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Waste Heat Recovery Analysis: An Overview of Reversed Heat Pump Systems

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Abstract

Heat recovery systems are usually assembled by combining a number of systems towards achieving the desired objective. To achieve waste heat recovery, heat pumps incorporate appropriate changeover or reversing valves to achieve cooling, thereby recovering the expected end product of heat. This paper presents an overview of reversed heat pump systems used for waste heat recovery. The review identifies the core components of reversed heat engines as compressor, condenser, expansion device evaporator and drying chamber. Also, the study identified the four basic types of heat pumps and they include air-to-air heat pumps, water-to-air heat pumps, water-to-water heat pumps and ground source heat pumps. Furthermore, the study identified the available waste heat recovery equipment and their classification. The common classification include steam generators, recuperators, shell and tube heat exchangers, fin tube heat exchangers, heat pipes and run-around-coils. Typical schematics of these systems, showing their component parts, are also presented. Finally, a study of the benefits of waste heat recovery systems is presented and the work identifies both direct and indirect benefits. Direct benefits include improved efficiency of a system while indirect benefits include reduction in pollution, reduction in equipment sizes, and reduction in auxiliary energy consumption. This findings presents a thorough knowledge base on reversed heat pumps for waste heat recovery.

Keywords

Heat Engines, Waste Heat, Recovery, Pumps; Systems

1. Introduction

A heat pump cycle absorbs heat from a source and transfers the heat to a sink in a cycle of series of activities involving the evaporator, refrigerant, compressor, condenser and the expansion valve. An evaporator extracts the heat from the source by transferring the heat to a refrigerant. The heat transferred to the refrigerant causes it to change from liquid to gas phase (i.e. evaporate). The evaporated refrigerant gas pressure and temperature is raised utilising a compressor and transferred to the condenser. Similarly, heat transfer to the sink causes the high pressure refrigerant gas to condense to a liquid state within the condenser. An expansion valve lowers the pressure of the liquid refrigerant and this expansion process also causes a drop in the liquid refrigerant temperature as the refrigerant enters the evaporator restarting the cycle. All refrigeration equipment (i.e. air-conditioners, chillers etc.) can be classified as heat pumps. However, in engineering, heat pump terminology is usually used for equipment that produces heat as the usable output as opposed to refrigeration plant that produces cooling as the usable output. In addition, heat pumps can also incorporate the ability to provide a cooling effect by including appropriate changeover/reversing valves [1-4].

Unlike heat pumps, that are typically available as a single package, heat recovery systems are assembled by combining a number of systems to enable heat recovery functionality. Some examples include: variable refrigerant flow systems that enable recovery of energy between cooling and heating systems, reverse cycle water-to-air heat pumps on a common water loop that allows recovery of energy between units rejecting heat and those requiring heat, heat-reclaim chillers that simultaneously provide heating and cooling and utilising run-around coils or heat-exchangers to recover energy from air exhausted from a building to pre-temper outside-air introduced into the building. A typical waste heat recovery system is as shown in Figure 1.

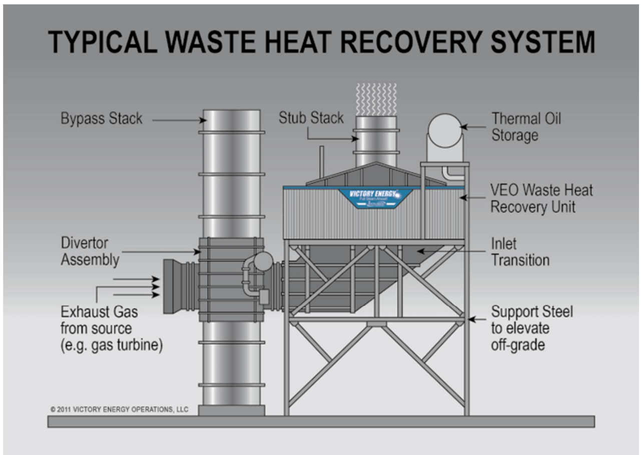

Figure 1. *A typical waste heat recovery plant (Source: Victory Energy Operations, LLC).*

In many industrial and commercial energy applications, only a portion of the energy input is used in the process. The remainder of the useful energy is rejected to the environment. This rejected energy can be recaptured as useful energy [5]. Recovering and re-using rejected heat is known as waste heat recovery [6].

The Siemens Switzerland Limited, Building Technologies Group [7] suggested that the utilization of waste heat is profitable wherever heating and refrigeration are required at the same time, or where waste heat can be stored in industrial processes for drying processes. It suggested the division of the heat from the hot refrigerant gas in the condenser into three stages:

1. The superheat region where heat is extracted from the hot compressed gas coming from the compressor.
2. The condensation region where the temperature of the recoverable heat corresponds to the condensation temperature.
3. The sub-cooled region where the already condensed refrigerant is cooled down to the heat sink temperature. Due to the low temperature and energy content of this region, it is hardly relevant for heat recovery. This implies that the useful and easily recoverable portion of the waste heat from the condensing refrigerant in the condenser are the superheat and latent heat of condensation.

The reversed heat engine (refrigerator/ heat pump) systems are mainly made up of five components - compressor, condenser, expansion device, evaporator and drying chamber. Their common operational characteristics include:

1. Only cooling or heating is relevant (useful) at a time.
2. Either of the energy in the condenser or evaporator is wastefully dissipated directly to the external environment.
3. It is more expensive to get both cooling and heating effects from the two systems independently (i.e. heat pump and refrigerator) since one must buy the two (with each having individual compressor) at the same time in order to enjoy the two effects.
4. In each case the expansion valve was used as the expansion device of the system. This component is expensive both in terms of initial and maintenance costs.

However, Wang [8] in a handbook of Air Conditioning and Refrigeration distinguishes heat pump and heat recovery systems in two ways. In a heat pump system, there is only one useful effect at a time, such as the cooling effect in summer or the heating effect during winter, while in a heat recovery system; both its cooling and heating effects may be used simultaneously. Also, there is a marked difference in the COP estimation as shown below:

The COP of the useful heating effect in a heat pump is:

$$\mathrm{COPhp} = \text{heat rejected in the condenser/work input} \quad (1)$$

Whereas for a heat recovery system without extractor fan,

$$\mathrm{COPhr} = (\text{heat rejected in the condenser} + \text{heat absorbed in the evaporator})/\text{work input} \quad (2)$$

Many industrial, commercial and institutional uses of energy result in excessive release of waste heat to the environment. Up to 20% of the input energy is lost in the flue gas [9]. The industrial recession in western countries in the mid-1970s created an active interest in the study of energy consumption and conservation. During this period, Japan imported 90% of its energy and its industry implemented conservation techniques more rigorously than the West. Waste-heat recovery systems, among others, contributed to making the energy costs of Japanese products 20% less than those of many of their competitors [10]. There are, therefore, many advantages and usefulness of waste heat recovery technology. Hence, the objective of this review is to examine the various heat engines utilized for waste heat recovery, identify their component parts and analyze their operational mechanisms.

2. Waste Heat Recovery Equipment

Heat pumps are typically classified by a number of parameters but the most common classifications utilise the heat source and heating distribution [11]. The four basic types of heat pumps available are air-to-air heat pumps – most common form of heat pump that utilises air as the heat source and air is utilised to distribute heating to the space/process, water-to-air heat pumps – water is utilised as the heat source and air is utilised to distribute heating to the space/process, water-to-water heat pumps – water is utilised as the heat source and water is utilised to distribute heating to the space/ process and ground source heat pumps – ground is utilised as the heat source (i.e. refrigerant circuit is reticulated in the ground). This type is different from a Ground Coupled heat pump that utilises a water loop to reject/absorb heat to/from the ground connected to a water-to-air heat pump. Mozzo [6] classified waste heat recovery equipment into heat recovery steam generator, recuperators, shell and tube heat exchanger, fin tube heat exchanger, heat pipes and run-around-coils. They are examined as below.

A. Heat Recovery Steam Generator.

Ahmed and Ahmed [12] studied thermal-hydraulic modeling of the steady-state operating conditions of a fire-tube boiler. This is a typical waste heat recovery system also known as a heat recovery steam generator (HRSG). Figure 2 shows a cross-section of the fire-tube boiler arrangement. It contains several horizontal fire-tubes mounted in a pressure shell that is partially filled with water covering the tubes.

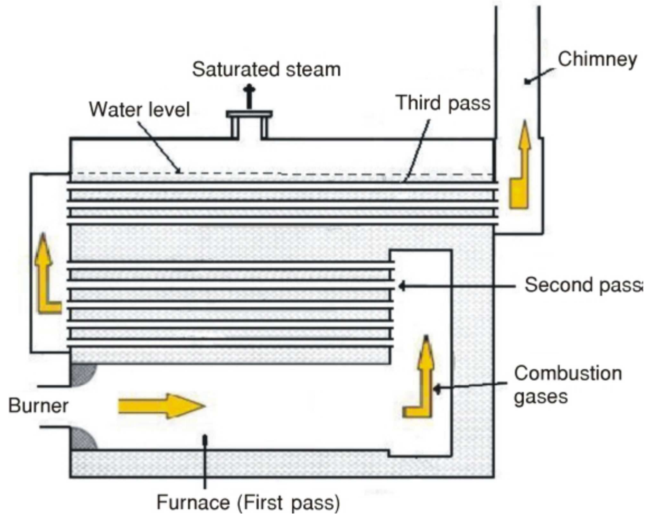

Figure 2. *Schematic representation of a typical 3-passfire-tube boiler.*

HRSG has the following features:

i. The steam boiler thermal efficiency decreases with the fuel mass flow rate increases. This decrease is mainly due to the heat rate dissipated by the exhaust gases to the atmosphere, knowing that higher exhaust gas temperatures lead to low operating efficiency.
ii. The boiler efficiency varies slightly and inversely with excess air variation.
iii. The ambient temperature influence on the gas temperature at the steam boiler outlet is negligible. The increase in ambient temperature enhances slightly the boiler thermal efficiency.
iv. The gas outlet temperature varies proportionally with the system pressure. For example, an increase of 0.5 bar leads to an elevation of 3 °C in the gas temperature. Regarding the boiler efficiency the variation of the operating pressure does not have a considerable effect on the steam boiler thermal efficiency.

B. Recuperator.

Recuperators are compact tubular air-to-air heat exchangers designed to recover the waste heat in industrial exhaust gases. The recovered heat is used to preheat the combustion air for the system's burners, thereby increasing the thermal efficiency. To ensure that all the wasted heat is drawn across the recuperator tubes, the recuperator is typically mated with an eclipse eductor. Figure 3 is a typical recuperator.

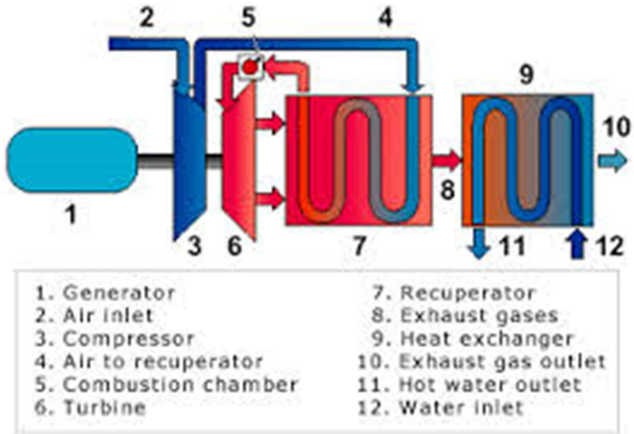

Figure 3. *Typical recuperator.*

C. Shell And Tube Heat Exchanger.

This equipment consists of a bundle of tubes within a steel shell. It is usually used for water-to-water heat recovery. One of its uses may be to recover heat from a boiler condensate blow down on the shell side to heat up boiler feed water on the tube side as shown in Figure 4.

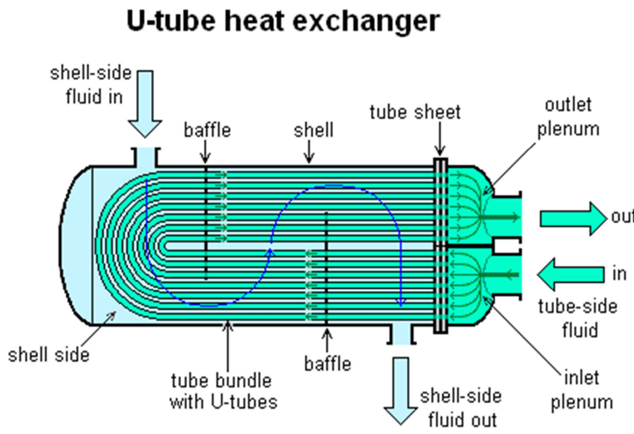

Figure 4. *Shell and Tube Heat Exchanger.*

D. Fin-Tube Heat Exchanger.

This type uses air (usually the waste heat stream) blowing across finned coils that contain water. A typical application for this type of heat exchanger is using boiler product of combustion gases to pre-heat boiler feed water. Typical fin-tube heat exchangers are seen in auto cooling system (radiators) and air-conditioners.

E. Heat Pipes.

A heat pipe is theoretically divided into three parts, the evaporator, the adiabatic section, and the condenser [13]. This equipment consists of a pipe heat exchanger with the interior containing a coolant. The coolant is alternately vaporizing and condensing between an exhaust and outside air, exchanging cooling and heating between the two extremes [8]. Figure 5 is a typical heat pipe.

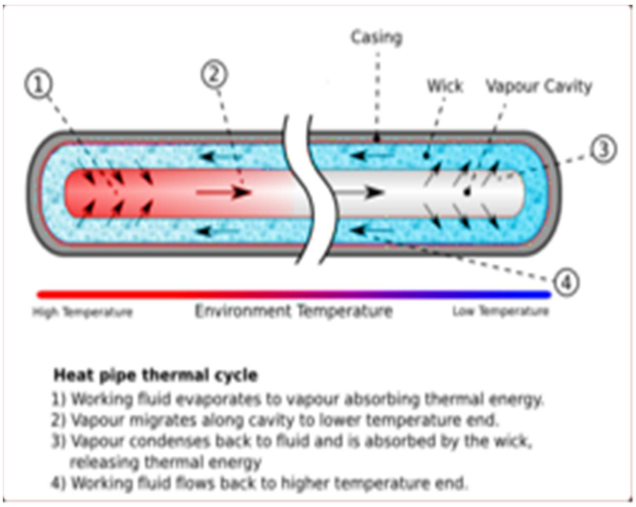

Figure 5. *A Typical Heat Pipe.*

F. Run-Around-Coils.

A run-around coil heat recovery system consists of at least two coiled heat exchangers. The coils are connected via pipes to a loop in which a fluid flows. The fluid is usually a mix of water and an anti-freeze fluid. Heat is "moved" from the hot side (extraction/exhaust air) to the cold side (supply air) via the brine fluid. Run-around-coils are similar to heat pipes in operation. They cool or heat exhaust air and outside air streams. Their typical construction is a finned water coil with air blown across the coil. The advantage of the run-around-coil is that the exhaust air and outside air ducts can be physically separated. The disadvantage is that a pump with pumping power is required. Figure 6 shows a typical run-around-coil.

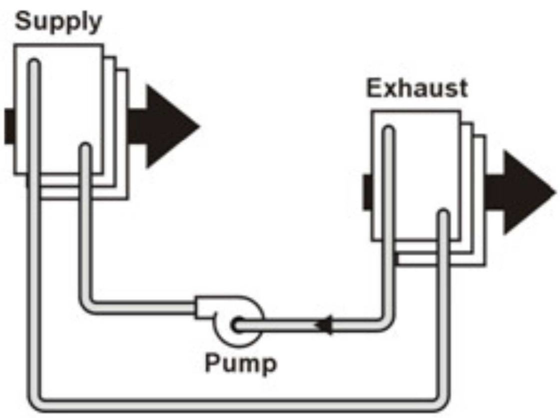

Figure 6. *Run-Around-Coil.*

3. Benefits of Waste Heat Recovery

An effective and efficient heat recovery system must present potential gains and profitability to the investor. There are various ways to profit from waste heat and they include saving fuel, generating electricity and mechanical work, selling heat and electricity, reducing cooling needs, reducing capital investment costs, increasing production, reducing greenhouse gas emissions, and transforming the heat to useful forms of energy. Most plants have the opportunity to make use of recovered energy in several ways. The optimum mix depends on the specific characteristics of the plant, its location, and energy price

These benefits can be broadly classified in two categories [14]:

1. Direct Benefits: Recovery of waste heat has a direct effect on the efficiency of the process. This is reflected by reduction in the utility consumption & costs, and process cost.
2. Indirect Benefits: a) Reduction in pollution: A number of toxic combustible wastes such as carbon monoxide gas, sour gas, carbon black off gases, oil sludge, Acrylonitrile and other plastic chemicals etc, releasing to atmosphere if/when burnt in the incinerators serves dual purpose i.e. recovers heat and reduces the environmental pollution levels. b) Reduction in equipment sizes: Waste heat recovery reduces the fuel consumption, which leads to reduction in the flue gas produced. This results in reduction in equipment sizes of all flue gas handling equipments such as fans, stacks, ducts, burners, etc. c) Reduction in auxiliary energy consumption: Reduction in equipment sizes gives additional benefits in the form of reduction in auxiliary energy consumption like electricity for fans, pumps etc.

4. Conclusion

The reversed heat engine (refrigerator/heat pump) systems reviewed are mainly made up of five components – compressor, condenser, expansion device, evaporator, and drying chamber. There are four basic types of heat pumps and they include air-to-air heat pumps, water-to-air heat pumps, water-to-water heat pumps and ground source heat pumps. Similarly, waste heat recovery equipment are classified into six broad areas of steam generators, recuperators, shell and tube heat exchangers, fin tube heat exchangers, heat pipes and run-around-coils. The benefits of waste heat recovery systems was highlighted to include both direct and indirect benefits. Direct benefits include improved efficiency of a system while indirect benefits include reduction in pollution, reduction in equipment sizes, and reduction in auxiliary energy consumption.

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