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Review Article

Advances on Process Heat Utilization: Systemic Review

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Abstract - *Waste heat has been described as the energy disposed of or given off to the environment. This waste energy, in many cases, arises from process operations in the industry. Heat utilisation has been shown to be of great effect when considering process requirements, costs, and unit-specific operation in terms of operating parameters. For this reason, the need to understand and utilize the waste heat becomes imminent. This report discusses the various scientific reviews on heat recovery and utilization applicable to process industries. This study is limited to heat utilization review and its impact on process industries. It will help industries position strategies and build top-notch technologies that will help improve existing process systems.*

Keywords - *Waste heat, Process utilization, Pinch technology*.

1. Introduction

Waste heat has been described as the energy disposed of or given off to the environment [1]. In many cases, this waste energy arises from process operations in the industry. About 20 – 35% of the heat used in refineries is mostly wasted [1]. The waste heat recovery (WHR) process can be described by the systematic approach to recovery and subsequent utilization of heat [2]. Recovered energy has been allocated for about 22% of energy consumption in some countries like the United States of America, which measures its energy usage as a function of the amount of recovered waste [3].

In most cases, about 52% of the total global energy consumed is discharged as waste heat in the exhaust gas and effluent systems [4]. It gave rise to the implementation of waste heat technology such as heat pumps, boilers, heat exchangers, and heating cycles in the energy utilization of heat. However, scientific innovations have made such implementations more efficient and accurate[5].

In oil refineries, a lot of energy demand has been recovered through oil recovery processes[6], and waste heat emission, such as CO_2 emission, has amounted to about 90% of total industrial emissions, where 65% comes from industrial furnaces and boilers [7]. To explain the strategies involved in the Optimization of energy usage in oil refineries, one such scheme would be the implementation of Pinch technology [8]. The key aspect of pinch technology used in refineries is energy target specifications. These specifications are described based on the prevailing thermodynamic conditions of the units involved.

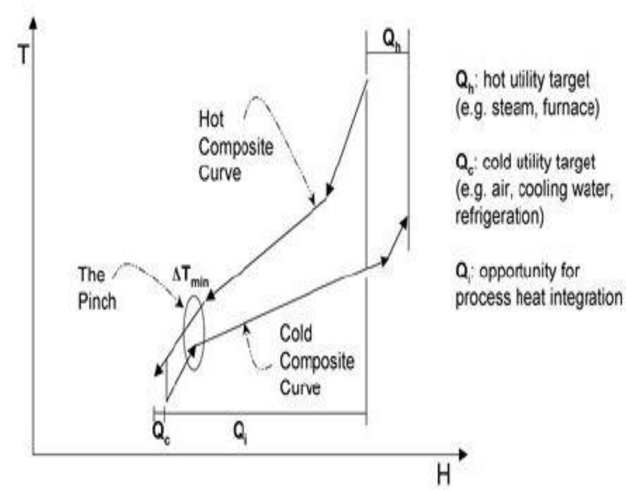

Fig. 1 Strategy used in applying Pinch Technology [8]

2. Discussion of Review

[9] describes the use of Organic Rankine cycle (ORC) engines and mechanical vapour compression (MVC) heat pumps to investigate the economic feasibility of on-site electricity and steam generation from recovered low-grade thermal energy in oil refineries. The assessment used Low-Grade heat as a benchmark for describing the temperature operations that best explain heat recovery's commercial viability in oil refineries. The low-grade heat was described by [10] as the heat source available at a temperature T_h that is lower than the minimum temperature $T_{h,min}$.

$$T_h < T_{h,min} \ and \ T_h > T_c + \Delta T_{min} \tag{1}$$

Where T_c is the lowest sink temperature available on-site. ΔT_{min} is the minimum temperature that is allowed for the given heat recovery process. Studies have shown that the estimation of waste heat recovery varies for different refineries.

Table 1. Low-grade heat stream characterization in oil refineries [9]

Stream type	Phase	Waste Energy Source	Temperature (℃)
Process	Liquid	Distillation cuts to be cooled	82 – 104
Process	Gas	Overhead condensers	65 – 148
Process	Liquid	Run-down and products streams	176 – 232
Process	Gas and Liquid	Products/gas to air coolers	112

The study also gave an empirical relation that fits the electricity or steam performance of the Organic Rankine Cycle (ORC) and MVC heat pumps. Using ORCs, electricity can be generated for a higher temperature/pressure steam. For the MVC system, the working fluid absorbs low-grade heat in an evaporator to evaporate. The fluid is compressed, which in turn, increases the saturation temperature and pressure.

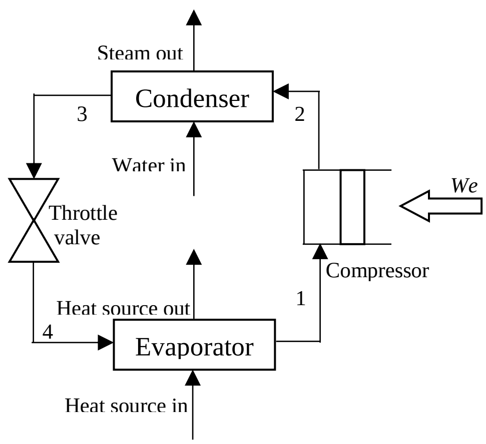

Fig. 2 MVC heat pump system [9]

It is then sent to a condenser, which releases heat to a higher-temperature heat sink. The low-grade waste heat recovery depends not only on the heat source temperatures but also on the heat sink temperatures.

It is important to extrapolate different methodologies that best explain the technology suitable for utilizing excess heat to capture energy. It will best illustrate how energy and climate targets are met. [11] describes a systematic approach involving implementing a new tool that illustrates the potential heat availability and mechanisms for heat utilization by considering different temperature scales and ranges. The author describes a pinch-based method for harnessing excess industrial heat. It also visualised excess heat considering the integration between process and utility systems. Excess heat is achieved mostly by raising the temperature of steam. An excess heat temperature (XHT) signature is constructed in these temperature intervals by approximating the available excess heat at different temperature levels.

[12] described integrating a trigeneration scheme in a natural gas process plant that utilizes waste heat from the gas turbine exhaust gas to generate steam in a waste heat recovery steam generator. Some certain part of the generated steam is used to generate power for a multiple-effect water-lithium bromide $(H_2O - LiBr)$ absorption chillers. This chiller provides a gas turbine compressor with inlet air cooling. At the same time, the remaining part of the steam is used in the furnace heating load and powers a regenerative Rankine cycle in an electrical-based plant. Waste heat from natural gas is produced using gas turbine systems. However, in a waste heat recovery system, high-pressured steam is generated to provide additional power for a Combined Heat and Power (CHP) plant. The thermodynamic cycle described by [12] shows that the power output increases by adding the Rankine bottoming cycle to the gas cycle. It can obtain the net heat transfer rate and network done of the Rankine cycle.

2.1. Heating Requirements for Reactors

As reported by [13], heat utilisation in reactors (i.e. biogas reactors) depends on a certain heating requirement. The heating reactors are, in some cases, comprised of two distinct parts [14]: the heat used to raise the temperature of the raw feed and the heat used to compensate for heat loss in the reactor. The heat is recovered either from the recovered energy or the product. According to [15], two types of heating schemes are used to generate heat in biogas systems; an external heating scheme, which uses out-tank incorporated heat exchangers and an internal heating scheme which uses an in-tank with a coiler.

Heat utilisation in distillation columns is imperative due to higher energy efficiency demands. [16] reviewed the energy-efficient designs of distillation columns by considering their designs and control. In the description, a divided wall column was considered the most used technique in designing an energy-efficient distillation column.

2.2. Diabatic Distillation Units

A diabatic column is a kind of column that has small heat exchangers inside the trays. The tray arrangements are such that a lower temperature difference is accounted for heat transfer between them. The diabatic distillation column has a higher thermodynamic efficiency than the adiabatic distillation column. It is because the energy loss in the adiabatic distillation unit is high. In a distillation column, the heat loss solely depends on two factors [16], [17]; the vapour temperature drops between the top and bottom of the column and a large amount of vapour and its corresponding condensation. When a diabatic distillation column is used, excessive vaporization is unnecessary, allowing the amount of vapour to leave the column [17], [18].

Waste heat utilization has helped eliminate power shortages [19]. It has also helped reduce energy production costs, thereby considering the environment. [19] integrated a CO_2 capture with a waste heat utilization process to utilize the energy of the coupled system by using advanced exergy and exergy economic analysis. Furthermore, an optimization scheme was used to reduce energy consumption.
Exergy analysis is a systematic tool used to determine inefficient and non-recirculation modules in an energy consumption process [20]. It helps to understand diverse scenarios that combine CO_2 capture and waste heat utilization. (fig. 7) gives a detailed flowsheet showing the integration of waste heat utilization in the process.

[21] conducted a waste heat recovery of a heat pump-reactive dividing wall column (HP-RDWC) by employing the Organic Rankine system (ORC). The ORC was used to recover the waste heat by considering five alternative working fluids. The ORC was further optimized by considering the net revenue and Rankine efficiency. [22] investigated the heat source generated from an oil refinery and how it can adversely affect the environment regarding its techno-economic feasibility. It further concluded that the fuel consumption by industries optimal studies depending on the number of objective functions. It also showed the economic benefits of operating such industries without affecting the environment.

[23] carried out a comprehensive study on integral heat generation from a high-temperature reactor (HTR) in an oil refinery. It showed how integrating heat exchangers could effectively account for the amount of heat generated. Since generating heat at different energy levels is easy, [23] showed that about 70% of the total heat generated is used for separation processes such as distillation.

2.3. Heat Utilization in Membrane Distillation

Membrane distillation is a thermal separation process using a porous interfacial surface to separate two solutions based on phase change. Its ability to address low-grade waste heat makes it suitable for thermal processes. In membrane distillation, heat is transferred through convection. As reported by [24], energy utilization in membrane distillation was evaluated by integrating a heat exchanger system to recover latent heat from condensation in the distillate stream. A waste heat energy utilization was also observed when operating a membrane distillation without an integral heat exchanger system. The waste heat stream was used as the heat source. [25] evaluated the heat transfer occurring in a direct contact membrane distillation column used in a desalination process. It was further explained that heat is gained by the permeate stream, which is then utilized by recovery heat exchanger units.

(DCMD) the process with an integral heat recovery unit [25]. Thermal Optimization is considered a part of heat utilization which involves the selective recovery and usage of heat from a given process. Industrial plants are inherent in heat waste. It substantially affects the environment if optimal recovery does not take effect. [26] implemented a multi-objective optimization on an organic Rankine cycle (ORC) integrated unit in waste to energy (WtE) plant at Tehran, considering thermodynamic principles to achieve utilization objectives while economic standards are effective. The performance of the ORC was compared for different working fluids. The released flue gas by the ORC was used to determine the total efficiency and net output power of the WTE plant.

An exergoeconomic analysis was carried out to identify each unit component's relative cost and design a cost-effective system. Other applications of the exergoeconomic analysis on waste heat plants are reported by [27], [28] and [29].

2.4. Flare gas utilization

Flare gas recovery systems are used to recover flammable gas for reuse as intermittent fuels for heaters in the process industries [65]. It substantially improves the energy efficiency of oil refineries by mitigating the rate of greenhouse emissions [31]. [32] reported research on Egypt's first oil refinery for its flare gas recovery. The sustainability of the oil and gas industries was improved hypothetically by measuring its flare gas recovery and utilization. It was analyzed from a triple-bottom-line perspective. The baseline emission of the flare gas recovery system was calculated as the sum of emissions from burning the waste gas. [33] investigated the potential of flare gas recovery in Iran. It was observed from the review that the major challenges in the applications of flare gas recovery systems in Iran might be the limitation of economic feasibility and structural and institutional challenges. These challenges are best addressed by capturing the proper gas-flaring technology that reduces greenhouse emissions. [34] reported three main schemes used to reduce energy consumption in a flare gas recovery system. The first scheme is done by pressurizing and injecting flare gas into oil wells, the second includes the generation of electricity by the injection of a large amount of flare gas into the oil wells, and the third scheme includes generating power through the use of a combined heat and power (CHP) plant and an integrated internal combustion engine (ICE). A marking point for the assessment is carried out using the HYSYS software to generate the flare gas used in power generation.

A comparative analysis was done by [35] to investigate the various methods used to recover flare gas. The author considered using Gas-to-liquid production, generating electricity with a gas turbine, and compressing and injection into the refinery pipelines. [66] also investigated the design and simulation of flare gas recovery using the ring compressor system.

2.5. Heat Exchanger (HX) heat utilization

Waste heat recovery from heat exchanger systems has predominantly been adapted for systems of thermodynamic operability. One of the instances was reported by [37], where a heat exchanger was designed to recover waste heat from the diesel engine gas. The waste heat recovery was represented by the amount of waste heat given off by the exhaust gas absorbed by the inlet air in the heat exchanger.
From the heat balance equation:

Heat absorbed by air = Heat carried by Exhaust gas

$$M_a C_{pa} \nabla_{ta} = m_e C_{pe} \nabla_{te} \quad (2)$$

The percentage of heat recovered can be calculated as [37]:

$$\%Q_{rec} = \frac{Q_a}{Q_e} * 100 \quad (3)$$

The effectiveness of the heat exchanger in transferring hot fluid to cold fluid is given by:

$$effectivenss = \left[\frac{Th_i - Th_0}{Th_i - Tc_i}\right] \quad (4)$$

It was found that the inlet air improves the performance of the stationary diesel engine and lowers the emission levels. The heat recovery was found to be satisfactory.

Flue gases are often given off as low-grade waste heat, and this flue gas is mostly made of different compositions. However, these flue gases have recorded the potential to provide heat utility for component condensation [38]. It will necessitate saving energy by reducing the number of fuels used. It will potentially reduce CO_2 emissions by 44% by 2035 [39] because of the primal usage of waste heat utilization.

[40] developed a systematic criterion for selecting waste heat utilization from recovered waste heat generated in oil and gas processing sites. One of which the author considered the thermodynamic techniques involved by studying waste heat recovery systems like the organic Rankine cycle (ORC) and the heat exchanger system (HX). A hierarchical procedure was used where the utilization scenarios for on-site and offsite were conducted. Figure 14, adapted from [40], shows how the heat source temperature affects the ranking criteria for CO2 emission.

[41] Screening criteria and a framework for comparing waste heat utilization technologies by considering different temperature sources. Based on [42], a natural gas liquefaction system integrated with a waste heat utilization system was investigated. The waste heat was generated by a turbine exhaust, while the utilization system employed was the organic Rankine cycle and absorption refrigeration. It was used to minimize the energy consumption of the liquefaction plant. The waste heat utilization efficiency was observed to be about 56.96% for the absorption refrigeration while 43.73% for the organic Rankine cycle.

[43] reported a case of recovering low-grade waste and utilising district heating. This paradigm was studied in northern China, where the energy efficiency of the utilization scheme was investigated. Waste heat recovery generally involves capturing and transferring waste heat from one process to another using a gas or liquid [44]. Once this is done, the captured great can be used to generate additional power. [45] surveyed the different techniques involved in heat recovery in the oil industry. Techniques include direct and indirect contact condensation recovery, transport membrane condensation, heat recovery steam generators (HRSGs), heat pipe systems, organic Rankine cycles etc.

Exergoeconomic assessment of the kalina cycle was investigated by [46]. The performance of a gas turbine modular helium reactor (GT-MHR) integrated with a waste heat kalina cycle was observed in the study. The waste heat was recovered for power generation. A sensitivity analysis was carried out to optimize the performance of the cycle. The optimal efficiency of the cycle was recorded to be 8.2% higher than the original value of the modular reactor.

[47] compared two alternative technologies for generating process heat. One is by heat pumps, while the other uses low-temperature heat engines (ORC, KC, trilateral cycle). The organic Rankine cycle (ORC), as illustrated previously, is a system that uses fluid with a liquid vapour phase that allows the rankine cycle to convert most of the heat to useful work. The kalina cycle is a process used in converting thermal energy into power. It uses a mixture of two fluids with different boiling points as working fluids. Low-grade waste has shown to be readily rejected by the oil industry in countries like the United Kingdom.

Integrating industrial heat exchanger systems can reduce heat consumption in oil refineries. [48] reported the efficacy of incorporating heat pumps in distillation. These heat pumps help upgrade heat from a lower temperature source to a higher source. Heat pumps are considered effective for a certain number of issues, such as [48]:

- Pinch temperature and the flexibility of the plant
- Thermodynamic cycle and heat pump efficiency
- Temperature lift required
- Enthalpy balance
- Selection and constraints of heat pump equipment

- Configuration of the system
- Available Utilities
- Capital and utility cost

The basic essence of the heat pump is to use the heat of condensation released from the condenser to heat the reboiler. As shown in Figure 18, the conventional column (CC) functions in an adiabatic state while heat is added to the reboiler and extracted in the condenser. The vapour compression (VC) column is operated via a working fluid evaporated at the condenser, which is then compressed to a higher temperature. In the vapour recompression column (VRC), the working fluid is the vapour left at the top of the column, which is compressed and condensed in a reboiler and partially refluxed to the top of the column after the pressure in the valve is reduced. An alternative for the vapour recompression column (VRC) is the bottom flash column (BFC). Waste heat recovery would create an environmentally friendly ecosystem such that its effect will reduce global warming conditions [49]. [50] The thermodynamic implications for using an ejector and organic Rankine cycle to utilize the waste heat generated from a gas turbine-modular helium reactor (GT-MHR). The effects of certain parameters include the compressor pressure ratio, reactor exit temperature, pinch point temperature difference etc.

2.6. Heat utilization from the Reforming process

Reforming processes plays a vital role in energy consumption situations. Reformers commonly combined with waste heat have improved reforming processes' efficiency [51]. Methanol steam reforming has been shown to be advantageous due to its low reaction temperature [52].
In the model described by [51], an improved small-scale plate reactor with new types of fins coupled with waste heat recovery was shown. The following assumptions were recorded [51]:

- Methanol and water are both in the gas phase, and the flow is incompressible, stable and laminar.
- Effects of gravity are negligible
- The outer wall of the reactor is considered to be adiabatic
- Ignoring the difference in temperature and concentration between the catalyst and the fluid
- The catalyst region is an isotropic porous medium, and the catalytic reaction only occurs in the catalyst region.

There are challenges limiting waste heat utilization, especially considering economic costs and low heat quality [53]. However, this limitation can be mitigated by the co-integration of alternative systems, especially systems of high utilization efficiency [54]. [55] investigated the effective utilization of heat generated from a Gas turbine Modular Helium Reactor (GTMHR) integrated with an organic Rankine cycle. The study also explained how parametric variables are used to determine the exergy efficiency of the system. [56] implemented an optimization strategy for the heat utilization of complex refinery processes. A real industrial operation was cited such that the total site energy optimization was used to demonstrate the refinery performance. A study on the capital and operational expenditures for the recovery of energy was evaluated by [57]. Here, the author applied a cost estimation of heat recovery to use excess heat for CO_2 absorption. [58] investigated the recoverability of exhaust gases in the internal combustion engine. For this study, a protracted counterflow heat exchanger system was designed and analyzed with a water-ethanol mixture. This mixture was used as the working fluid. The investigation asserted the efficacy of the heat exchanger in increasing the working fluid's outlet temperature. [67] elucidated the implications of integrating the first and second laws of thermodynamics into a water-water heat pipe exchanger for a cooling process in the steel industry.

With oil and gas being an energy subjective industry, it is important to reduce utility costs by implementing low-temperature heat. One of the possible ways is to use a heat exchanger which operates on a low-temperature basis. A study has shown that using a low-temperature heat exchanger reduces energy costs by about 15% [60]. [61] The influence of using an organic Rankine cycle (ORC) parameter in designing a heat exchanger system was analysed. The heat exchanger design is based on the supercritical parameters of the working fluid [62] and the convective coefficients of the heat transfer surface. [63] also reviewed the current approaches used in the earth-air exchanger systems for effective heat recovery.

3. Conclusion

Heat utilisation has shown great effect when considering process requirements, costs, and unit-specific operation parameters. For this reason, the need to understand and utilize the waste heat arises [64] is imminent. The various techniques used in the utilization of heat have been reviewed. The working principle, advantages and disadvantages of these technologies were also reviewed. Likewise, the recent state-of-the-art implementation of this technology in the oil refinery was also reviewed by considering the processing unit that exhibits the tendency to generate waste and the integration of waste heat recovery and utilization technologies such as the organic Rankine cycle, Heat exchangers, turbines etc.

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