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Towards Sustainable Energy Practices: Experimental Assessment of Waste Heat Recovery from Multistage Air Compressor Operations

Abstract: - Compressed air is inefficient and uses a lot of energy, yet it has many industrial uses nevertheless. The thermal energy produced by the compressor accounts for the bulk of its energy consumption. When compared to the amount of energy used by the compressor, the amount of compressed air being supplied to the compressed air network is insufficient. Whether air cooled or water cooled compressors are used, efficient methods can be used to capture the thermal energy that is generated during the process of compressing air. This research looks at a number of different approaches of reusing thermal energy, compares the efficiency of different heat recovery devices, and finds out how well they work. The results shed light on the practicality and efficiency of waste heat recovery systems in industrial compressor operations, thanks to experiments and data analysis. The results of this study have important implications for the advancement of sustainable energy practices in manufacturing.

Keywords: Waste Heat Recovery; Multistage Air Compressor; Heat Exchangers Sustainable Energy Practices

1.1 Introduction

Reducing emissions is impossible without energy efficiency measures and the use of renewable energy sources. In India, 41% of all energy consumption was in the industrial sector. About 36% of India's overall energy consumption comes from the industrial sector, with manufacturing alone being responsible for about 66%. In political, economic, and technological settings, ensuring sustainable and dependable energy is of the utmost importance.[2]

Industrial energy efficiency is a dependable home energy source and a globally acknowledged solution. Equipment that draws air from the environment and compresses it to a specific pressure can produce compressed air. A machine that uses auxiliary equipment to compress air is known as a compressor. Energy can be transported by means of pressurized air. Manual tools, pneumatic actuators, pneumatic conveyance, cleaning, and drying can all be powered by this energy. Compressed air has many desirable practical properties. This process involves drawing air down from above and releasing it back into the sky. This eliminates the requirement for return pipework. According to **Sapmaz, Kaya, and Eyidoğan (2016),** the use of compressed air poses no risk of flashback or burning in locations free of open flames or sparks. Equally important to water, power, and natural gas as an industrial resource is compressed air. A large amount of power is consumed by the compressed air system in many industrial facilities **(Eras, et al., 2022).** A considerable 43% of industrial electricity usage in the Asia Pacific area is attributed to compressed air, according to a study by **Vittorini & Cipollone (2016).** Due to the gravity of the situation, a comprehensive study into compressed air systems' energy efficiency is required. Compressed air using an air compressor turns mechanical energy into pressure energy. This transformation streamlines the energy management process, including transmission, storage, and control. The correct treatment of compressed air is required prior to its use. According to **Benetti et al. (2020),** there are multiple steps involved in treating air, including filtration, chilling, water separation, drying, and lubricating. A compressor that runs around the clock usually uses more energy per year than it cost to install. In terms of delivered unit energy, compressed air is more costly than three alternative sources: electricity, natural gas, and steam. Compressed air systems typically account for a larger percentage of overall energy costs when they are integral to the production system. Prioritizing energy saving measures should not be overlooked when selecting a compressor system (Doyle, & Cosgrove, 2018). Considerations including availability and energy economy should guide the selection of compressor types, capacities, drive systems, and combinations thereof. It is well-known and thoroughly covered in the literature that there are energy efficiency potential in many areas of compressed air production, including the air grid, system design, end use devices, treatment, and operation **(Vittorini, & Cipollone, 2016),** Some possibilities call for prearranged measurement and maintenance tasks, while others must be considered during system installation.

In this research, we look at the possibility of recovering heat from air-cooled and water-cooled compressors. The

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thermal energy generated during compression can be efficiently recovered and utilized with the correct technologies in place.

1.1.1Waste Heat Recovery

According to **Hernandez-Herrera et al. (2021)** 80-93% of the electrical energy supplied to the compressor does not reach the compressed air's utilization point. Very little of this energy is wasted to sound and friction; the majority is transformed into heat. The process of compression raises air temperature. Air can be cooled to room temperature to recover between 60 and 80 percent of the electrical energy supplied to the compressor. As long as the plant is running, this supply of heat energy is available. It is possible to compute waste heat potential both practically and theoretically. Equations of thermodynamics are utilized in theoretical computations. Equation (1.1) can be used to compute the temperature rise in a compression proof. The specific heat of air ratio $(\mathrm{Cp/Cv})$ indicated by the letter k in equation (1.1), can be considered to be 1.4 in the case of adiabatic compression. Heat transmission is made feasible by the temperature differential between compressed air and surrounding air. Recoverable specific heat energy is computed using equation (1.2). Calculated using the compressor's compressed air capacity, the total possible waste heat.

$$\Delta \mathrm{T} = \mathrm{T}_2 - \mathrm{T}_1 = \mathrm{T}_1 \times \left[\left(\frac{\mathrm{P}_2}{\mathrm{P}_1} \right)^{\frac{\mathrm{k}-1}{\mathrm{k}}} - 1 \right] \ldots \ldots (1.1)$$

$$\mathrm{Q} = \mathrm{m} \times \mathrm{c} \times (\mathrm{T}_2 - \mathrm{T}_1) \ldots \ldots (1.2)$$

Even if the theoretical computation is simple and helpful, it is predicated on certain assumptions. Measurement values can be used to determine waste heat potential in a sensitive manner. It is necessary to measure the mass flow rate and current cooling agent temperature. Equation (1.2) makes use of measurement values. The instantaneous thermal power (kWth) in both of these computations needs to be converted to heat energy using working hours. The capacity and consumption variables of the compressor determine the total potential for the year. The ratio of compressor operating hours to total plant working hours is known as the use factor. The compressor's average annual working capacity is its capacity factor. The cooling system is a crucial component of the compressor's waste heat recovery mechanism. Compressors will be categorized as either water-cooled or air-cooled. Both have specific process requirements, even though they are both appropriate for waste heat recovery.

1.1.2 Air Cooled Compressors

Compressors that use air cooling have a fan that draws air from the surrounding air into the compressor housing. After being heated to temperatures between 85 and 90 degrees Celsius, this air is expelled back into space. But when the air is too hot, heat transfer becomes inadequate, and the compressor overheats and shuts down unexpectedly. Having more fans on hand could be necessary for transferring waste compression energy over large distances. On the other hand, this may cause the air channel, elbows, and joints to experience temperature and pressure declines. The use of hot air close to the manufacturing site for waste heat utilization can be justified from a practical and financial standpoint.

1.1.3 Water Cooled Compressors

The cooling system of a multi-stage compressor employs intercooler cooling heat exchangers to efficiently handle the excess heat produced during the air compression process. After compression, the compressor cools the air to near-ambient temperatures before proceeding to the next stages. A water-cooled compressor's waste heat recovery system effectively harnesses surplus heat from the air for a variety of purposes.

This study used plate heat exchangers and shell-and-tube heat exchangers to effectively extract heat from a multistage air compressor. Out of the several heat exchangers shown in Figure 1.1, we are specifically interested in these types of heat exchangers since they have high efficiency and are suitable for our unique requirements. Integrating those heat exchangers can achieve effective heat recuperation from the compressor, resulting in enhanced energy utilization and reduced operational expenses. Due to their versatility and robust construction, they are well-suited for managing various operating circumstances, guaranteeing reliable performance in commercial environments.

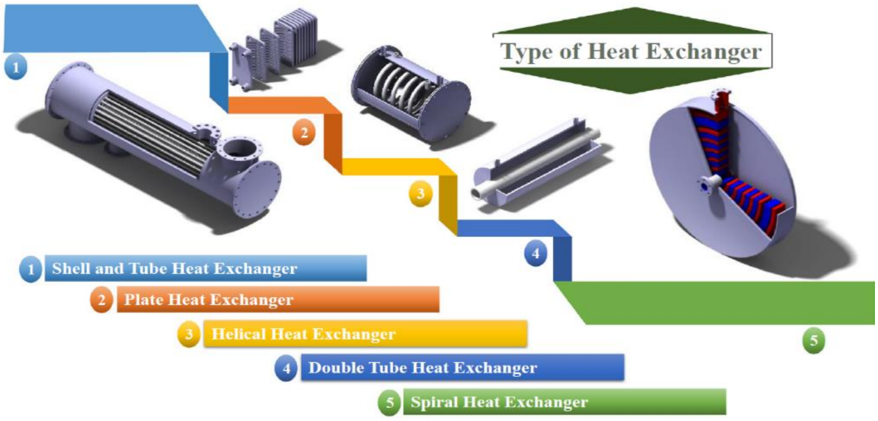

Figure 1.1 - Versatile Heat Exchanger Options for Industrial Applications **(Hajatzadeh Pordanjani et al. 2019)**

1.2 Objectives

- To calculate the potential of heat recovery from an air compressor.
- To enhance energy savings by recovering the heat generated from an air compressor unit in beverage industrial plant.
- To make a comparison between 'shell and tube' and 'plate heat exchanger' in terms of the best heat recovery option from an air compressor.

1.2Material and methods

1.2.1Background

An industrial plant, specializing in beverage industries, operates three-stage air compressors with a rated motor power of 215 Horsepower. These compressors are water-cooled and have a capacity of 540 cubic feet per minute. This multistage compressor is designated to supply high-pressure air at 38 bar, although the achieved pressure nearly ranges from 33 to 36 bar. Upon examination, it was observed that the compressors are water-cooled, with cooling tower water temperature maintained at nearly 290K. The cooling tower cold water circulates through the intercooler and aftercooler, where it captures heat from the hot air, this is also circulated in intercooler and aftercooler. As a result, the cooling tower (CT) cold water capture heat and then becomes heated before being go to the cooling tower, resulting in energy loss. To implement the waste heat recovery (WHR) system effectively, a most effective solution is proposed. This involves recovering heat from the heated CT water, obtained through the use of either a plate heat exchanger or a shell-and-tube heat exchanger. These types of heat exchangers offer versatility to utilize heat in a variety of processes, making them an indispensable component of the waste heat recovery systems.

1.2.2Procedure

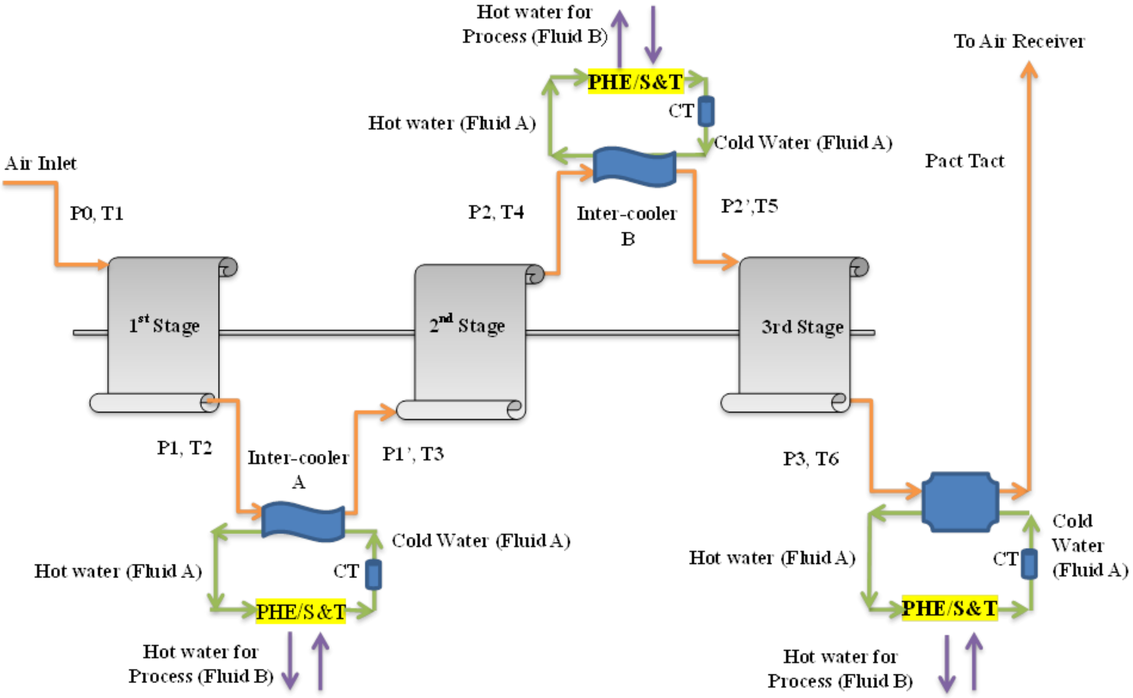

Figure 1.2 Experimental setup of waste heat recovery

An industrial multi-stage compressor's first cylinder's function is to compress the air that enters the machine at atmospheric pressure. This compression process increases both the air pressure and temperature. Following that, the already warm air is cooled down before it undergoes further compression by being directed through the intercooler. To ensure optimal efficiency of the compression cycle, it is crucial to implement this cooling procedure.

Through the intercooling process, heat energy is lost by passing hot air through various coolers. However, plate or shell and tube heat exchangers have the ability to recover the lost heat **(Sarode, et al. 2023).**
During the recovery phase, a cooling medium, typically cold water (referred to as fluid A), is utilized to remove heat from the high-temperature air entering the intercooler. As fluid A absorbs heat from the high-temperature air, its temperature increases accordingly. In industrial settings, the hot water (fluid A) is usually discarded into a cooling tower or the environment as waste. Nevertheless, this hot water with high energy has the potential to be utilized as an additional valuable heat source. Therefore, in this experiment, rather than allowing the hot water from the intercooler to be wasted, it is directed towards the plate heat exchanger or shell and tube heat exchangers. Fluid A (hot water) and Fluid B (water used for industrial purposes) typically start at different temperatures and flow through separate channels in either a plate heat exchanger or a shell and tube heat exchanger. Fluid B absorbs heat from Fluid A (hot water) as they pass through the heat exchanger, causing Fluid A to lose heat. Through the utilization of the reclaimed heat from Fluid A, a notable enhancement in the overall energy efficiency can be attained, providing advantages to numerous industrial processes.

1.3Results

To calculate the total potential heat recovery from the air compressor, we'll sum up the heat loss by air from all coolers. The formula to calculate heat loss by air is given as:

$$Q = m \times C_p \times \Delta T \ldots. (1.3)$$

Where:

- Q is the heat loss by air (in $\mathrm{kJ/min}$ or kW)
- m is the mass of air delivered per minute (in $\mathrm{kg/min}$)
- ΔT is the temperature difference between outlet (Tout) and inlet (Tin) air temperature of intercooler/ aftercooler (in $^\circ\mathrm{C}$ or K)
- C_p is the Specific Heat Capacity at Constant Pressure (in kJ /kg k)

Let's calculate the total potential heat recovery using the provided values:
Given:

- $m = 18.37\ \mathrm{kg/min}$
- $\Delta T_{\text{lst Intercooler}} = T_2 - T_3$ = 391 K − 295 K = 96 K
- $\Delta T_{\text{2nd Intercooler}} = T_4 - T_5$ = 379 K – 300 K = 79 K
- $\Delta T_{\text{After-cooler}} = T_6 - T_{\text{act}}$ = 396 K – 304 K = 92 K

Let's calculate:

$$Q_{\text{total}} = Q_{1\text{ st Intercooler}} + Q_{\text{2nd Intercooler}} + Q_{\text{After-cooler}} \ldots.. (1.4)$$

$$Q_{\text{total}} = \left(m \times C_p \times \Delta T_{\text{lst Intercooler}}\right) + \left(m \times C_p \times \Delta T_{\text{2nd Intercooler}}\right) + \left(m \times C_p \times \Delta T_{\text{After-cooler}}\right) \ldots \ldots (1.5)$$

Now, let's plug in the values:

$$Q_{\text{total}} = (18.372 \times 1.004 \times 96) + (18.372 \times 1.004 \times 79) + (18.372 \times 1.004 \times 92)$$

$$Q_{\text{total}} = (1770.78) + (1457.20) + (1697.00)$$

$$Q_{\text{total}} = 4924.99\ \mathrm{kJ/min}$$

So, the total potential heat recovery from the air compressor is approximately $4924.99\ \mathrm{kJ/min}$ or 82.08 KW

1.3.1 Heat recovery potential between the shell and tube heat exchanger

To compare the heat recovery potential between the shell and tube heat exchanger and the plate heat exchanger, we need to calculate the actual heat gained by water (Fluid B) for each type of heat exchanger.

$$\text{Efficiency} = \frac{\text{Actual Heat Transfer}}{\text{Maximum Possible Heat Transfer}} \times 100\% \ldots\ldots. (1.\ 6)$$

$$\text{Efficiency} = \frac{\text{Actual Heat gain by Water (fluid B)}}{\text{Actual Heat Gained by Water (Fluid A)}} \times 100\% \ldots\ldots. (1.\ 7)$$

Given:

1. Actual Heat Gained by Water (Fluid A) in 1st Intercooler = $1665.2\ \mathrm{kJ/min}$
2. Actual Heat Gained by Water (Fluid A) in 2nd Intercooler = $1363.30\ \mathrm{kJ/min}$
3. Actual Heat Gained by Water (Fluid A) in After-Cooler = $1589.97\ \mathrm{kJ/min}$

We'll use the efficiency values provided:

1. Plate Heat Exchanger Efficiency: 92.67% (or 0.9267 as a decimal)
2. Shell and Tube Heat Exchanger Efficiency: 68.72% (or 0.6872 as a decimal)

Let's calculate the actual heat gained by water (Fluid B) for each heat exchanger type:

- **For the Plate Heat Exchanger**

$$\text{Actual Heat Gained by Water (Fluid B)})_{\text{Plate}} = \text{Actual Heat Gained by Water (Fluid A)} \times \text{Efficiency}_{\text{ Plate}}$$

Actual Heat Gained by Water (Fluid B) $)_{\text{Plate}} = 1665.2 \text{ x } 0.9267 = 1543.14 \text{ kJ/min}$
Actual Heat Gained by Water (Fluid B) $)_{\text{Plate}} = 1363.30 \times 0.9267 = 1263.37 \text{ kJ/min}$
Actual Heat Gained by Water (Fluid B) $)_{\text{Plate}} = 1589.97 \times 0.9267 = 1473.43 \text{ kJ/min}$

- **For the Shell and tube Heat Exchanger**

$$\text{Actual Heat Gained by Water (Fluid B)})_{\text{Shell}} = \text{Actual Heat Gained by Water (Fluid A)} \times \text{Efficiency}_{\text{ Shell}}$$

Actual Heat Gained by Water (Fluid B) $)_{\text{Shell}} = 1665.2 \text{ x } 0.6872 = 1141.32 \text{ kJ/min}$
Actual Heat Gained by Water (Fluid B) $)_{\text{Shell}} = 1363.30 \text{ x } 0.6872 = 936.86 \text{ kJ/min}$
Actual Heat Gained by Water (Fluid B) $)_{\text{Shell}} = 1589.97 \text{ x } 0.6872 = 1092.63 \text{ kJ/min}$

1.4 Conclusion and Discussion

The use of secondary energy sources, such electricity, to produce compressed air is something that operators should be aware of. This suggests that, in comparison to other resources, compressed air is rather expensive. Avoiding the squandering of this resource is possible through the use of multiple tactics.

Finally, the research goals of our experimental study—which compared two heat recovery options developed using two heat exchangers, a "shell and tube heat exchanger" and a "plate heat exchanger"—have been met. Our study primarily focused on the potential of heat recovery from an air compressor and significantly improved energy savings in an industrial plant.

First, the study's results clearly show that recovering waste heat from a multistage air compressor system could greatly reduce energy consumption. It is clear that there is a great deal of untapped thermal energy available for use in a variety of industrial processes, as the estimated total potential heat recovery is almost 4924.99 kJ/min.

Secondly, we have found encouraging outcomes from our inquiry into improving energy savings in an industrial plant that produces beverages. We have successfully reduced the plant's dependence on conventional energy sources and operational expenses by implementing heat recovery devices, which allow us to collect waste heat from the air compressor unit.

Finally, the most effective heat recovery solution has been revealed by our comparison of "shell and tube heat exchanger" and "plate heat exchanger" technologies. The analysis showed that the plate heat exchanger was very efficient, with a gain in heat of 1263.37 to 1543.14 kJ/min for fluid B, which is water, and an efficiency of 92.67%. The shell and tube heat exchanger, on the other hand, showed lower efficiency levels; fluid B's actual heat gain varied between 936.86 and 1141.32 kJ/min, or 68.72%.

Based on particular industrial needs and operating circumstances, these results show how important it is to choose the best heat recovery option. Although both plate and shell and tube heat exchangers can recover waste heat, plate heat exchangers have shown to be more efficient, therefore they may be the best option for industrial settings looking to save energy and the environment.

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