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Advancements In Waste Heat Recovery from Multistage Air Compressor Operations

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Abstract

In industrial production processes, waste heat is an important consequence, especially in sectors that rely significantly on composites and polymers. Frequently, this heat is released into the atmosphere without being captured, which raises operating expenses in addition to wasting potential energy. In these sectors, waste heat recovery, or WHR, has become a key tactic for raising sustainability and energy efficiency. The WHR potential of multistage air compressors—essential parts of industrial manufacturing setups—is examined in this study. Businesses can cut their energy use and carbon footprint by recovering waste heat. The efficiency of two popular heat exchanger technologies—plate heat exchangers and shell-and-tube heat exchangers—in recovering heat from multistage air compressors is assessed in this paper. Important variables including temperature differentials, specific heat capacities, and mass flow rates form the basis of the analysis. The total recoverable heat in the system is determined by these variables, which are crucial. The multistage air compressor systems exhibited an outstanding 4883.65 kJ/min of recoverable energy, indicating a large potential for heat recovery, according to our findings. Comparing the two types of heat exchangers, it can be shown that plate heat exchangers recover 4256.82 kJ/min at a substantially higher efficiency than shell-and-tube heat exchangers, which recover 3156.67 kJ/min. These findings highlight how crucial it is to choose the right WHR technology in order to optimize energy recovery. The study emphasizes how important it is to use cutting-edge WHR technologies to improve industrial sustainability. Industries may significantly cut energy consumption, greenhouse gas emissions, and operating expenses by recycling waste heat in an efficient manner. This will help to create a more sustainable and energy-efficient future.

Keywords: Waste heat recovery, multistage air compressors, polymer manufacturing, composite manufacturing, heat exchanger

INTRODUCTION

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Large volumes of waste heat are frequently produced by industrial processes, especially in the production of polymers and composites. If this heat is not used, it leads to energy inefficiency and higher operating costs. These sectors depend heavily on multistage air compressors, which have significant prospects for waste heat recovery (WHR) because of their high operating pressures and temperatures. Using two common types of HEs — plate heat exchangers and shell-and-tube heat exchangers—this study focuses on the WHR potential from the intercoolers and aftercoolers of such compressors.

A compressor is a mechanical device that works by reducing the volume of a fluid, typically air or gas, to increase its pressure. This process is

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governed by fundamental principles of thermodynamics. According to Gay-Lussac's law, which states that pressure and temperature are directly proportional in a closed system (when volume is constant), an increase in pressure leads to a corresponding rise in temperature. Consequently, as the compressor works to elevate the fluid's pressure, the internal temperature within the compressor increases significantly. This heat generation is an inherent part of the compression process, and managing this high temperature is crucial for the efficiency and safety of the system.

Multistage compressor is a type of compressor where the fluid is compressed in different stages, meaning, more compression. Naturally, when pressure rises, so does temperature. We employ an intercooler to lower the system's temperature. As the name suggests, it is employed in between a compressor's two stages. It can lessen the chance that the compressor cylinder adjacent to it will explode. Additionally, it aids in lowering the amount of water vapor in compressed air. These molecules of water vapor, if left behind, will cause the system to malfunction. Additionally, I have heard that they improve volumetric efficiency. The air that exits the compression unit's last stage is cooled by an after-cooler.

These coolers remove heat, which is a sizable quantity of energy that can be recovered. Making use of this heat can result in increased energy savings, decreased greenhouse gas emissions, and decreased operating expenses, all of which are in line with the global movement towards more environmentally friendly industrial processes.

Quantifying the WHR potential from an industrial multistage air compressor and contrasting the efficiency of plate and S-and-T heat exchangers in this application are the main goals of this study. We determine the total recoverable heat from the system using temperature differentials, specific heat capacity, and mass flow rate.

The latest advancements in WHR technologies center on enhancing the integration of heat exchangers in compressor systems and refining heat recovery techniques. Significant advancements have been made in the construction and functionality of intercoolers and after-coolers, which are essential parts of multistage compressors. More effective heat transfer and recovery are now possible because to improved materials and sophisticated heat exchanger designs. These developments help to cut energy expenses and greenhouse gas emissions in addition to increasing the efficacy of WHR systems.

Waste Heat Recovery

Industries can reduce waste and increase efficiency with the use of a waste heat recovery system. This kind of technology can significantly reduce energy consumption at the plant level. On the other hand, waiting to install a waste heat recovery system is a good idea until a suitable waste heat source has been identified. Thus, this study focuses on recovering the heat produced by a multistage air compressor, which is one of the most significant optimization sources that are frequently disregarded [4].

The following formula, according to Jouhara et al. 2018 [8]. and Sarode et.al 2024 [3]. can be used to represent the heat recovery potential:

$$\mathrm{Q = m\ X\ Cp\ X\ (Tout - Tin)}$$

Where,

- m is the air's mass flow rate,
- Cp is its specific heat capacity,
- Tout is the air's exit temperature, and
- Tin is the air's input temperature.

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Sarode et al. (2024) [3]. highlight the substantial potential of utilizing plate HE and S-and-T HEs to retrieve waste heat from compressors. The waste heat produced by multiple stages air compressors can be effectively captured and repurposed by these heat exchangers, offering an extra useful heat source. Many industrial operations can make use of this recovered heat, improving sustainability and overall energy efficiency.

Specifically, the recovered heat can be used for a number of crucial industrial applications, such as Cleaning in Place (CIP), where it ensures effective sanitation and maintenance of equipment. Additionally, it performs a crucial function in the production of raw syrup, enhancing the end product's consistency and quality. Furthermore, the recovered heat supports different manufacturing and processing stages by performing crucial roles in product and process heating.

Industries may greatly reduce their energy usage and environmental effect by utilizing these waste heat recovery systems, which will encourage more sustainable practices. The findings highlight how crucial it is to incorporate cutting-edge heat recovery systems in order to maximize resource use and raise industrial operations' general efficiency.

LITERATURE REVIEW

Research on waste heat recovery (WHR) has become essential for improving energy efficiency within industrial applications, especially in the production of polymers and composites. One of the most expensive energy sources is a compressed air system [5]. Even yet, only 10-30% of electrical energy reaches the terminal point, with the remaining 70–90% being lost as heat [6] [7]. Means savings potential is 70–90%.As a result, a lot of research has been done on how to integrate WHR systems to capture and use this energy in a way that lowers operating expenses and greenhouse gas emissions. Because each stage of a multistage air compressor produces a significant quantity of heat, using them in industrial operations increases the possibility for WHR.

Heat exchangers are essential to WHR systems' effectiveness. The efficiency of plate HE and S-and-T HEs in moving heat from compressed air to a secondary fluid is highlighted by research conducted in [3] and [4]. Owing to its compact shape and great efficiency, plate HEs are especially well-suited for spaces that are limited in size. In contrast, S-and-T HEs are frequently utilized in heavy-duty industrial applications due to their reputation for durability and ability to withstand higher pressures and temperatures. These heat exchangers improve the system's overall energy efficiency by making it easier to recover heat from intercoolers and aftercoolers, which are essential parts of multistage air compressors.

WHR systems have demonstrated significant potential in the manufacture of polymers and composites. Research has indicated that the adoption of waste heat recovery (WHR) in various sectors leads to increased energy efficiency and more sustainable industrial processes.

The goal of subsequent research has been to maximize the efficiency of WHR systems through optimal design and operation. Theoretical frameworks for improving heat recovery can be obtained by integrating sophisticated thermodynamic principles. Research conducted by the U.S. Department of Energy [2]. and Saidur et al. [1]. has investigated these approaches and provided evidence of their usefulness in industrial environments. These developments emphasize how crucial it is to choose the right heat exchanger technology in order to attain the best possible WHR performance. dos Santos Mascarenhas J. et al. [9]: An extensive examination of the energy efficiency, CO_2 emissions, sustainability, energy performance, and economic consequences was carried out on industrial air compressors in a TiO_2 production facility located in Bahia, Brazil. Energy efficiencies in the range of 5.27% to 21.94% and sustainability indices, such as a Sustainability Index (SI) of 1.05 to 1.28, were found in the study. Discharge pressure reduction, power factor improvement and Waste heat recovery have all been noted as important benefits. Lowering the discharge pressure can result in yearly savings of 347.7 tons of CO_2 and 3515.180 MWh of electricity. With a $570,000 investment, 5634.2 MWh and 557 tons of CO_2 may be saved overall, translating into a 9-month return on investment.

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Vance et al. [10]. In five industries—lime, cement, glass, aluminum and steel—this article investigates the possibility for WHR, in hard settings, defined as waste heat streams with temperatures above 650°C or containing reactive elements. These sectors were chosen in light of their production volume, the properties of their exhaust gases, and their potential for heat recovery. A total of 113.6 TWh in potential energy savings are found by the analysis (15.4% of process thermal energy lost in U.S. manufacturing). The greatest potential is seen in the steel industry, particularly in blast furnaces (46 TWh/year). Notwithstanding previous obstacles, technological developments could greatly improve WHR in many industries, resulting in significant energy and cost savings.

Wang et al. [11] Thermal power stations in northern China take advantage of absorption heat pumps' exceptional waste heat recovery capabilities to recover LG heat from turbine exhaust steam. The waste heat recovery system design idea presented in this study matches the actual heating load of the heating network with the design power of the HP. It presents an economic analysis approach to identify the ideal design power and describes in detail the operation mode for various heat pump design powers. A waste heat recovery system for a particular unit was constructed, and a detailed analysis of the elements affecting the system's economic viability was conducted.

Kamran et al. [12]. in the manufacturing industry, compressed air systems are expensive and ineffective energy sources. Variations in flow rate and air pressure have an impact on efficiency. Energy analysis is not as useful as energy analysis since it fails to identify internal and external losses. The present research assesses compressed air systems by considering energy consumption, exergy efficiency, and thermoeconomic considerations. An extensive analytical tool for this purpose is the exergy weighted sum (EWS). Energy-wise optimization is aided by EWS's assessment of improvement scenarios. According to the findings, the optimum optimization techniques for power usage, energy efficiency, and thermoeconomics are waste heat recovery and air leak reduction.

In conclusion, research shows that WHR systems are critical to enhancing energy efficiency in multistage air compressors used in the production of polymers and composites. When combined with sophisticated thermodynamic analysis, the efficient usage of plate and shell-and-tube heat exchangers can result in significant energy savings as well as positive environmental effects. Efficient WHR system development and deployment will be essential to achieving the sustainable energy practices that enterprises are still pursuing.

Research Gaps

1. Determining the viability and effectiveness of energy recovery systems requires computing the heat recovery potential from air compressors. Nevertheless, current research frequently lacks thorough procedures for precisely estimating the potential heat recovery using the given parameters (ΔT, V, ρ, CP). Furthermore, there isn't much attention paid to the real-world uses and differences in heat recovery capability between compressor types and operating environments. This discrepancy emphasizes the requirement for more thorough and varied case studies in order to verify and improve computation techniques.
2. Research focusing on the possibility of increasing energy savings via waste heat recovery from air compressors is scarce. The body of research on heat recovery systems' ability to save energy costs and boost overall productivity in industrial settings is currently lacking. This suggests that further investigation is required into case studies, practical applications, and the measurement of energy savings attained by means of different heat recovery devices.
3. Although extensive research has been conducted on heat recovery systems, there remains a noticeable gap in the literature when it comes to detailed comparative studies between "shell and tube" and "plate heat exchangers" specifically for multi-stage air compressor applications. Existing publications do not adequately address the efficiency, cost-effectiveness, and performance differences of these heat exchangers within the context of air compressor heat recovery. This gap underscores the need for a comprehensive comparative analysis to identify the optimal heat recovery solution for various operational scenarios.

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PROCEDURE

In industrial multi-stage compressors, the process begins with air entering the compressor at atmospheric pressure. As the air undergoes initial compression in the first cylinder, its pressure is increased, and its temperature rises significantly due to the compression process. This high-temperature air is then directed into an intercooler, a crucial component designed to cool the compressed air before it moves on to the next stage of compression. Cooling the air at this point is essential because it not only improves the efficiency of the subsequent compression stages but also helps prevent potential overheating issues within the compressor.

The intercooler works by removing the excess heat from the compressed air, making it suitable for further compression in the second cylinder. This cycle of compression and cooling continues across multiple stages, each of which involves a significant reduction in the temperature of the compressed air. To ensure optimal performance, heat must be removed efficiently at various points, particularly in the first intercooler, second intercooler, and after-cooler stages. This wasted heat is recovering using Heat Exchanger (Figure.1)

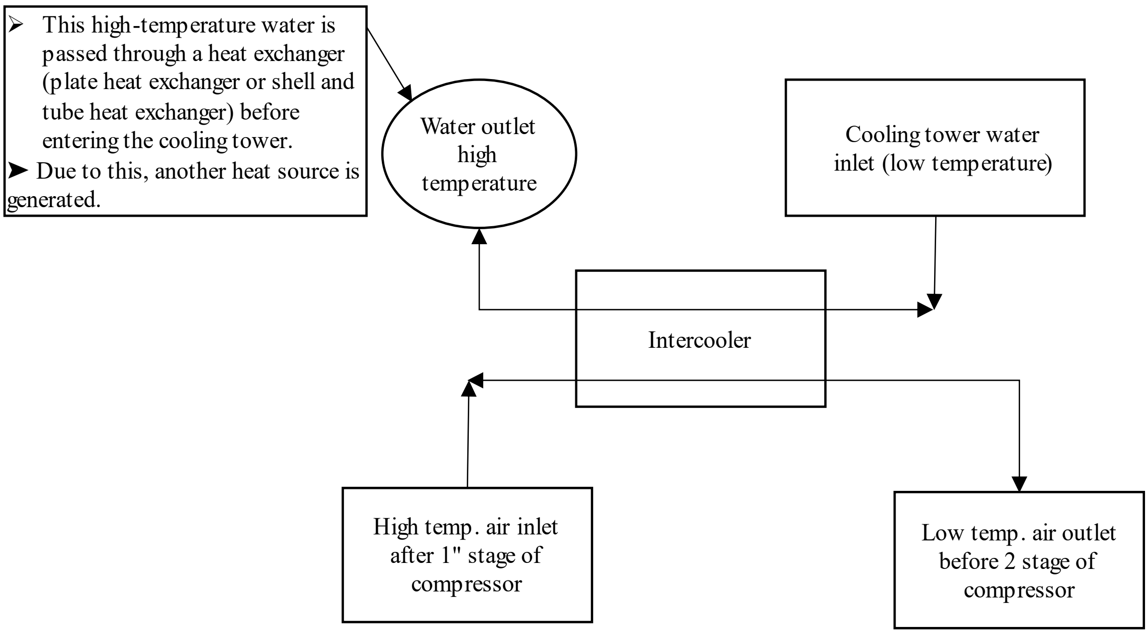

Figure 1. Waste heat recovery system

CALCULATIONS

We add up all of the coolers' air loss heat in order to determine the air compressor's overall potential heat recovery. The following is the formula to find heat loss through the air:

$$Q = m \, X \, C\_p \, X \, \Delta T$$

Where:

- Q is the heat loss by air (in kJ/min or kW)
- m is the mass of air delivered per minute (in kg/min)
- ΔT is the temperature difference between outlet (Tout) and inlet (Tin) air temperature of intercooler/after cooler (in ∘C or K)
- C_p is the specific heat capacity at constant pressure (in kJ/kg·K)

Total Potential Heat Recovery Calculation

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Given:
- m=17.35 kg/min
- $\Delta T1st$ Intercooler = T2−T3 = 414 K−314 K = 100 K
- $\Delta T2nd$ Intercooler = T4−T5 = 404 K−320 K = 84 K
- ΔT After-cooler = T6−Tact = 405 K−309 K = 96 K

The total potential heat recovery (Q_{total}) is calculated as:

$$\text{Qtotal} = \text{Q1st Intercooler} + \text{Q2nd Intercooler} + \text{QAftercooler}$$

$$\text{Qtotal} = \left(\text{m X } C_p \text{X}\Delta\text{T1st Intercooler}\right) + \left(\text{m X } C_p \text{X}\Delta\text{T2nd Intercooler}\right) + \left(\text{m X } C_p \text{X}\Delta\text{TAfter} - \text{cooler}\right)$$

Plugging in the values:
Qtotal = (17.35×1.005×100) + (17.35×1.005×84) + (17.35×1.005×96)
Qtotal = 1744.162 + 1465.096 + 1674.395
Qtotal = 4883.653 kJ/min

So, the total potential heat recovery from the air compressor is approximately 4883.65 kJ/min or 81.4 kW.

Comparing the Heat Recovery Potential of Shell and Tube Heat Exchangers with Plate Heat Exchangers

We must determine the actual heat gained by water (Fluid B) for each type of heat exchanger in order to compare the heat recovery potential between the shell and tube and plate heat exchangers.

Efficiency Formula:

$$\text{Efficiency} = \frac{\text{Actual Heat Transfer}}{\text{Maximum Possible Heat Transfer}} \text{ X } 100\ \%$$

$$\text{Efficiency} = \frac{\text{Actual Heat Gain by Water (Fluid B)}}{\text{Actual Heat Gain by Air (Fluid A)}} \text{ X } 100\ \%$$

Given:
- Actual Heat Gained by Water (Fluid A) in 1st Intercooler = 1631.6 kJ/min
- Actual Heat Gained by Water (Fluid A) in 2nd Intercooler = 1404.19 kJ/min
- Actual Heat Gained by Water (Fluid A) in After-Cooler = 1557.69 kJ/min

Efficiency values:
- Plate Heat Exchanger Efficiency: 92.67% (or 0.9267 as a decimal)
- Shell and Tube Heat Exchanger Efficiency: 68.72% (or 0.6872 as a decimal)

a. For the Plate Heat Exchanger:
Actual Heat Gain by water (fluid B)$_{\text{Plate}}$ = Actual Heat Gain by water (fluid A) X Efficiency $_{\text{Plate}}$

Calculations:
1631.6×0.9267=1512.04 kJ/min
1404.19×0.9267=1301.26 kJ/min
1557.69×0.9267=1443.51 kJ/min

Total actual heat gained by water (Fluid B) for the plate heat exchanger: 1512.04 + 1301.26 + 1443.51 = 4256.82 kJ/min

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b. For the Shell and Tube Heat Exchanger:
Actual Heat Gain by water (fluid B) $_{shell}$ = Actual Heat Gain by water (fluid A) X Efficiency $_{shell}$

Calculations:
1631.6×0.6872=1121.26 kJ/min
1404.19×0.6872=964.96 kJ/min
1557.69×0.6872=1070.44 kJ/min

Total actual heat gained by water (Fluid B) for the shell and tube heat exchanger:
1121.26 + 964.96 + 1070.44 = 3156.67 kJ/min

RESULTS AND DISCUSSION

Based on calculations, the air compressor's total potential heat recovery was estimated to be 81.4 kW, or 4883.65 kJ/min. There were notable variations in efficiency between the shell and tube heat exchanger and the plate heat exchanger. The shell and tube heat exchanger recovered 3156.67 kJ/min, compared to 4256.82 kJ/min for the plate heat exchanger. This shows that, with an efficiency of 92.67%, the plate heat exchanger is more efficient than the shell and tube heat exchanger, which has an efficiency of 68.72%. The plate heat exchanger's improved thermal conductivity and bigger surface area, which facilitate heat transfer, are responsible for its higher efficiency(Table.1)

The findings emphasize how crucial it is to choose the right kind of heat exchanger for industrial applications in order to maximize energy recovery and raise overall system efficiency.

Table 1. Result Table.

S. No.	Parameter	Value (KJ/min)
1.	Total Potential Heat Recovery	4883.65
2.	Plate Heat Exchanger	
a)	Actual Heat Gained by Water (1st Intercooler)	1512.04
b)	Actual Heat Gained by Water (2nd Intercooler)	1301.26
c)	Actual Heat Gained by Water (After-cooler)	1443.51
	Total Heat Gained by Water (Plate)	4256.82
3.	Shell and Tube Heat Exchanger	
a)	Actual Heat Gained by Water (1st Intercooler)	1121.26
b)	Actual Heat Gained by Water (2nd Intercooler)	964.96
c)	Actual Heat Gained by Water (After-cooler)	1070.44
	Total Heat Gained by Water (Shell and Tube)	3156.67

This Line chart presents a comparison of heat recovery performance between Plate Heat Exchangers and Shell & Tube Heat Exchangers across different components with broader perspective on trends and total (Figure.2)

- The x-axis represents the components where heat recovery is analyzed.
- The y-axis shows the heat recovery in kilojoules per minute (kJ/min).

The blue line represents the heat recovery achieved by the Plate Heat Exchanger, which generally outperforms the Shell & Tube Heat Exchanger (represented by the green line) across all components. The red dashed line at the top indicates the total potential heat recovery, showing the maximum possible recovery that could be achieved with ideal conditions. The figure demonstrates that both heat exchanger types recover less heat than the total potential, with the Plate Heat Exchanger recovering more heat overall.

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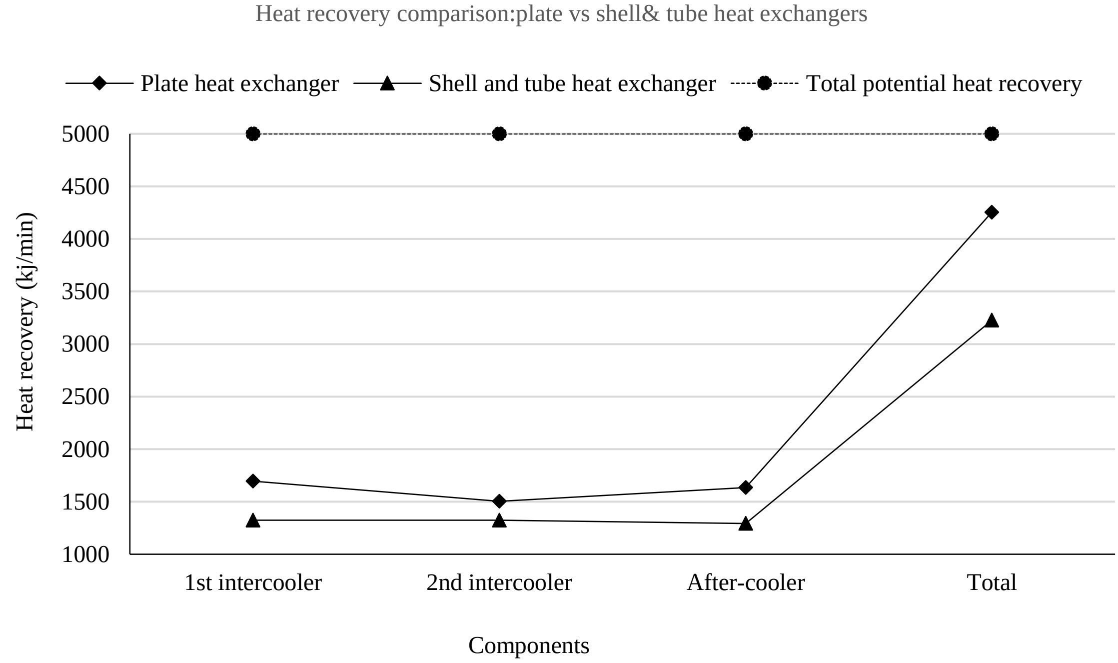

Figure 2. Line chart.

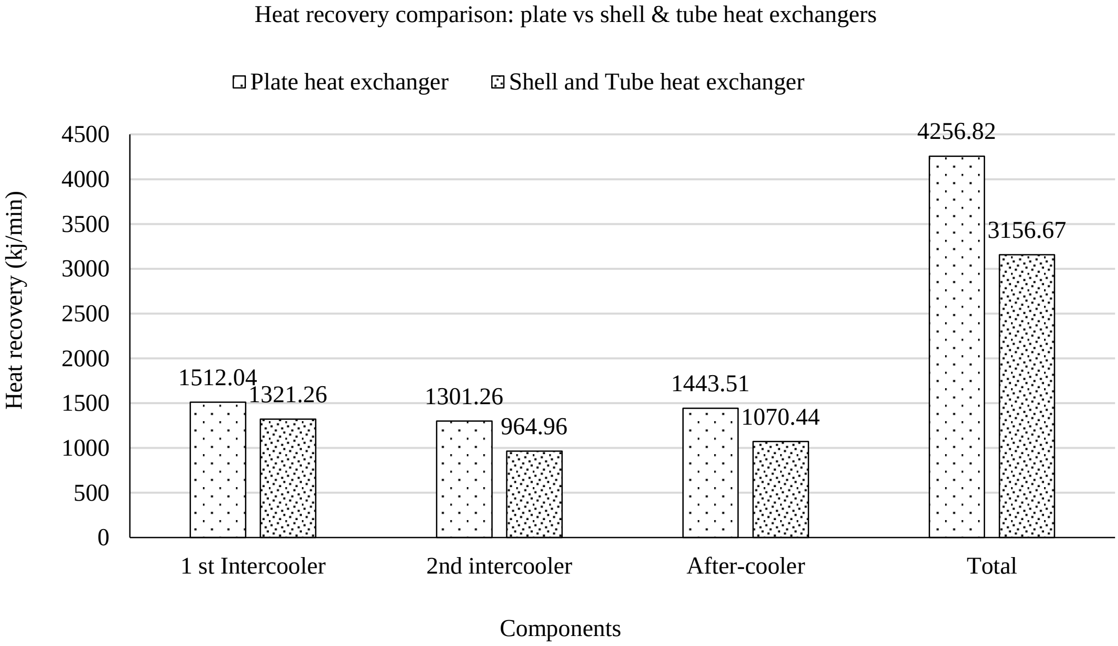

Figure 3. Bar graph.

The Figure 3 uses a bar chart to illustrate specific heat recovery values for both types of heat exchangers. For the 1st intercooler, the Plate Heat Exchanger recovers 1512.04 kJ/min, while the Shell & Tube Heat Exchanger recovers 1121.26 kJ/min. The 2nd intercooler shows a similar trend, with the Plate Heat Exchanger recovering 1301.26 kJ/min and the Shell & Tube Heat Exchanger recovering 964.96 kJ/min. In the after-cooler, the Plate Heat Exchanger continues to outperform the Shell & Tube Heat Exchanger, with recovery values of 1443.51 kJ/min and 1070.44 kJ/min, respectively. The total heat recovery achieved by the Plate Heat Exchanger is 4256.82 kJ/min, which is significantly higher than the 3156.67 kJ/min recovered by the Shell & Tube Heat Exchanger. The bar chart provides a clear visual comparison of exact recovery values, showing that Plate Heat Exchangers are more efficient across all components.

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Both figures are important because they provide complementary perspectives on heat recovery performance. The first diagram focuses on overall trends, making it easier to see how efficiency varies across components and how both types of heat exchangers compare to the total potential heat recovery. The second diagram, on the other hand, emphasizes precise numerical values, offering a more detailed breakdown of heat recovery for each component. Together, these figures provide a comprehensive view of heat recovery performance, helping engineers and researchers make well-informed decisions when choosing between Plate and Shell & Tube Heat Exchangers for specific applications.

CONCLUSION

The study's result highlights the substantial potential that multistage air compressor waste heat recovery offers for industrial applications. Through the computation of heat loss from intercoolers and aftercoolers, a potential heat recovery of 4883.65 kJ/min, or 81.4 kW, was determined. The better choice for optimizing heat recovery is the plate heat exchanger, as demonstrated by its higher efficiency of 92.67% when compared to the shell and tube heat exchanger. In comparison to the shell and tube heat exchanger, which recovers 3156.67 kJ/min, this efficiency results in a total heat recovery of 4256.82 kJ/min. In the manufacturing of polymers and composites, putting such effective heat recovery systems into place can result in significant energy savings and support sustainable energy practices.
The results highlight how crucial it is to choose heat exchangers optimally in order to improve industrial operations' total energy efficiency.

ABBREVIATION

Heat Exchanger	HE
Heat Pump	HP
Shell and tube	S-and-T
Waste Heat Recovery	WHR
low-grade	LG

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