preheated by exhaust gases leaving the furnace. While boiler feedwater preheating is a standard practice, load preheating of material prior to melting in direct fired systems is not as widely used. This is due to a variety of factors, including difficulties in controlling product quality, issues associated with environmental emissions, and the increased complexity and cost of building advanced furnace loading/heat recovery systems. Nevertheless, heat recovery via load preheating has received increased attention. The available technologies and barriers for different load preheating furnaces will vary substantially depending on the type of furnace and load in question.

**6.3.3 Low Temperature Energy Recovery Options and Technologies**

While economics often limit the feasibility of low temperature waste heat recovery, there are various applications where low grade waste heat has been cost effectively recovered for use in industrial facilities. The large quantities of waste heat available in the range of 38­200°C and the inherent challenges to its recovery and use warrant a separate and in depth investigation of low temperature waste heat recovery.

Much industrial waste heat is in the low temperature range. For example, combustion systems such as boilers frequently use recovery technologies that exhaust gases at around 150°­180°C. Meanwhile, large quantities of waste heat can be found in industrial cooling water and cooling air. One integrated steel mill in Japan successfully installed a power generation plant with a 3.5 MW capacity using cooling water at only 98°C[[6]](#footnote-6).

In the case of combustion exhaust gases, substantial heat can be recovered if water vapour contained in the gases is cooled to lower temperatures. Minimum temperature limits around 120­-150°C are frequently employed in order to prevent water in the exhaust gases from condensing and depositing corrosive substances on the heat exchanger surface. However, cooling the flue gas further could significantly increase heat recovery by allowing the latent heat of vaporization to be recovered. This latent heat comprises a significant portion of the energy contained in exhaust gases. Technologies that can minimize chemical attack while cooling exhaust gases below the condensation point can achieve significant increases in energy efficiency via recovering the latent heat of evaporation. If gases are cooled from 150°C to 60°C, then the facility can obtain a 3% efficiency increase. Cooling gases further to 38ºC captures a portion of the latent heat and can provide an 11% efficiency increase.

**6.3.3.1 Challenges to Recovering Low Temperature Waste Heat**

Low temperature heat recovery faces at least three challenges:

* *Corrosion of the heat exchanger surface:* As water vapour contained in the exhaust gas cools, some of it will condense and deposit corrosive solids and liquids on the heat exchange surface. The heat exchanger must be designed to withstand exposure to these corrosive deposits. This generally requires using advanced materials, or frequently replacing components of the heat exchanger, which is often uneconomical.
* *Large heat exchange surfaces required for heat transfer:* Heat transfer rates are a function of the thermal conductivity of the heat exchange material, the temperature difference between the two fluid streams, and the surface area of the heat exchanger. Since low temperature waste heat will involve a smaller temperature gradient between two fluid streams, larger surface areas are required for heat transfer. This limits the economics of heat exchangers.
* *Finding a use for low temperature heat:* Recovering heat in the low temperature range will only make sense if the plant has a use for low temperature heat. Potential end uses include domestic hot water, space heating, and low temperature process heating. Other options include using a heat pump to “upgrade” heat to a higher temperature to serve a load requiring higher temperatures. Additionally, low temperature power generation technologies are slowly emerging.

Technologies are available that can cool gases below dew point temperatures to recover low temperature waste heat. Options include deep economizers, indirect contact condensation recovery, direct contact condensation recovery, and recently developed transport membrane condensers. These technologies are discussed below. Commercialization has been limited due to high costs and because facilities lack an end­ use for the recovered heat. When facilities lack an end use for waste heat, some have found other means for recovery, including heat pumps and low temperature power generation. These technologies are also frequently limited by economic constraints.

**6.3.3.2 Low Temperature Heat Exchange**

***Deep Economizers***

Deep economizers are designed to cool exhaust gas to 65ºC­-71ºC and to withstand the acidic condensate depositing on its surface. Designs include the following options:

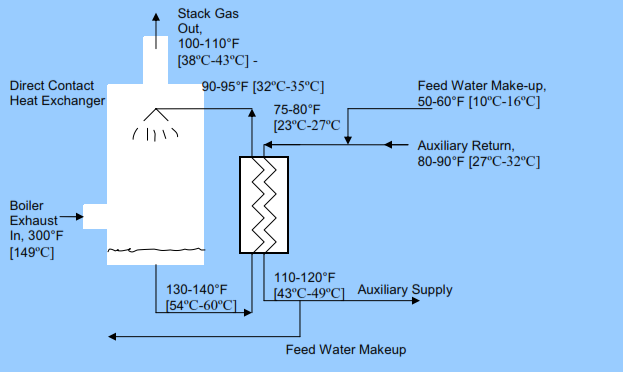
* Installing a “throwaway” section on the cold end of the economizer. The tubing in the cold end will degrade over time and will need to be repeatedly replaced. The frequency of replacements will depend on the flue gas composition and the material of construction.
* Designing the economizer with stainless steel tubes. Stainless steel can withstand acidic gases better than the mild steel typically used in construction.
* Using carbon steel for the majority of the heat exchanger, but using stainless steel tubes in the cold end where acidic deposits will occur.
* Using glass tube heat exchangers (mainly for gas to gas applications such as air preheaters).
* Using advanced materials such as Teflon[[7]](#footnote-7).

***Indirect Contact Condensation Recovery***

Indirect contact condensation recovery units cool gases to 38-­43ºC. In this range, the water vapour in gases will condense almost completely. Indirect contact exchangers consist of a shell & tube heat exchangers. They can be designed with stainless steel, glass, Teflon, or other advanced materials.

***Direct Contact Condensation Recovery***

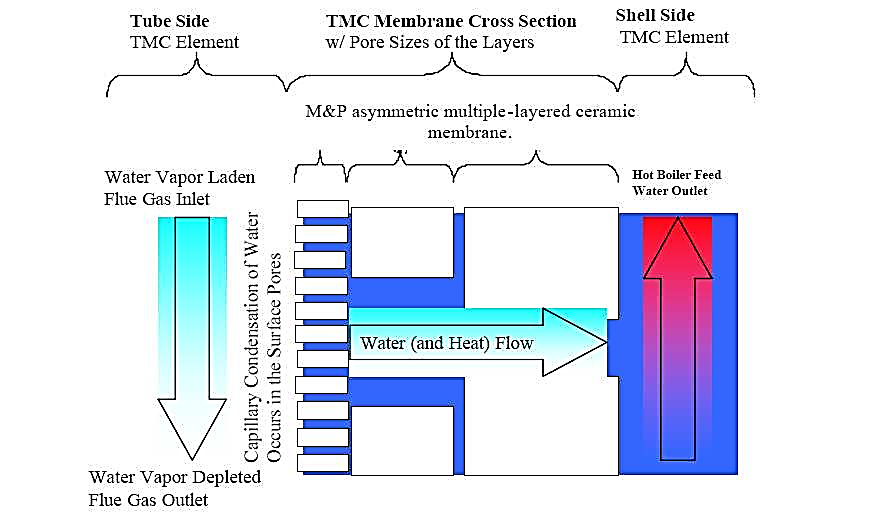
Direct contact condensation recovery involves direct mixing of the process stream and cooling fluid. Since these systems do not involve a separating wall across which heat must be transferred, they avoid some of the challenges of large heat transfer surfaces required for indirect contact units. An example system is shown in Figure 6.9. As flue gases enter the heat exchanger, they are cooled by cold water introduced at the top of the unit. The heated water stream exits through the bottom of the exchanger and provides heat to an external system. A challenge with direct contact condensation is that the water can be contaminated by substances in the flue gas.



**Figure 6.9 Direct Contact Condensation Heat Recovery (Adapted from Goldstick, 1986)**

***Transport Membrane Condenser***

Transport Membrane Condensers (TMCs) are a developing technology for capturing water (along with water’s latent heat) from the water vapour in gas exhaust streams. Water is extracted from the flue gas at temperatures above dew point by employing capillary condensation and recycled into the boiler feedwater. A schematic of the TMC in operation is shown Figure 6.10. Like direct contact heat recovery units, TMCs extract hot water directly from the flue gas; however, since TMCs recover the water via transport thorough a membrane, the recovered water does not become contaminated as in a direct contact unit. The technology has been demonstrated for clean exhaust streams in a natural gas-­fired boiler; however, TMCs require more research in advanced materials before widespread implementation for dirtier waste streams is possible.



**Figure 6.10 Transport Membrane Condenser[[8]](#footnote-8)**

***Heat Pumps (Upgrading Low Temperature Waste Heat)***

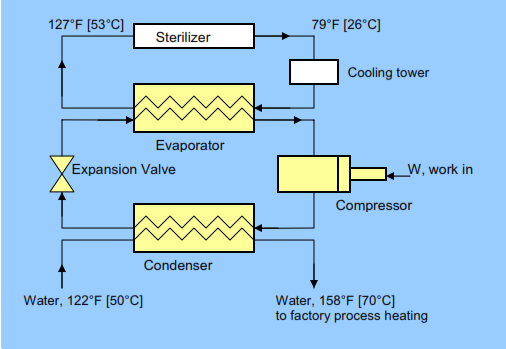
Heat exchange technologies described above involve flow of energy “downhill” from a high temperature to a lower temperature end use. This can place limitations on opportunities for heat recovery when the waste heat temperature is below the temperature needed for a given heating load. In such cases, a heat pump may provide opportunities for “upgrading” heat to the desired end use temperature. Heat pumps use external energy inputs to drive a cycle that absorbs energy from a low temperature source and rejects it at a higher temperature. Depending on the design, heat pumps can serve two functions: either upgrading waste heat to a higher temperature, or using waste heat as an energy input for driving an absorption cooling system. Heat pumps are most applicable to low­ temperature product streams found in process industries including chemicals, petroleum refining, pulp and paper, and food processing.

Upgrading heat can be economical in some cases depending on the temperature differential required and the relative costs of fuel and electricity. If a facility has a heat load at a slightly higher temperature than the waste heat source, the heat can sometimes be provided more efficiently by a heat pump than if it were obtained from burning additional fossil fuels.

An important consideration in determining the feasibility of heat pumps is the waste heat temperature and the desired “temperature lift.” The type of cycle used and the type of working fluid chosen will influence the temperatures at which the heat pump can receive or reject heat, as well as determine the maximum temperature lift achievable. The efficiency of a heat pump decreases as the desired temperature lift increase. Research to develop advanced cycles and novel fluids to increase heat pump performance and flexibility in different temperature ranges could enhance the use of heat pumps for waste heat recovery.

***Closed Compression Cycle***

Figure 6.11 displays an example use of a closed compression cycle to recover heat from cooling water leaving a sterilizer in a dairy plant. The sterilizer in the plant discharges cooling water at 53°C. A heat pump is used to lower the temperature of the cooling water, while using the heat extracted to increase the temperature of process water used elsewhere in the plant. The heat pump consists of an evaporator, compressor, condenser, and expansion valve. In the evaporator, energy is transferred from the waste heat source to the refrigerant. Then the refrigerant enters the compressor, where its temperature increases. Superheated refrigerant then enters the condenser and transfers heat to the heat sink. Finally, refrigerant is throttled in an expansion valve before returning to the evaporator.



**Figure 6.11 Heat Pump Application in a Dairy**

***Open Cycle Vapour Recompression***

These systems use compression to increase the pressure (and consequently the temperature) of waste vapour. Mechanical vapour recompression (MVR) uses a mechanical compressor, while thermal vapour recompression (TVR) uses a steam ejector, and therefore is heat driven rather than mechanically driven.

***Absorption Heat Pumps***

Absorption heat pumps are very similar to the closed compression cycle, except the compressor is replaced by a more complex, heat driven absorption mechanism. Depending on the plant needs, the system can be configured in multiple ways. A “Type I” heat pump can use a lower and a higher temperature heat input to reject heat at an intermediate level (e.g., upgrade the low temperature heat). A “Type II” heat pump can use a medium temperature input to reject heat in one lower temperature stream and one higher temperature stream. This second application can be used for air conditioning and/or refrigeration. Chilling cycles can be valuable for applications such as food refrigeration or for cryogenic processes in various industries.

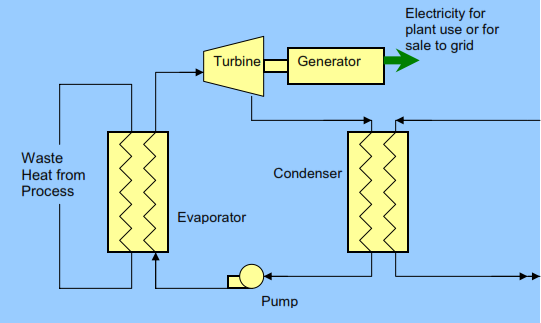
**6.3.4 Power Generation**

Generating power from waste heat typically involves using the waste heat from boilers to create mechanical energy that then drives an electric generator. While these power cycles are well developed, new technologies are being developed that can generate electricity directly from heat, such as thermoelectric and piezoelectric generation. When considering power generation options for waste heat recovery, an important factor to keep in mind is the thermodynamic limitations on power generation at different temperatures. As discussed, the efficiency of power generation is heavily dependent on the temperature of the waste heat source. In general, power generation from waste heat has been limited to only medium to high temperature waste heat sources. However, advances in alternate power cycles may increase the feasibility of generation at low temperatures. While maximum efficiency at these temperatures is lower, these systems can still be economical in recovering large quantities of energy from waste heat.

**6.3.4.1 Generating Power via Mechanical Work**

***Steam Rankine Cycle***

The most frequently used system for power generation from waste heat involves using the heat to generate steam, which then drives a steam turbine. A schematic of waste heat recovery with a Rankine cycle is shown in Figure 6.12. The traditional steam Rankine cycle is the most efficient option for waste heat recovery from exhaust streams with temperatures above about 340­-370°C[[9]](#footnote-9). At lower waste heat temperatures; steam cycles become less cost effective, since low pressure steam will require bulkier equipment. Moreover, low temperature waste heat may not provide sufficient energy to superheat the steam, which is a requirement for preventing steam condensation and erosion of the turbine blades. Therefore, low temperature heat recovery applications are better suited for the organic Rankine Cycle or Kalina cycle, which use fluids with lower boiling point temperatures compared to steam.



**Figure 6.12 Waste Heat Recovery with Rankine Cycle**

***Organic Rankine Cycle***

The Organic Rankine Cycle (ORC) operates similar to the steam Rankine cycle, but uses an organic working fluid instead of steam. Options include silicon oil, propane, haloalkanes (e.g., “freons”), iso­ pentane, iso­butane, p­xylene, and toluene, which have a lower boiling point and higher vapour pressure than water. This allows the Rankine cycle to operate with significantly lower waste heat temperatures— sometimes as low as 66ºC. The most appropriate temperature range for ORCs will depend on the fluid used, as fluids’ thermodynamic properties will influence the efficiency of the cycle at various temperatures.

In comparison with water vapour, the fluids used in ORCs have a higher molecular mass, enabling compact designs, higher mass flow, and higher turbine efficiencies (as high as 80­85%)[[10]](#footnote-10). However, since the cycle functions at lower temperatures, the overall efficiency is only around 10­-20%, depending on the temperature of the condenser and evaporator. While this efficiency is much lower than a high temperature steam power plant (30-­40%), it is important to remember that low temperature cycles are inherently less efficient than high temperature cycles. Limits on efficiency can be expressed according to Carnot efficiency. A Carnot engine operating with a heat source at 150ºC and rejecting it at 25ºC is only about 30% efficient. In this light, an efficiency of 10­-20% is a substantial percentage of theoretical efficiency, especially in comparison to other low temperature options, such as piezoelectric generation, which are only 1% efficient.

ORC technology is not particularly new; at least 30 commercial plants worldwide were employing the cycle before 1984[[11]](#footnote-11). Its applications include power generation from solar, geothermal, and waste heat sources. As per an article published in Distributed Energy, ORCs are most useful for waste heat recovery among these three applications[[12]](#footnote-12). Waste heat recovery can be applied to a variety of low to medium temperature heat streams. An example of a recent successful installation is in Bavaria, Germany, where a cement plant installed an ORC to recover waste heat from its clinker cooler, whose exhaust gas is at about 500°C. The ORC provided 12% of the plant’s electricity requirements and reduced CO2 emissions by approximately 7,000 tons[[13]](#footnote-13). Although the economics of ORC heat recovery need to be carefully analyzed for any given application, it will be a particularly useful option in industries that have no in house use for additional process heat or no neighbouring plants that could make economic use of the heat.

***Kalina Cycle***

The Kalina cycle is a variation of the Rankine cycle, using a mixture of ammonia and water as the working fluid. A key difference between single fluid cycles and cycles that use binary fluids is the temperature profile during boiling and condensation. For single fluid cycles (e.g., steam or organic Rankine), the temperature remains constant during boiling. As heat is transferred to the working medium (e.g., water), the water temperature slowly increases to boiling temperature, at which point the temperature remains constant until all the water has evaporated. In contrast, a binary mixture of water and ammonia (each of which has a different boiling point) will increase its temperature during evaporation. This allows better thermal matching with the waste heat source and with the cooling medium in the condenser. Consequently, these systems achieve significantly greater energy efficiency.

The cycle was invented in the 1980s and the first power plant based on the Kalina cycle was constructed in Canoga Park, California in 1991. It has been installed in several other locations for power generation from geothermal energy or waste heat. Applications include a 6 million metric tons per year steelworks in Japan (1999)[[14]](#footnote-14), heat recovery from a municipal solid waste incinerator (1999), and from a hydrocarbon process tower (2003)[[15]](#footnote-15). The steelworks application involved using a Kalina cycle to generate power from cooling water at 98°C. With a water flow rate of 1,300 metric tons per hour, the electric power output was about 4,500 kW[[16]](#footnote-16).

**6.3.4.2 Direct Electrical Conversion Devices**

Whereas traditional power cycles involve using heat to create mechanical energy and ultimately electrical energy, new technologies are being developed that can generate electricity directly from heat. These include thermoelectric, thermionic, and piezoelectric devices. There is no evidence that these systems have been tested in industrial waste heat recovery applications, although a few have undergone some prototype testing in applications such as heat recovery in automotive vehicles.

***Thermoelectric Generation***

Thermoelectric (TE) materials are semiconductor solids that allow direct generation of electricity when subject to a temperature differential. These systems are based on a phenomenon known as the Seebeck effect: when two different semiconductor materials are subject to a heat source and heat sink, a voltage is created between the two semiconductors. Conversely, TE materials can also be used for cooling or heating by applying electricity to dissimilar semiconductors. Thermoelectric technology has existed for a long time (the thermoelectric effect was first discovered in 1821), but has seen limited use due to low efficiencies and high cost. Most TE generation systems in use have efficiencies of 2 to 5%; these have mainly been used to power instruments on spacecraft or in very remote locations. However, recent advances in nanotechnology have enabled advanced TE materials that might achieve conversion efficiencies 15% or greater.

A recent study by PNNL and BCS, Incorporated examines the opportunity for TE generation in various industrial waste heat streams and identifies performance requirement and RD&D needs[[17]](#footnote-17). The study concluded that advanced TE packages would be appropriate in medium to high temperature, high flow rate exhaust streams where facilities have little use for recovered waste heat. Two example opportunities are glass furnaces and molten metal furnaces. Before TE materials can be used in these applications, advances are needed in both TE production technology and in heat transfer systems. Obtaining high heat transfer rates will require advances in heat transfer materials and heat exchange systems with high heat transfer coefficients.

***Piezoelectric Power Generation***

Piezoelectric Power Generation (PEPG) is an option for converting low temperature waste heat 100-­150°C to electrical energy[[18]](#footnote-18). Piezoelectric devices convert mechanical energy in the form of ambient vibrations to electrical energy. A piezoelectric thin film membrane can take advantage of oscillatory gas expansion to create a voltage output. A study[[19]](#footnote-19) identified several technical challenges associated with PEPG technologies:

• low efficiency: PEPG technology is only about 1% efficient; difficulties remain in obtaining high enough oscillatory frequencies; current devices operate at around 100 Hz, and frequencies closer to 1,000 Hz are needed,

• high internal impedance,

• complex oscillatory fluid dynamics within the liquid/vapour chamber,

• need for long term reliability and durability, and

• high costs ($10,000/W).

While the conversion efficiency of PEPG technology is currently very low (1%), there may be opportunities to use PEPG cascading, in which case efficiencies could reach about 10%[[20]](#footnote-20). Other key issues are the costs of manufacturing piezoelectric devices, as well as the design of heat exchangers to facilitate sufficient heat transfer rates across a relatively low temperature difference[[21]](#footnote-21).

*Thermionic Generation*

Thermionic devices operate similar to thermoelectric devices; however, whereas thermoelectric devices operate according to the Seebeck effect, thermionic devices operate via thermionic emission. In these systems, a temperature difference drives the flow of electrons through a vacuum from a metal to a metal oxide surface. One key disadvantage of these systems is that they are limited to applications with high temperatures above 1,000°C. However, some development has enabled their use at about 100­-300°C[[22]](#footnote-22).

*Thermo Photo Voltaic (TPV) Generator*

TPV Generators can be used to convert radiant energy into electricity. These systems involve a heat source, an emitter, a radiation filter, and a PV cell (like those used in solar panels). As the emitter is heated, it emits electromagnetic radiation. The PV cell converts this radiation to electrical energy. The filter is used to pass radiation at wavelengths that match the PV cell, while reflecting remaining energy back to the emitter. These systems could potentially enable new methods for waste heat recovery. A small number of prototype systems have been built for small burner applications and in a helicopter gas turbine[[23]](#footnote-23).

**6.4 Case Example**

Exhaust steam from evaporator in a fruit juice concentrator plant was condensed in a pre-condenser operation on cooling water upstream of a steam jet vaccum ejector

The equipment suggested was either a Thermo-compressor or a shell & tube heat exchanger. The cost of the thermo-compressor was Rs.1.5 Lakhs. The savings of jacket steam due to recompression of vapour was Rs.5.0 Lakhs per annum.

Cost of shell &tube exchanger to preheat boiler feed water was Rs.75,000/- and the savings in fuel cost was nearly Rs.4.5 Lakhs per annum.

**SELF-ASSESSMENT EXERCISE**

1. Explain the term waste heat recovery? What are the different types of waste heats? How these waste heats can be recovered?
2. Why waste heat recovery is essential?
3. On what factors the design of a waste heat recovery system is based?
4. What are the various types of recuperators?
5. Explain the operating principle of the following :
   1. Regenerator
   2. Heat wheels
   3. Heat Pipe
   4. Economiser
   5. Shell and tube heat exchanger
6. Explain the operating principle of a waste heat recovery boiler with examples.
7. Explain how power can be generated directly from waste heat through different methods.
8. What the limitations for low temperature waste heat recovery?

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