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Original Article

Efficient Heat Recovery in Industrial Air Compressing: Analyzing Plate vs. Shell-and-Tube Heat Exchangers for Beverage Plant Applications

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***Abstract** - In industrial beverage plants, efficient heat recovery is crucial for reducing energy consumption and operational costs. The goal of this research is to assess the performance of Plate Heat Exchangers and Shell-and-Tube Heat Exchangers for heat recovery in industrial air compressors, particularly in beverage plant applications. A detailed experimental setup that comprises the construction of prototypes and installation of instruments, among other aspects, is established. To simulate real-world conditions, a testing protocol is developed, and operational data, such as temperatures, pressures, flow rates, etc, are logged. Within this analysis, the focus would be on calculating the efficiency of the heat exchanger as well as the potential of waste heat recovery. The findings reveal that while PHEs offer superior heat transfer efficiency and compact design, STHEs excel in handling higher pressures and longer operational life. The comprehensive analysis aims to provide engineers and plant managers with insights into selecting the most efficient heat recovery option, enhancing energy efficiency, and optimizing the performance of industrial air compressors operating in beverage production. Plate Heat Exchangers exhibit a notably higher efficiency at 92.67%, compared to the Shell and Tube HEs, which have an efficiency of 68.72%.*

***Keywords** - Waste heat recovery, Shell-and-Tube Heat Exchanger, Renewable energy source, Plate Heat exchanger, Industrial air compressors.*

1. Introduction

Industrial air compressors are widely used across various manufacturing processes, including beverage production plants, where they serve a crucial role in supplying compressed air for numerous operations. However, the compression process inherently generates significant heat, leading to energy inefficiencies and increased operational costs [1].

To address these challenges, heat recovery systems provide a promising solution by capturing and repurposing waste heat for other industrial processes [2]. Efficient heat recovery reduces energy waste and offers an opportunity to generate additional heat sources for heating water or air, thereby reducing reliance on electricity as the primary heating source, promoting sustainability, and saving on energy costs. Another promising avenue for utilizing recovered waste heat lies in CAES systems, which convert electrical energy into compressed air for energy storage, enhancing overall energy efficiency and storage capacity when waste heat is incorporated into the compression process [3].

Heat recovery from air compressors offers a viable opportunity to lower energy use and carbon emissions while simultaneously enhancing the sustainability and competitiveness of industrial facilities [4, 5]. By capturing and utilizing waste heat, heat recovery systems not only lower energy bills but also contribute to environmental conservation efforts by reducing reliance on fossil fuels [6].

This research aims to explore the synergies between efficient heat recovery and secondary heat utilization for water and air heating. Through the investigation of various heat recovery techniques, such as heat exchangers and advanced thermodynamic cycles, and their integration into heating systems, this study seeks to elucidate practical pathways for minimizing electricity consumption in industrial heating processes.

1.1. Various Heat Recovery System Approaches

Heat recovery systems encompass a diverse range of methodologies and technologies tailored to specific industrial applications and process requirements [7]. Common methodologies include:

1.1.1. Heat Exchangers

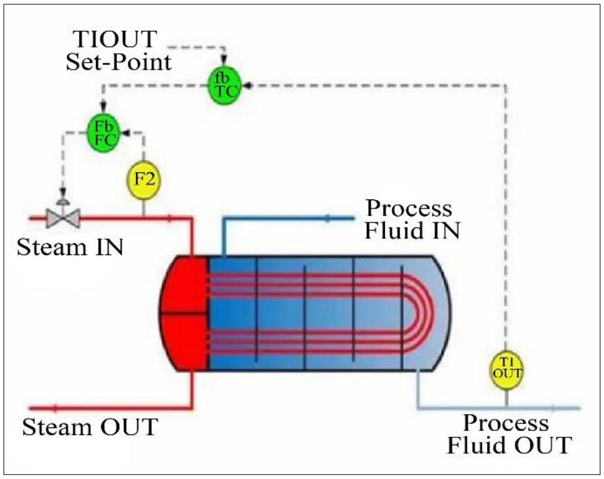

Fig. 1 Heat exchanger control [10]

Heat exchangers form the backbone of many heat recovery systems, facilitating heat transmission between different fluid streams while minimizing energy losses [8]. Efficiency of Heat transfer, pressure drop, and available space are some of the criteria that determine which heat exchanger type is used. Numerous kinds of heat exchangers are commonly employed across various industries, including finned-tube exchangers, PHEs, and STHEs. Each type offers specific advantages and limitations. Finned-tube exchangers are commonly utilized for applications that demand extensive heat transfer surfaces are required, while PHEs are valued for their compact size and high thermal efficiency. STHEs, on the other hand, are favored for their robust design and ability to handle high-pressure applications. Figure 1 shows the heat exchanger control.

1.1.2. Cogeneration and CHP

Utilizing the waste heat produced during power generation for heating or cooling purposes, cogeneration systems, commonly referred to as CHP systems, are designed to maximize energy usage efficiency [11, 12]. CHP systems are particularly advantageous in applications where simultaneous demand exists for both electricity and thermal energy [13].

1.1.3. Heat Pump Technologies

Heat pumps offer an efficient means of extracting energy via low temperatures and upgrading it to higher temperatures suitable for industrial processes or space heating [14]. Advanced heat pump technologies, including absorption heat pumps and ORC systems, enable heat recovery from diverse sources, such as heat from waste, energy from geothermal sources, and industrial exhaust streams [15, 16]. The heat pump sketch is displayed in Figure 2.

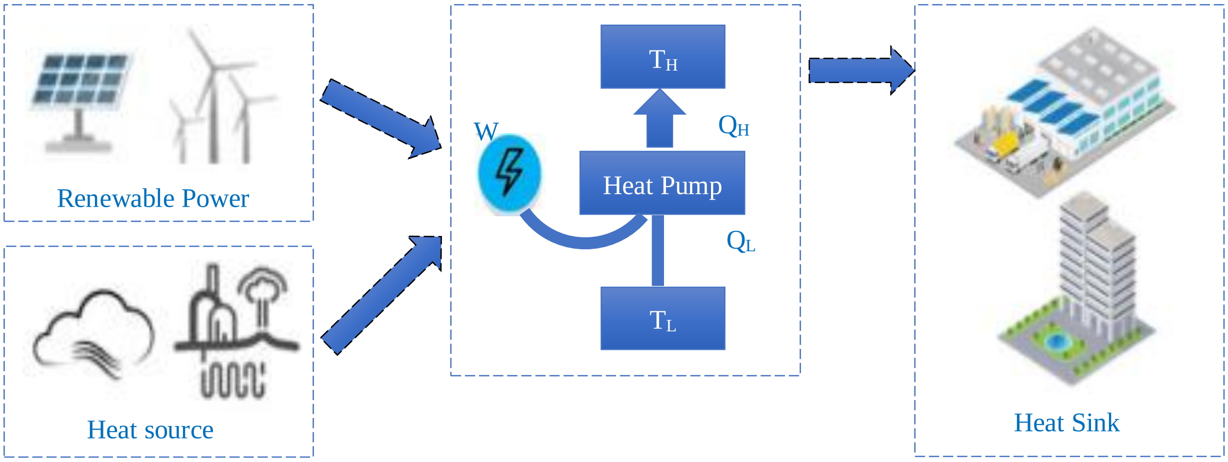

Fig. 2 Sketch of heat pump [16]

1.1.4. Thermal Storage Systems

Thermal storage systems store excessive heat generated at off-peak hours and released during especially busy periods, thereby boosting energy usage as well as lowering utility costs [17]. Sensible heat storage systems and Phase change materials are often used for thermal energy storage applications in industrial settings [18, 19]. This research is dedicated to identifying the most effective waste heat recovery strategy in industrial settings, with a strong focus on the application of HEs as the primary method for capturing and reusing waste heat. Industrial processes often generate significant amounts of waste heat, which, if not properly managed, can lead to energy inefficiency and increased operational costs. By emphasizing the role of heat exchangers with the objective of determining the most suitable solution for harnessing this waste heat, we can boost overall energy efficiency and lower the ecological repercussions. The goal is to present actionable facts that can guide industries in selecting the optimal heat recovery system, resulting in more sustainable and economical operations.

1.2. Plate Heat Exchangers vs. Shell-and-Tube Heat Exchangers

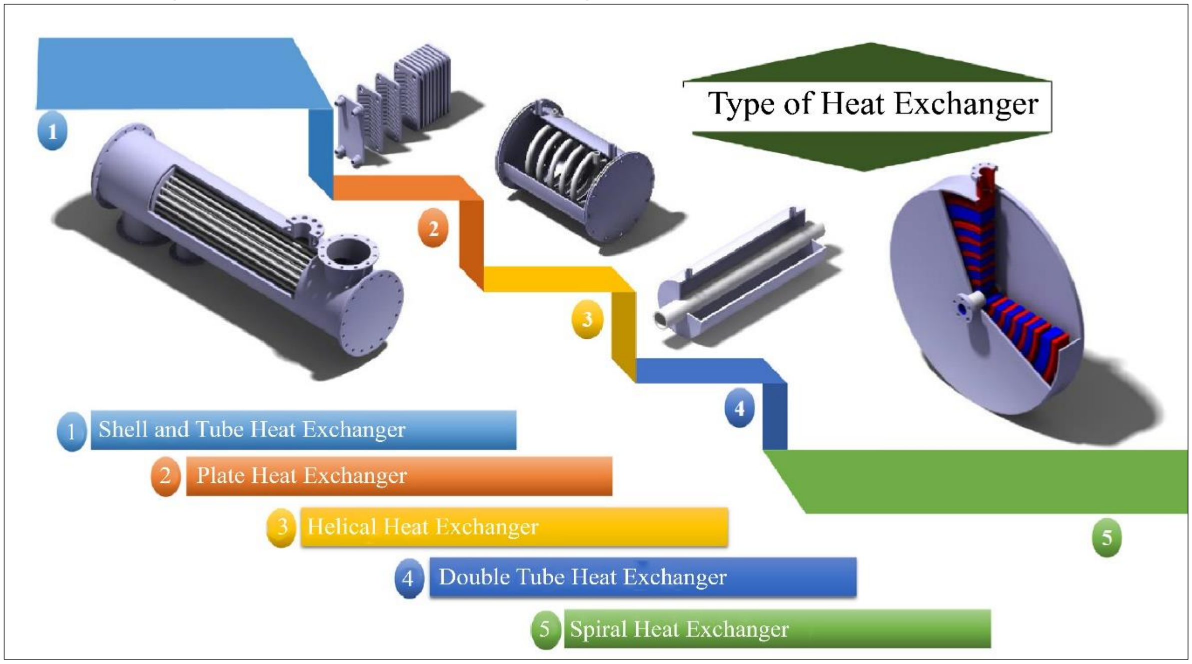

Fig. 3 Illustration of diverse heat exchanger types in industrial applications [20]

This study focuses on the use of PHEs and STHEs to extract thermal waste in a multistage air compressor efficiently. Among the diverse Heat Exchanger types in industrial applications shown in Figure 3, these two are of particular interest. In industrial settings, PHEs and STHEs are commonly employed for heat recovery [21, 22].

PHEs offer various benefits, such as compact size, high heat transfer efficiency, flexibility and ease of maintenance, making them suitable for applications with space limitations and fluctuating heat loads [21, 23]. On the other hand, STHEs are renowned for their robustness, versatility, and suitability for high-pressure and high-temperature environments [22, 24, 25]. However, STHEs typically require more space and are relatively more complex to install and maintain compared to PHEs.

This paper aims to provide insights that help in deciding which waste heat recovery option for an industrial multistage air compressor is more suitable by comparing the efficiency and suitability of two commonly used heat exchanger technologies: PHEs and STHEs.

1.3. Research Gap and Problem Statement

In industrial processes, especially within beverage plants, air compressors are essential for various operations. However, these systems generate significant waste heat, which, if not recovered, leads to energy inefficiencies and increased operational costs. While HEs are widely used for waste heat recovery, selecting the most appropriate type is crucial to maximizing energy savings.

Numerous studies have investigated the performance of heat exchangers in different contexts, with PHEs and STHEs being the most commonly evaluated. PHEs are often praised for their compact design and high HT efficiency, while STHEs are valued for their robustness and ability to handle high-pressure systems.

Despite this, there is a lack of research that directly compares these two heat exchanger types under the same industrial conditions specifically in the context of air compressor systems used in beverage production. Most existing studies focus on theoretical models or laboratory setups, failing to address the practical performance metrics, maintenance, and cost factors in real-world applications.

This research aims to fill this gap by providing a comparative analysis of PHEs and STHEs for heat recovery in industrial air compressors, specifically tailored to the beverage industry. The study addresses the following problem: What is the most efficient and cost-effective heat exchanger for waste heat recovery in industrial air compressors, and how do PHEs and STHEs compare in terms of operational performance, maintenance, and energy savings?

By investigating these factors under realistic operating conditions, this research will offer valuable insights for plant managers and engineers, helping them make informed decisions on optimizing energy efficiency and operational costs in beverage production facilities.

1.4. Novelty of the Work

This study introduces a direct, real-world comparison between PHEs and STHEs for waste heat recovery in industrial air compressors, specifically in beverage production-a context not extensively explored in previous research. While existing studies often focus on theoretical models or controlled laboratory settings, this research evaluates both heat exchangers under actual industrial conditions, providing practical insights into their performance, efficiency, and operational considerations.

Unlike prior research that typically highlights either the efficiency of PHEs or the durability of STHEs, this study presents a comprehensive comparison, incorporating factors such as maintenance, cost-effectiveness, and fouling resistance. This holistic approach offers a more nuanced understanding of heat exchanger selection, filling a gap in the existing literature by addressing both technical performance and long-term operational impacts in a specific industrial setting.

1.5. Work Outlines

The structure of this paper is defined in Section 1. This section discussed the brief overview of "Efficient Heat Recovery in Industrial Air Compressing: Analysing PHEs vs. STHEs for Beverage Plant Applications." In Section 2, previous research is examined and addressed. Section 3 details the experimental process. Section 4 presents the results of the experiments and engages in a thorough discussion, analyzing the data and its implications. The study is completed in Section 5, which summarizes the major conclusions and provides insights into possible future research directions to enhance the discipline.

2. Literature of Review

The literature Review presents a summary of previous research on Efficient Heat Recovery in Industrial Air Compressing: Analysing PHEs vs STHEs for Beverage Plant Applications.

Hanan et al. (2023) [26] used Computational Fluid Dynamics (CFD) to examine the impact of a few performance optimization parameters on the heat exchanger. This paper's primary objective was to show how the STHE performance optimization factors affect the efficiency of the HT and the drop in shell output temperature. Seven more models were developed with one parameter that differed from the original standard model (Model 1) to do the comparison study. When the steam velocity at the intake was doubled, the heat transfer rose by around 48%, according to a comparison of each model's heat transfer results with the Standard model (Model 2).

Marouf and Fouad (2023) [27] highlighted the impacts of Air Bubble Injection (ABI) to provide a detailed energetic-exergetic examination of performance. This study aimed to see what happens when submillimeter-sized air bubbles are injected into both hot and cold fluid streams just before the entrance of a ten-plate corrugated PHE in a counterflow configuration, which was the primary focus of this investigation. Seven distinct flow rates were examined for heated streams, with 100 L/h as the normal step, 50 ◦C as the constant temperature for the heated water, and 290 L/h as the chilled water. This evaluation resulted in four different flow rates for the air released, from 150 to 840 L/h. Findings showed that the ABI method was critical in raising the NTU by 59% and efficacy by 18.6% for Counterflow Water Streams (CWS).

Zeinali and Neshat (2023) [28] examined several geometries in relation to the exergy and exergoeconomics of a shell and spiral tube HE. The Realizable k-ε turbulent model was used to model the HE and determine irreversibility in the shell spiral tube. Results showed that the heat exchanger's second law efficiency dropped by 4%, and the cost value of the equipment went up by 3.54% as the coil pitch went from 20 mm to 40 mm. A similar drop of around 19% in heat exchanger efficiency was obtained by expanding the coil radius.

Chai and Tassou (2023) [29] investigated the heat-to-power conversion efficiency of a supercritical Brayton cycle recuperated from Carbon Dioxide (CO_2). One of the main factors causing these advantages is compact heat exchangers. Heat addition, rejection, and recuperation were among the cycle's several stages where microtube, printed circuit, and PHEs were showing the greatest promise. Using the e-NTU method and a distributed modelling methodology, a cycle model was built by combining simulations of the heater, recuperator, and cooler with models of the turbomachinery. For the power system under investigation operating in undesignated conditions, the cycle's net thermal efficiency varied between 14.1% and 16.8%.

Anand Patel (2023) [30] researched how to optimize the thermal performance of a sunlight heater by integrating it with an STHE. The study combined state-of-the-art modelling techniques in solid works with engineering basics and followed a qualitative research strategy. The results demonstrated that the model can efficiently gather solar energy, transform it, and channel it via the heat exchanger for use in practical heating systems.

Wang et al. (2022) [31] presented a technique for optimizing HENs using Plate Heat Exchangers (PHEs) as a key component, utilizing a thorough design of PHEs. A mathematical model that optimizes the HEN structure is the basis of the approach that was created. This model is based on the Advanced Grid Diagram. With the constraints that make a solution thermodynamically possible, the model minimized the cost of energy use. A case study of a crude oil distillation system provided evidence that using Alfa Laval's CB series Brazed plate Heat Exchangers (BHEs) can reduce the expenditure cost for new heat exchangers by 6.6% when compared to a retrofit plan that solely uses STHE as well as double pipe heat exchangers.

Kim et al. (2021) [32] examined the water's temperature distribution, drop in pressure, and single-phase transfer of heat in a high-temperature industrial Plate as well as a Shell Heat Exchanger (PSHE). In this experiment, there was a downward flow of hot fluid on the plate side and an upward flow of cold fluid on the shell side. When compared to the results obtained on the PHE, the single-phase HT experiment conducted on water yielded a much lower Nu value (ranging from 7.85 to 15.2) and Re value (1200 to 3200). The flow imbalance in the PSHE reduced the cross-sectional heat transfer area, which in turn caused the Nu to fall.

Lin et al. (2020) [33] performed a study that looked into a new way to store thermal energy by tapping into latent heat. A pillow-PHE with multiple flowing channels and Phase Change Material (PCM) is a modern energy storage device. The system was charged or discharged by means of water flowing via the dispersed channels within the plates. The experimental results demonstrated that the system's released energy can attain 6.3 MJ with a 4KW average power. From 100 to 500 L/h, the total heat transfer area and coefficient were in the 25 to 70 W/k range. With its small size and rapid heat transfer, the pillow type-PHE demonstrated excellent thermal performance.

Fares et al. (2020) [34] explored how graphene nanofluids affected convective heat transfer using a vertically stacked STHE. The efficiency of the heat exchanger was improved by adding graphene nanofluid to its tube side and presented an in-depth analysis of how characteristics like intake temperature, flow rate, and nanofluid concentration affect thermal efficiency and heat transfer coefficients. Findings demonstrated that graphene/water nanofluids enhance the thermal efficiency of an STHE installed vertically.

Opoku et al. (2020) [35] investigated an innovative Staggered Tube Crossflow Exchanger (STC-HX) with multiple tube passages for heating processes during a cocoa production firm, drawing heated air from two industrial air compressor heat exchangers.

The findings demonstrated that with an upper limit of 158 kW for heat recovery, it could produce 40 litres of heated water per minute at an average temperature of 56 degrees Celsius, among the 163 kW that the two compressors and their blowers together used for power, approximately 54.5% can be attributed to the heat recovery rate. With an annual compressor runtime of 8,000 hours, this translated to energy savings of 710 MWh.

3. Experimental Setup

The experimental setup was designed to investigate the heat exchange efficiency of PHEs and STHEs within an industrial multi-stage compressor system. In this system, the first cylinder compresses air, raising both its pressure and temperature. To prevent excessive temperature rise and ensure optimal performance, the warm compressed air is routed through an intercooler before undergoing further compression.

3.1. Intercooler and Aftercooler Description

In the cooler, there are two fluids involved:

- The hot air: This is the air that has been compressed and is now warm.
- Fluid A: This is cooler water, usually coming from a cooling tower.

The hot air and Fluid A flow through separate channels within the intercooler. As the hot air moves through its channel, it transfers its heat to Fluid A, which flows through its channel. As a result, the hot air cools down, and the temperature of Fluid A rises.

3.2. Heat Exchanger Selection

In the industrial process, after the hot water (Fluid A) leaves the intercooler, it is often discarded, which wastes the energy it contains. Instead of letting this energy go to waste, we can use it more effectively by sending the hot water via a HE. The following types of heat exchangers were evaluated in this study:

1. Plate Heat Exchanger (PHE):
    - Material: Stainless steel plates for durability and corrosion resistance.
    - Design Features: Thin plates with corrugated surfaces to maximize heat transfer area.
2. Shell-and-Tube Heat Exchanger (STHE):
    - Material: Carbon steel tubes and shell for robust construction.
    - Design Features: Multiple tube passes to enhance HT efficiency.

In these heat exchangers:

- Fluid A (hot water) transfers its heat to another fluid (Fluid B), which is used for other purposes. This process recovers valuable heat and heats up Fluid B.
- By reusing the heat from Fluid A, industries can lower their energy expenses. This not only makes the process more economical but also reduces the environmental impact by lowering the overall energy consumption.

3.3. Instrumentation

A variety of instruments were employed to ensure accurate measurements during the experiments:

- Thermocouples: Installed at the inlet and outlet of both the hot air and cooling fluid to monitor temperature variations. The thermocouples were calibrated to ensure precise readings within a specified range.
- Flow Meters: Used to measure the flow rates of both fluids, ensuring that the operational conditions could be maintained according to design specifications.
- Pressure Gauges: Monitored the pressure drop across the heat exchangers to assess performance and ensure safety during operation.
- Data Logger: An integrated system that collects and stores data from all instruments for real-time analysis and post-experiment evaluation.

3.4. Measured Parameters

The following parameters were measured to assess the performance of both heat exchangers:

- Inlet and Outlet Temperatures: For both hot air and cooling fluid, determine the HT efficiency.
- Flow Rates: To calculate the actual heat transfer using the mass flow rate of the cooling fluid.
- Pressure Drops: Across the heat exchangers to evaluate resistance and operational efficiency.
- Heat Transfer Rates: Calculated using the formula $Q=m\times Cp\times\Delta T$

This detailed experimental setup enhances the credibility and reproducibility of the research findings, providing essential information on the types and models of heat exchangers used, the specifics of the instrumentation employed, and the exact parameters measured during the experiments

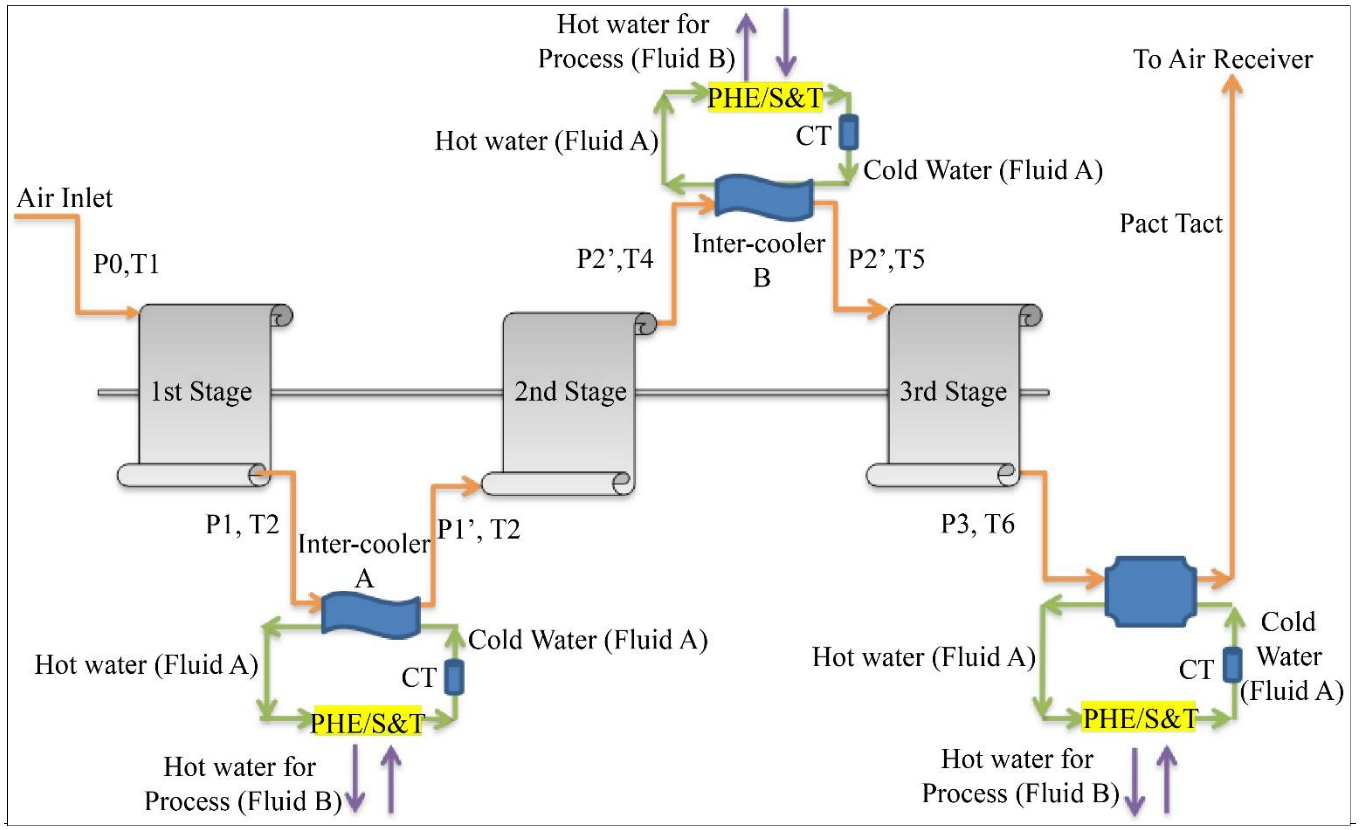

Fig. 4 Experimental configuration for waste heat utilization

4. Results and Discussion

The results of this experiment are shown below, along with their respective matrices.

4.1. Observations

In this section of the work, design specifications, pressure reading, temperature reading, and explanation of all these observations are discussed in detail.

- Design Specifications: To understand the performance and efficiency of the air compression unit, it is essential to consider the properties of thermodynamics and some metrics of the air being processed. The properties provided in the data allow for a comprehensive analysis:
- Pressure Reading: The pressure values at various stages of the compression process are essential to understanding the performance of the air compression system. Each stage is explained in detail:

4.1.1. Initial Pressure (P0)

In both design and actual conditions, the initial air pressure entering the compressor is 1 bar, which sets the baseline for subsequent stages of compression.

4.1.2. First Stage Compression (P1)

Design Pressure: After the first stage of compression, the design pressure is 5 bar.

Actual Pressure: The actual pressure obtained was 4 bar, which indicates that there may be problems with this stage or leakage in the system.

4.1.3. Second Stage Compression (P2)

Design Pressure: After the second stage of compression, the design pressure becomes 15 bars.

Actual Pressure: The actual pressure achieved was 14 bar, which shows that there might be little inefficiency associated with this process.

4.1.4. Third Stage Compression (P3)

Design Pressure: The design pressure after the third stage compression should be 38 bars.

Actual Pressure: The actual pressure obtained was 36 bar, which means there could be issues with this third stage compression process leading to significant differences between it and the goal determined during the planning phase.

- Temperature Reading: The provided data details the temperature changes of air through various stages of compression and intercooling in an industrial compressor system. Table 1 below summarizes the temperature readings at each stage, followed by a detailed explanation.

Table 1. Temperature data through compression stages

Temperature (K)	
T1	290
T2	391
T3	295
T4	379
T5	300
T6	396
T7	304

4.2. Calculation of Heat Gained by Fluid B for Industrial Purposes

As illustrated in Figure 4, the process begins with Cooling Tower (CT) cold water, designated as Fluid A, which is initially used to absorb heat from high-temperature air in both the intercooler and after-cooler stages. This results in a rise in the temperature of Fluid A. As shown in Table 2, the quantity of heat gained by fluid A. The heated Fluid A is subsequently directed into either PHE or STHE.

These heat exchangers are specifically designed to transfer heat from Fluid A to other fluid streams efficiently. As Fluid A flows through these exchangers, it releases its absorbed heat, which is then captured by the secondary fluid, resulting in the generation of hot water, referred to as Fluid B.

The hot water (Fluid B) that exits these heat exchangers is utilized in various industrial applications, leveraging its high thermal energy for multiple processes. Table 3 presents a comparative analysis of the heat gained by fluid B in PHE and STHE.

Table 2. Experimental evaluation of heat absorption by Fluid A

		1st Intercooler	2nd Intercooler	After-Cooler
Heat Loss by Air	kJ/min	1770.79	1457.21	1697.0
Actual Output Temperature (Fluid A)	°C	91.5	85.8	84.06
	K	364.5	358.8	357.06
Actual Heat gained by water (Fluid A)	kJ/min	1665.2	1363.30	1589.97

Table 3. Comparison of heat transfer performance in PHE and STHE

		1st PHE	2nd PHE	3rd PHE
Actual Heat gained by water (Fluid B)	kJ/min	1543.14	1264.37	1472.15
Outlet water Temperature (Fluid B)	K	357	350	349
		1st STHE	**2nd STHE**	**3rd STHE**
Actual Heat gained by water (Fluid B)	kJ/min	1144.32	935.63	1094.05
Outlet water Temperature (Fluid B)	k	340	335	333

Fluid B is widely used in industrial settings for Cleaning-In-Place (CIP), raw syrup preparation, process heating, and bottle warming. It facilitates effective cleaning without disassembly, assists in precise syrup production, and helps maintain consistent heating processes. Additionally, it preheats bottles to prevent thermal shock during filling.

4.3. Heat Exchanger Efficiency Calculation

PHE and STHE are two types of heat exchangers that provide waste heat recovery. It is conventional to compare the efficiency with which they transfer heat to evaluate which of these two types of HEs is superior. Calculate the efficiency of the HE by dividing the actual heat gained by fluid B by the maximum possible HT.

$$\text{Efficiency} = \frac{\text{Actual Heat gained by Fluid B}}{\text{Maximum Heat Transfer Potential of Fluid A}} \times 100\% \quad (1)$$

- For the Plate Heat Exchanger: The efficiency figures for Plate Heat Exchangers (PHEs) are based on the comparison between the actual heat gained by fluid B and the maximum HT potential of the hot fluid (Fluid A). This maximum HT potential is calculated based on the inlet and outlet temperatures, specific heat capacities, and flow rates of the fluids. The actual heat transfer is measured directly through an experimental setup by determining the heat gained by fluid B. The efficiency, expressed as a percentage, is calculated using the Equation (1).

The actual heat transfer and maximum potential for each PHE setup are as follows:

1. 1st Plate Heat Exchanger:
   - Actual heat gained by Fluid B: 1543.14 kJ/min
   - Maximum heat transfer potential of Fluid A: 1665.2 kJ/min
   - Efficiency: 92.67%
2. 2nd Plate Heat Exchanger:
   - Actual heat gained by Fluid B: 1264.37 kJ/min
   - Maximum heat transfer potential of Fluid A: 1363.30 kJ/min
   - Efficiency: 92.75%
3. 3rd Plate Heat Exchanger:
   - Actual heat gained by Fluid B: 1472.15 kJ/min
   - Maximum heat transfer potential of Fluid A: 1589.97 kJ/min
   - Efficiency: 92.58%

Three different plate heat exchangers were analyzed, yielding efficiencies of 92.67%, 92.75%, and 92.58%, respectively. These calculations show that the Plate Heat Exchangers operate at an efficiency between 92.58% and 92.75%, indicating minimal losses and high performance. Calculating the average efficiency from these values gives a collective performance indicator across the analyzed heat exchangers, which stands at 92.67%.

- For the Shell and Tube HE: The efficiency of STHEs is evaluated by comparing the actual heat gained by fluid B and the maximum heat transfer potential of the hot fluid (Fluid A). This evaluation is similar to that used for PHEs. The efficiency, expressed as a percentage, is calculated using the Equation (1).

The actual heat transfer and maximum potential for each STHEs setup are as follows:

1. 1st Shell and Tube HE:
   - Actual heat gained by Fluid B: 1144.32 kJ/min
   - Maximum heat transfer potential of Fluid A: 1665.2 kJ/min
   - Efficiency: 68.72%
2. 2nd Shell and Tube HE:
   - Actual heat gained by Fluid B: 935.63 kJ/min
   - Maximum heat transfer potential of Fluid A: 1363.30 kJ/min
   - Efficiency: 68.63%
3. 3rd Shell and Tube HE:
   - Actual heat gained by Fluid B: 1094.05 kJ/min
   - Maximum heat transfer potential of Fluid A: 1589.97 kJ/min
   - Efficiency: 68.81%

Three different shell and tube heat exchangers were analyzed, yielding efficiencies of 68.72%, 68.63%, and 68.81%, respectively. Calculating the average efficiency from these values gives a collective performance indicator across the analyzed heat exchangers, which stands at 68.72%.

5. Performance Comparison and Analysis of Plate and Shell and Tube HEs

In addition to efficiency, various key performance metrics are essential when comparing PHEs and STHEs. These metrics provide a comprehensive view of each heat exchanger type’s operational characteristics, suitability for specific applications, and overall cost-effectiveness.

To strengthen our analysis, we have expanded our discussion to include the following critical factors: maintenance requirements, cost analysis, and the impact of fouling on long-term efficiency. Each of these considerations plays a significant role in the decision-making process for selecting the most appropriate heat exchanger for a given application.

1. Maintenance Requirements:
   - PHEs are easier to maintain and clean because they can be disassembled, and individual plates can be accessed easily. This makes them suitable for applications prone to fouling or scaling, as regular maintenance is simpler.

- STHEs, on the other hand, are more challenging to clean due to their closed shell-and-tube structure. Cleaning typically requires specialized equipment, increasing maintenance downtime and cost.

2. Cost Analysis:
   - Initial Cost: PHEs tend to be more cost-effective for smaller to medium applications due to their compact design, which requires less material and space. However, their price can rise significantly for larger applications.
   - Operational Cost: STHEs may have higher initial costs, but they are built to handle more extreme conditions (higher pressures and temperatures), making them suitable for industrial applications where long-term durability is key.
   - Energy Efficiency: Given that PHEs have higher efficiencies (around 92.6%-92.8%), they are generally more energy-efficient than STHEs, which operate at around 68.6%-68.8%. Over time, these energy savings can result in lower operational costs for PHEs.
3. Impact of Fouling on Efficiency:
   - PHEs are more sensitive to fouling due to the narrow plate channels, but because they are easier to clean, their efficiency can be restored regularly. In systems where frequent maintenance is possible, PHEs will maintain high efficiency over time.
   - STHEs, while less prone to fouling due to their larger flow paths, are harder to clean. Over time, fouling can significantly degrade efficiency if regular cleaning is not performed, resulting in higher energy consumption and lower performance.

4. Trade-offs Between Efficiency, Cost, and Longevity: When selecting between PHEs and STHEs, several trade-offs need to be considered:
   - Efficiency: PHEs offer superior efficiency but may require more frequent maintenance in fouling-prone environments.
   - Cost: PHEs are generally more cost-effective for applications that do not demand extreme operating conditions. STHEs, while less efficient, may be more economical in high-pressure or high-temperature applications, where durability and longevity are crucial.
   - Longevity: STHEs are robust and can handle more demanding operating conditions, making them suitable for heavy industrial applications, but their efficiency can suffer from fouling if not properly maintained.

6. Conclusion and Future Work

Efficient heat recovery is vital for industrial beverage facilities to reduce operating costs and energy usage. PHEs and STHEs are the subject of this investigation because of their widespread use in industrial air compressors, particularly in beverage processing facilities. In this setup of multistage air compressors, after-coolers and intercoolers are used to assess and compare the heat recovery capabilities of PHEs and STHEs.

To capture operating data under different situations, a prototype setup is used, complete with installed instrumentation. Heat transfer efficiency and waste heat recovery potential are determined by analyzing the acquired data, which includes temperatures, pressures, and flow rates. The findings show that PHEs are better at heat transmission and smaller in size, whereas STHEs are better at withstanding greater pressures and have a longer lifespan.

Comparative analysis shows that PHEs exhibit a notably higher efficiency at 92.67%, compared to the STHEs, which have an efficiency of 68.72%. Engineers and plant managers can use this research to understand better how to maximize the performance of industrial air compressors, improve energy efficiency, and choose the best heat recovery solution for beverage manufacturing facilities.

Further research needs to be conducted to conduct a comprehensive cost-benefit analysis that takes into account the environmental impact and long-term energy savings in addition to the initial investment and maintenance expenses. Additionally, exploring hybrid systems that leverage the strengths of both heat exchanger types could yield optimal solutions for specific beverage plant requirements.

Nomenclature

Symbols

R	Gas Constant
c_p	Specific Heat at Constant Pressure
c_v	Specific Heat at Constant Volume
K	Ratio of Specific Heats
m	Mass of Air Delivered per Minute

Acronyms

PHE	plate heat exchangers
STHE	Shell and tube heat exchangers
HE	Heat Exchanger
HENs	Heat Exchanger Networks
HT	Heat Transfer
FAD	Free Air Delivery
ORC	Organic Rankine Cycle
CAES	Compressed Air Energy Storage
NTU	Number of Transfer Units
CHP	Combined Heat and Power

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