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Waste Heat Recovery: An Energy-Efficient and Sustainability Approach in Industry

Amr Abbass*

University of Idaho, Moscow, United States

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* Corresponding author:

Amr Abbass
E-mail: Calgary732@hotmail.com

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ABSTRACT

Waste heat recovery (WHR) is a method that improves energy efficiency and sustainability in industries like distillation, gas systems, and power generation. It captures and reuses waste heat from condensers and reboilers, reducing the need for external heating or cooling. Flue gas waste heat recovery (FGWHR) also holds potential for energy conservation. Technologies like Organic Rankine Cycle (ORC) and Kalina Cycle (KC) convert low-grade waste into electricity, enhancing overall efficiency. Combined Heat & Power Systems (CHP) achieve efficiency above 80%. However, feasibility studies are crucial before applying WHR technologies in practical applications.

1. REVIEW OF THE LITERATURE

A valuable resource for comprehending and executing Waste Heat Recovery (WHR) systems in various environments is the book titled "Waste Heat Recovery: Principles and Industrial Applications." Authored by Chirla Chandra Sekhara Reddy and Gade Pandu Rangaiah in the year 2023. This site is highly significant as it encompasses a comprehensive array of information regarding the principles, technologies, and practical applications of WHR. Moreover, it elucidates that waste heat recovery is crucial for process businesses in terms of enhancing energy efficiency and diminishing operational costs along with environmental consequences.

In addition, the authors have provided detailed explanations of several types of equipment, including heat exchangers, economizers, absorption heat pumps, and others, that are necessary for waste heat recovery. They have also included thorough guidelines for selecting suitable WHR systems based on the individual requirements of different industries. The primary focus of this discussion is the utilization of Waste Heat Recovery (WHR) to enhance the sustainability of industrial operations. This involves the conversion of waste heat into valuable forms of energy, resulting in a reduction of carbon footprints.

The study conducted by Reddy and Rangaiah is characterized by its strong emphasis on practicality, as evidenced by the inclusion of case studies showcasing the effective application of waste heat recovery (WHR) in various industries such as petrochemicals, electricity generation, and chemical processing. These writers also examined economic factors, such as cost-benefit analysis and payback periods, which pertain to the long-term financial benefits that can be gained by implementing the ideas they detailed.

Recognition

The extensive research findings presented in this literature review are derived from the insightful arguments and carefully worked out materials published by Reddy & Rangaiah in their book "Waste Heat Recovery: Principles and Industrial Applications" (2023). The book provides an extended discussion from various perspectives, highlighting the considerable variations that can exist within these matters.

2. METHOD STATEMENT AND DISCUSSION

Distillation is known for its low energy conversions, with around 40% of the total energy used in process industries being consumed by this commonly utilized process. Additionally, there is a significant amount of heat required for the process of vaporization. This means that the combination must be heated until it reaches the temperature at which it changes from a liquid to a gas. Hence, the overhead condenser necessitates substantial cooling in order to facilitate the condensation of the vapor back into a liquid state. Consequently, there are elevated energy consumption expenses resulting in augmented operational costs and amplified carbon emissions. Minimizing energy consumption during distillation is crucial for optimizing overall process efficiency and promoting sustainability and economic feasibility. This can be achieved by minimizing costs and emissions associated with the recovery of waste heat from distillation. However, when there is a higher rate of usage, there is a significant emission of greenhouse gases. Therefore, enhancing the efficiency of distillation is important in order to comply with environmental rules and achieve sustainability goals.

There exist multiple approaches to enhance energy efficiency in distillation operations. Adjusting pressure can decrease energy consumption by making operational changes. Operating at the lowest possible pressure reduces the boiling point of the liquid mixture. Preheating the feed brings it closer to its boiling point, reducing the amount of heating required for evaporation. Similarly, optimizing the internal design to minimize low-pressure drops reduces resistance to vapor flow, resulting in lower overall power consumption by reducing the rate of heat entering the column from the reboiler/condenser interface. Additionally, utilizing absorption heat pumps (AHPs) can lead to significant energy savings by utilizing waste heat generated during the distillation process. This is achieved by transferring thermal energy from the condenser to the reboiler, hence decreasing the reliance on external heat sources.

Mechanical Vapour Recompression (MVR) is a technique that harnesses the energy from the above vapor to generate power. Enhance energy efficiency in the context of meeting the need for evaporation using renewable energy sources. Heat integration is a method used to maximize energy efficiency by transferring heat between different process streams within a system. By employing heat exchangers, it alters processes to enhance the efficiency of heat transfer. One method that can be used to improve separation efficiency and decrease energy usage is the implementation of Dividing Wall Columns (DWC). DWCs combine multiple distillation columns into a single unit, resulting in a reduction in the number of reboilers and condensers needed. This, in turn, lowers both capital and operating expenses. In addition, overall energy efficiency can be enhanced by employing organic Rankine cycle (ORC) and Kalina cycle (KC) techniques to generate electricity from waste heat.

To enhance distillation efficiency, the initial action is operational optimization. This process entails making adjustments to existing operational parameters, such as pressures, temperatures, and flow rates, without the need for any equipment modifications. This method provides a simple and efficient approach to enhance energy efficiency. Furthermore, it is crucial to perform an extensive feasibility analysis on various waste heat recovery (WHR) methods. This analysis should encompass both technical and economic considerations in order to determine the most suitable solutions that can be implemented in different distillation systems.

In order to demonstrate the technological effectiveness of waste heat recovery (WHR) methods in practical situations, a comprehensive evaluation utilizing several WHR techniques can be conducted in industrial distillation systems. Case studies will be utilized to illustrate the successful implementation of waste heat recovery (WHR) applications, including the procedures, settings, and energy saved. One method to decrease the energy usage of the reboiler and condenser and enhance efficient vapor-liquid interaction is by optimizing the placement of the feed. Utilizing process simulation software such as Aspen Hysys and Pro/II can aid in achieving proper design by accurately determining the optimal feed placement. If overpurification occurs, it indicates a significant and unnecessary surge in power use. For example, implementing advanced control schemes can assist in operating more closely to the desired product specifications. This entails teaching operators about the usage of advanced controls, as opposed to relying on conservative operational approaches that result in excessive purification. Thus, by regulating the reflux rate according to the feed flow rate (FR), automated control systems may optimize the reflux rate to maximize efficiency, allowing the distillation column to operate efficiently under different feed conditions and conserve electricity.

Low-Cost/Complexity Modifications

Others include; exchanging trays with packings or designing low-fouling internals among others that have significant energy savings potentials with quick payback periods such as retrofitting existing columns with more efficient internals and heat exchangers. A typical example involves preheating the feed through bottom stream preflash drums before entering into the main fractionation column; this reduces load on main distillation system and lowers reboiler duty during feed-bottom stream heat exchange

Medium-Cost/Complexity Solutions

Also available are average-cost solutions such as heat pumps (HPs) MVR utilises overhead stream flow rates that are high enough while having a low-temperature lift, hence being appropriate for energy recovery via compression of overhead vapour and reuse as a heat source thereby reducing external heating requirements. Meanwhile, AHP works at medium or high pressure steam to boost waste heat without cooling utilities. These applications require careful evaluation of process conditions and compatibility with existing systems, moderate capital investment and potential process modifications.

Advanced WHR configurations such as Mechanical Vapour Recompression (MVR), Bottom Flash (BF), Closed Cycle Compression (CCC), Absorption Heat Pumps (AHP) and Absorption Heat Transformers (AHT)

MVR applies this technology for large overhead stream flow rates with low temperature rise by compressing the vapour over the head, reusing it as a heating source thereby reducing need for external heating In BF, pressure on high-temperature bottom streams is reduced through their flashing to provide both the vapour and heat required for distillation thus enhancing energy efficiency On the other hand, CCC makes use of a working fluid that is externally circulated in order to avoid changes in pressure for process streams; this involves compressing the working fluid, transferring heat at the reboiler, and utilising latent heat for evaporation. AHP utilizes steam at medium or high pressure to enhance the waste heat, whereas AHT raises the temperature of a portion of the waste heat, allowing for greater flexibility in the recovery of heat from various sources.

Utilizing chilled water derived from waste heat recovery systems or steam condensate can effectively reduce the overhead pressure of a column, resulting in a fall in the boiling point of the overhead stream. This, in turn, reduces the energy required for re-boiling and enhances overall energy efficiency. This approach enables operational flexibility by utilizing temperature control to employ fluids with lower boiling points.

Various methods exist for generating electricity from waste heat, including the organic Rankine Cycle (ORC) and the Kalina Cycle (KC), both of which enhance total energy efficiency. The Organic Rankine Cycle (ORC) employs an organic working fluid with a low boiling point to produce electricity from waste heat. On the other hand, the Kalina Cycle (KC) utilizes an ammonia-water mixture that partially evaporates in an evaporator, generating high-pressure vapor that is then used in an expander. These approaches offer a versatile and effective way to produce energy from low-quality waste heat.

Distillation columns employ both external and internal heat integration strategies. External integration refers to the utilization of a distillation column reboiler to heat it up, while simultaneously integrating the waste heat among several columns within a single plant operation. The Heat-Integrated Distillation Column (HIDiC), Petyluk Configuration, and Dividing-Wall Column (DWC) are internal integration techniques. The HIDiC is a column that combines rectifying and stripping functions. The Petyluk Configuration splits ternary mixtures into two columns, using only one reboiler and condenser. The DWC reduces the number of columns to one unit by minimizing the duties of the reboiler and condenser. By employing these strategies, the reboiler and condenser tasks are minimized, resulting in substantial energy savings for efficient separations. This approach also requires less capital investment and lowers operational expenses.

WHR demonstrates strong performance in industrial case studies involving propylene-propane separation, bad water strippers, C4 separation, and other similar applications. These instances have shown that designs aided by MVR have led to significant decreases in costs and improved energy efficiencies. Extensive research has been conducted to assess the practicality of some WHR technologies for DWC. The findings show significant energy conservation, decreased operational expenses, and a return on investment in less than one year. Steam is generated by processing businesses using boilers, fired heaters, furnaces, or cogeneration plants for either thermal use or electricity generation, respectively. These systems produce flue gas (FG) that contains substantial quantities of waste heat (WH). Enhancing energy efficiency can be achieved by reclaiming and reutilizing waste heat, while also minimizing expenses related to operation and maintenance, hence alleviating the impact of air and water pollution. Process plants necessitate the use of Flue Gas Waste Heat Recovery (FGWHR) systems to ensure long-term viability and environmental responsibility. FGWHR Equipment Types: This classification encompasses a range of commercially accessible FGWHR equipment options. To make a suitable selection, it is important to understand the specific applications of the device, such as direct heating or indirect use through steam, hot water, or oil circuits. Additionally, factors such as ADP corrosion, cost, payback period, space, and dependability must be considered. The transfer of heat between the hot flue gas (FG) and the combustion air occurs through the utilization of air preheaters (APHs), economizers, or heat pipes. Furthermore, the recycling of waste heat by returning it to the machines that generate it leads to a reduction in fuel consumption, resulting in many advantages. Economizers and heat pipes are more space-efficient than APHs due to the condensation and evaporation of the working fluid, making them the most compact and efficient FGWHRs. Conversely, if the heat transfer coefficients are low, it would be necessary to have larger plots in order to accommodate larger air preheaters (APHs), as they tend to be the largest among all types. On the other hand, regenerative APHs take up less space compared to tubular-type recuperative ones, but they require more maintenance activities.

The indirect heat transfer method involves the exchange of heat between the hot flue gas and combustion air through an intermediary liquid stream, such as pressurized water or hot oil. This technology can also be used when there are limitations on space for installing a direct heat-exchange APH. Nevertheless, it necessitates greater initial investment in WHR heat exchangers, water circulation pumps, holding containers, and drums.

A proposal has been made to optimize the sizes of the equipment and waste heat recovery (WHR) by combining a regenerative or recuperative air preheater (APH), a condensing economizer (CE), and a heat pipe. As a result, this process leads to an increase in the quantity of FGWHR equipment needed. The steam produced by FGWHR can be utilized, similar to the steam created by incinerators, to provide heat for various applications in other process units, such as heating the combustion air in fired heaters or furnaces, and for utility purposes. Highlighting the significant financial investment required when the primary steam cylinder of the facility is located far away from the FGWHR (Flue Gas Waste Heat Recovery) equipment.

Boiler flue gas ducting uses efficiencies to reclaim waste heat from exhaust gas and/or to warm boiler feed water (BFW). Plain tube economisers are employed for fouling applications, whereas a conventional economiser consists of a finned coil constructed from either carbon steel (CS) or stainless steel (SS). In a BFW system, the temperature increase should generally be around 50-55 °C compared to the flue gas temperatures in an economizer, which will be lowered by 150-170 °C. The device is positioned within the flue gas duct, namely between the superheater and the APH, as the gas travels towards the stack. In order to avoid the formation of steam inside a boiler's steam drum, it is necessary to maintain the water outflow temperature at least 15-20 °C lower than the saturation temperature. Additionally, the outer surface temperature of the heating coil at the entrance of the boiler feed water (BFW) should not drop more than 10 °C below the approach to dew point (ADP).

Condensing economizers (CEs) extract both sensible and latent heat from the water vapor present in flue gases (FGs). Furthermore, BFW is subjected to noncontact CE heating, ensuring that it does not make direct contact with FG. Tubes can be fabricated from borosilicate glass, Teflon, or glass-coated CS in order to withstand corrosion. CE systems efficiently extract both sensible and latent heat from flue gas, making them ideal for placement downstream of non-CE systems in order to further lower the temperature of the flue gas. Nevertheless, these corrosion concerns can be particularly severe for combustion engines (CEs), particularly when the fuel used in the boiler contains a significant amount of sulfur. To address this problem, the application of anti-corrosion materials and coatings could provide relief.

Various techniques have been suggested to mitigate cold-end corrosion in economizers. An alternative method involves raising the working pressure of the deaerator to maintain the Boiler Feed Water (BFW) temperature above the Air Distribution Plate (ADP). Furthermore, a preheater for boiler feed water (BFW) that is heated by low-pressure steam (LPS) or medium-pressure steam (MPS) can be employed before to the economizer. Subsequently, the high-temperature boiler feed water (BFW) can be directed back to a BFW preheater, where it raises the temperature of the colder water that is discharged from an economizer outlet. An alternative method would consist of installing coiled heat exchangers inside drums to preheat the Boiler Feed Water (BFW) prior to its entry into an economizer. Additionally, another approach involves employing a condensing economizer (CE) to heat the boiler feed water (BFW) while directing a hot fluid over the air preheater (ADP) to avoid corrosion at the cold end. Air preheaters are equipped with internal tubes and fins that facilitate the passage of combustion air. This process raises the temperature of the air from approximately 20 °C to typically 300-350 °C. By heating the surrounding air before it enters a furnace or burner, the efficiency of the boiler is improved. The boiler's thermal efficiency rises by approximately 1% for every 20 °C increase in combustion air temperature. There are three categories of APH: the first is direct waste heat recovery (WHR) using a recuperative APH, the second is direct WHR using a regenerative type such as a heat wheel, and the third is indirect WHR through intermediary circulating fluids such as water or high-temperature oils. APHs are often installed on boilers of small and medium sizes solely for the purpose of preventing the mixing of flue gas and combustion air. These items are designed to minimize leakages while maximizing heat transfer efficiency.

Air preheaters are used to recover waste heat from flue gas in fired heaters and furnaces that are used to heat process fluids. FGWHR is essential for these specific fired heaters and furnaces due to the necessary enhancement in efficiency. Convection sections aim to maximize the recovery of flue gas heat, rendering economisers unnecessary or insignificant in their function. Currently, the most prevalent approach for flue gas waste heat recovery (FGWHR) in fired heaters is utilizing an air preheater (APH). Alternative waste heat recovery (WHR) methods, such as steam production or the utilization of water or oil systems to capture exhaust gases from the convection section, are employed in many other process equipment in different locations. This article also suggests adhering to a specific air-fuel ratio to minimize waste heat losses and prevent leaks from damaged ducting or convection side apertures.

Heat pipe exchangers are equipped with slanted or vertical tubes that contain a wick and working fluid, which are defining features of these devices. These APHs are renowned for their exceptional efficiency due to the condensation/vaporization of their working fluids, resulting in a significantly reduced size and weight compared to other APHs. In addition to this, heat pipes are also utilized in boilers, fired heaters, and furnaces. Systems with low approach temperatures prevent leakages from combustion air onto the FG side, eliminating the need for moving parts and decreasing maintenance requirements. However, they tend to be costly and have a restricted temperature range due to their choice of working fluids.

Combustion systems generate NOx, SOx, CO, CO2, particulate matter, volatile organic compounds (VOCs), and other pollutants. These emissions must be regulated in conjunction with the implementation of FGWHR measures by enterprises who are concerned about environmental impact. Synergy offers advantages such as enhanced process efficiency, resulting in reduced environmental consequences and adherence to rules.

Cogeneration systems that utilize gas turbines (GTs) in conjunction with renewable energies (REs), biomass steam turbines (BSTs), and microturbines (MTs) have the potential to achieve energy efficiencies exceeding 80%. Process heating applications can harness steam energy using a Boiler Steam Turbine (BST) system. Additionally, lithium bromide (LiBr) absorption chillers can be used as alternate options for creating chilled water (ChW) or generating electricity through organic Rankine Cycle (ORC) / Karalina Cycle (KC) by utilizing waste heat (WH) from power generation.

The boiler feed water (BFW) is subjected to high pressure in order to heat it to its boiling point within the boiler. Once heated, it is transformed into high-pressure steam (HPS), which subsequently undergoes superheating as it expands in the CST. Typically, the cooling medium is cooling water, which is used to condense steam. This process dissipates the latent heat previously contained in the extracted steam into the cooling water, resulting in inefficiency in terms of energy usage. The process of cooling water results in the dissipation of over two-thirds of the energy derived from fuel, causing the conversion efficiency of electrical energy to drop below one-third.

Similar to CST, the steam that is taken out is supplied as medium pressure steam (MPS)/low pressure steam (LPS) to the process for the purpose of heating, while its condensate goes back into the boiler's system. When comparing, it can be observed that BST (Biogas Steam Turbine) exhibits an energy efficiency over 80% while generating electricity in response to the steam demand. Therefore, it is suitable for small and intermediate-scale power generation using steam as the process heating medium.

The combustion chamber is where compressed atmospheric air and high-pressure fuel are combined, resulting in the expansion of combustion gasses through a turbine. This rotation of the turbine powers an electric generator. Stand alone gas turbines with low efficiency are common, often about 35%. Nevertheless, the overall percentage may surpass 80% if a heat recovery steam generator (HRSG) is incorporated into the system. Thus, gas turbines (GTs) are employed in situations that require substantial quantities of power and huge amounts of heat energy.

Small-scale gas turbine generators with power outputs ranging from 25 to 250 kW utilize natural gas, biogas, or hydrocarbon gases. Although waste heat recovery (WHR) systems can achieve a system efficiency of over 80%, the efficiency of electric power generation typically falls within the range of 20% to 30%. Microgrids are well-suited for small-scale power generation applications.

The reciprocating engines consist of spark-ignited engines, which operate on Otto cycles using gaseous or liquid fuels, and diesel engines, which are fueled by liquids through the heat of compression. The pistons are propelled by a combustion combination of air and fuel through a crankshaft that generates electrical power. The thermal efficiencies vary between 25% and 45%. Significant quantities of waste heat can be recovered by waste heat recovery (WHR) systems, leading to enhanced overall efficiency. Residential electric systems are designed to meet lower electricity needs while also accommodating fluctuating low power consumption or hot water requirements.

The electricity generation efficiency for ORC (Organic Rankine Cycle) and KC (Kalina Cycle) systems using waste heat (WH) at temperatures ranging from 100°C to 300°C is typically between 10% and 20%. The ORC system utilizes organic fluids, whereas the KC system utilizes a mixture of ammonia and water. Steam turbines typically have a higher price compared to these cycles, but they do not require any fuel for operation. Therefore, they are beneficial for waste heat recovery and generating more power. All of these systems have similar structures, however there are variations specifically designed for generating power by recovering waste heat.

Cogeneration is the process of generating energy and heat at the same time. Cogeneration systems, such as boiler-BST/CST, GT-HRSG, GT-HRSG-BST/CST, MT-WHR, and RE-WHR, offer several major advantages. These include high thermodynamic efficiencies ranging from 80% to 95%, low fuel costs, increased reliability for electricity and steam delivery, reduced CO2 emissions, and lower costs for emission treatment.

Trigeneration reduces operational expenses by conserving resources such as chilled water, CO2 and deionized water, steam, and hot water, while simultaneously generating electricity. Tri-generation serves several functions, such as generating chilled water with LiBr absorption chillers, extracting CO2 for use in greenhouses or the food sector, and desalinating deionized water using heat.

Quad-generation is a system that provides four different outputs: electricity, heat in the form of steam, chilled water, and carbon dioxide (CO2). If there is a high demand for recovered CO2 utilization, it is both economically and technically possible. Additional advantages include minimal or no carbon emissions, reduced operational expenses compared to individual utility purchases, and the utilization of segregated CO2 in various industrial applications.

The power production will increase when high-pressure steam is reintroduced into the gas turbine inlet. Consequently, the turbine experiences a higher mass flow, resulting in a 50% increase in power generation and a simultaneous reduction in NOx emissions. However, it is necessary to increase the amount of water delivered during the system design phase in order to accommodate the increased consumption rates needed for successful deployment.

By utilizing chilled water to cool the air intake for the GT compressor, the air density at the compressor input is heightened, hence causing a rise in the mass flow rate and subsequently resulting in an amplified power output. This approach allows for a cost-effective increase in power generation. Proper drainage is essential in retrofit projects to prevent corrosion and damage to the compressor. It is also important to guarantee the compatibility of materials used.

Utilizing an Organic Rankine Cycle (ORC) to recover low-grade waste heat from the exhaust gases at the Heat Recovery Steam Generator (HRSG) outlet can provide more electricity. The cost-effectiveness of this technology makes it highly suitable for large-scale systems with significant potential for recovery.

3. CONCLUSIONS

The discourse on power generation highlights the significance of waste heat recovery (WHR) in industrial processes, especially in distillation, which is a very energy-intensive operation. The renowned publication 'Waste Heat Recovery Principles and Industrial Applications' authored by Reddy and Rangaiah provides a comprehensive array of insights into the significance of WHR systems in augmenting efficiency, diminishing operational costs, and mitigating environmental repercussions in pursuit of sustainable development. Advanced systems such as DWC's MVR or HRSG have been utilized to achieve substantial enhancements in system efficiency. These systems employ Mechanical Vapour Recompression (MVR), which can result in the maximum possible changes. However, it is worth noting that the condensing temperature may eventually decrease below the original level when comparing different approaches. It is also worth considering that steam absorption-based refrigeration using adsorption may be superior to all other methods. Therefore, they should not alone serve the purpose of optimizations, but should also operate if feasible. This review emphasizes the importance of conducting a methodical evaluation and adoption of Waste Heat Recovery (WHR) technologies in order to achieve environmentally sustainable industrial processes that are also economically feasible.

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