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Improvement of Air Compressor Cooling with Intercooler Fine Pruning

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Abstract

An intercooler serves as a heat exchanger between the several stages of the working compressor, assisting in the transmission of thermal energy between fluids of varying temperatures. This article is about the experimental analysis of the effectiveness of an intercooler. Multiple variables oversee the performance evaluation under different circumstances. Standard operational values are used to calculate performance evaluation metrics such as total heat transfer coefficient and others. Heat rejection of intercoolers has been enhanced from 61% to 65% by the variation of different fin lengths. Furthermore, the recently added intercooler's isothermal efficiency, which reached an astounding 56.5% significantly, outperformed the earlier unit. This serves to highlight how well the intercooler design was modified. Furthermore, the effectiveness of the Intercooler was assessed considering the circumstances during operation. The intercooler fin is primarily concerned with the performance of the air compressor. This work analyses the many characteristics of fin length, fin number, and fin diameter. When compared to the existing intercooler, this modified intercooler has a high performance.

Keywords: Air Compressor; Compressor efficiency; Fin Length; Heat enabling factor; Inter Cooler, Reciprocating

1. Introduction

A reciprocating compressor, also known as a positive-displacement air compressor, uses an electric motor, diesel engine, or gasoline engine as its prime mover, among other things, to transform power into potential energy and store it as compressed air. For delivering high-pressure fluid (air or gasses), a crankshaft powers a piston. The suction valve allows atmospheric air to enter the compression chamber, where a piston driven by a crankshaft reciprocates to compress the air. [1]-[4]. the single-acting reciprocating compressor, which compresses air in the cylinder on just one side of the piston, is the focus of this research. Fig. 1 displays the AutoCAD 3D model of the belt guard and arm-equipped single-acting reciprocating compressor used in this study. [5]-[7] the purpose of this study is to analyze the accomplishment of a single-acting reciprocating air compressor made of materials that are readily available locally using thermodynamic ideas. The mechanical and aerospace engineering laboratory will employ the reciprocating compressor to conduct hands-on demonstrations of topics related to fluid machinery, thermodynamics, and applied fluid mechanics. Additionally, workshops and other locations requiring pressured air—such as tire inflation; dusting, and spray painting—will employ the compressor. [8]-[14]

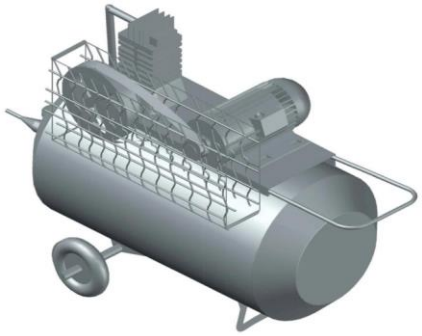

Figure 1: The single-acting reciprocating compressor's AutoCAD 3D model

An air compressor draws air from the atmosphere, compresses it, and then distributes the air under high pressure to a container for keeping it that can be piped to any location where compressed air is required. Rajput, in 2015. The compressor requires prime mover power since it undergoes maintenance throughout the compression process. The compressor is a device that uses the whole energy it receives from the main shaft to perform a number of operations, some of which are performed in opposition to friction and others of which are carried out inside the air. A certain amount of the electrical energy from the source is transferred into work by the prime mover that is utilized (Khurmi and Gupta, 2005). [15]-[17] The necessity for novel approaches to the design challenge at a reduced cost of machine manufacturing made

Thermodynamic principles are relevant to this research since thermodynamics is an understanding of the interactions among heat and other types of energy. This covers temperature and heat, as well as how it relates to the effort and energy of the air compressor. Compute the compressor's total efficiency with ease according to the principles of thermodynamics. The p-V diagram in Fig. 2 shows the thermodynamic process of a compressor with a reciprocating mechanism graphically. [18]-[20]

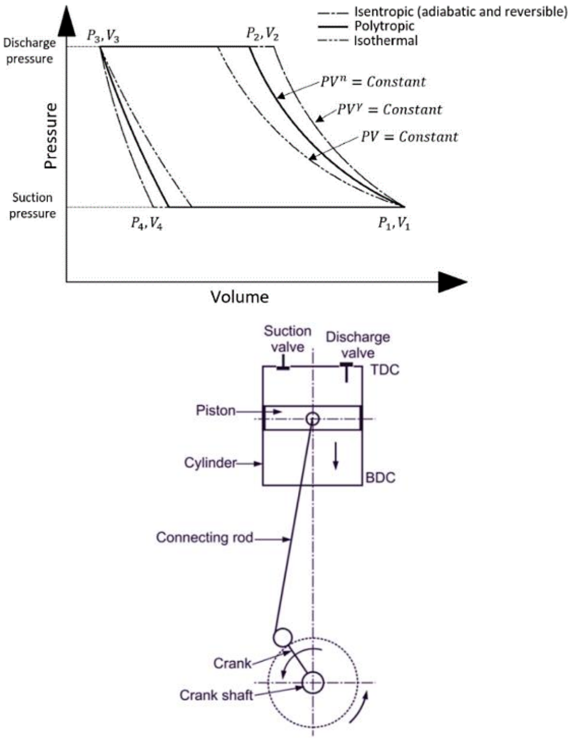

Figure 2: p-V & schematic diagram of the single-acting reciprocating compressor

Use the p-V diagram to examine the operation sequence of a single-acting reciprocating compressor. According to the order of events, route 4-1 is an intake/induction procedure. Once the induction valve opens, air is produced into the cylinder, expanding

Volume and mass while maintaining constant pressure and temperature at P_1, T_1. This occurs when the piston travels from the top dead center (TDC) to the bottom top center (BDC). The piston squeezes the air as it advances from BDC to TDC, closing the inlet valve. Along with a rise in temperature, this results in a decrease in air volume and an increase in pressure that rises to P_2 at point (2). Path 2–3 receives high-pressure air when the delivery valve at point (2) opens. The delivery technique is now complete. P_2 remains at the same temperature and pressure throughout the process. [21],[22]

A cooling system is an air-to-air or wind-to-liquid heat exchanger system that passes heat intake charge to an intermediate fluid that eventually refuses heat into the cold. A shell & tube style heat exchanger is especially suitable as an air compressor intercooler between the compression stages. The process for defining a configuration, heat transfer region & pre-is a feature of the heat exchanger system. [23]. Therefore, certain thermodynamic and fluid dynamic parameters are included throughout the design phase. Therefore, this state should accommodate and save time utilizing a machine. The rate a tube inserts within the tube is improved. There are a few drawbacks of software to remember. U Bend Exchanger is selected to reduce the scale and expense of the heat exchanger. Tubing systems are usually for a commonly used triangle design that requires more tubing to find. Shell diameter limitation is within a minimum of 0.3 m and a maximum of 0.4 m. It is also presumed there's little benefit in varying less than the allowable pressure decrease, and baffles are included in the graphs to represent the mean (one-fifth of the shell diameter) and average (within the same variable and its effect on certain variables). Results obtained are contrasted with the current configuration outcome and the shell diameter.

One crucial statistic for assessing the volumetric operation of positive displacement air compressors is volumetric efficiency. Due to leakage and valve dynamics, the actual volumetric efficiency numbers are frequently less than the optimum theoretical values. Compression efficiency, which is the ratio of the actual work required each cycle to the theoretical effort required, is another performance metric. These are some possible ways to describe the compression efficiency, depending on the chosen theoretical procedure [24]–[29].

Intercooler optimization involves maximizing the efficiency and effectiveness of intercoolers in various applications, such as reciprocating compressors, turbocharged engines, and refrigeration systems. Here are some key aspects and techniques for intercooler optimization:

- **Optimal Design:** Design intercoolers with appropriate dimensions, including length, width, and thickness, to maximize heat transfer surface area while considering space constraints. Optimize the internal flow path geometry to minimize pressure drop and enhance heat transfer.

- **Material Selection:** Choose materials with high thermal conductivity and corrosion resistance to maximize heat transfer efficiency and ensure long-term reliability. Consider lightweight materials to reduce the overall weight of the intercooler assembly.
- **Enhanced Heat Transfer:** Implement advanced heat transfer enhancement techniques such as tabulators, fins, and extended surface geometries to increase heat transfer coefficients. Explore the use of enhanced heat transfer fluids or phase change materials to improve cooling efficiency.
- **Flow Optimization:** Optimize the flow distribution within the intercooler to ensure uniform cooling across the entire heat transfer surface. Use computational fluid dynamics (CFD) simulations to analyze flow patterns and optimize the internal flow path design.
- **Pressure Drop Reduction:** Minimize pressure drop through the intercooler by optimizing the flow path geometry, reducing flow obstructions, and using smooth internal surfaces. Balance pressure drop considerations with heat transfer efficiency to achieve optimal performance.
- **Integration with System:** Integrate the intercooler seamlessly into the overall system design, considering factors such as inlet and outlet configurations, mounting options, and compatibility with other components. Ensure proper airflow or coolant flow management to prevent overheating and maintain optimal operating conditions.
- **Control and Monitoring:** Implement control strategies to optimize intercooler operation based on real-time operating conditions, such as adjusting coolant flow rate or airflow direction. Incorporate sensors and monitoring systems to track intercooler performance and detect potential issues early.
- **Multi-Objective Optimization:** Consider multiple objectives such as cooling efficiency, pressure drop, weight, and cost in the optimization process. Use multi-objective optimization techniques to find trade-offs and identify Pareto-optimal solutions that balance conflicting objectives.

1.2 Experimental Validation:

Validate the performance of optimized intercooler designs through experimental testing under representative operating conditions. Compare experimental results with simulation predictions to verify the accuracy of the optimization process.

1.2.1 Continuous Improvement: Implement a continuous improvement process to incorporate feedback from field testing, monitor performance over time, and identify opportunities for further optimization. Intercooler optimization requires a multidisciplinary approach combining engineering principles, computational analysis, and experimental validation to achieve optimal performance and efficiency in various applications.

Increasing the surface contact area can speed up the rate of heat transmission. The compression ratio and amount of work completed can both rise with increased heat transmission. In addition, Fig.3 shows the annular fin area variation. According to this theory, extending the fin's length increases the conduct surface area. Selecting the precise fin length and building the intercooler required a lot of trial and error. An intercooler with a changed fin length may dissipate heat over a longer distance. Although there are several ways to improve heat transmission, fin length or area plays a crucial role in extending the component's lifespan.

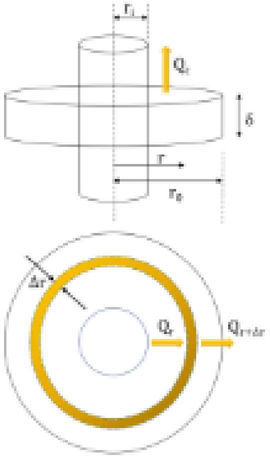

Figure 3 Schematic of an Annular Fin

1.3 Statement of research gap:

- Studies on the impact of fin length differences on the intercooler's overall performance may be scarce now. Gaining insight into this connection may help designers create designs that are more effective and optimize heat transmission while reducing energy loss and pressure drop.
- It is crucial to investigate the compromises between fin length, energy consumption, pressure drop, and heat transfer efficiency. This entails considering variables including the intercooler's flow characteristics, heat transfer coefficient, and Reynolds number.
- For the purpose of designing and operating multi-stage revolving air compressors used in a variety of industrial applications, it might be useful to comprehend the sequences of fin length variation among intercoolers.
- The development of multi-stage reciprocating compressors and intercooler designs might result in more economical and energy-efficient systems.

1.4 Novelty of the research:

- One new angle to consider is how different fin lengths affect the intercooler's heat exchange efficiency. This would entail adjusting the fins' length to improve heat transfer and reduce pressure drop, which would eventually raise the compressor's overall efficiency.

2. Literature Review

Venkatesan, J et al. [30] investigate the optimal thickness of rectangular fins in an array configuration to enhance natural convection heat transfer. The study aims to improve the thermal performance of heat sinks, which are crucial components in various engineering applications such as electronics cooling, HVAC systems, and thermal management of power systems. Bar-Cohen's work builds upon existing research in the field of heat transfer and thermal management. Natural convection, which occurs due to temperature differences between a surface and its surrounding fluid, is a significant mechanism for heat dissipation in many engineering systems. Fins are commonly employed to enhance heat transfer by increasing the surface area for convective cooling.

Wang T et al. [31] contribute to the understanding of heat transfer phenomena in reciprocating compressors and provide practical tools for engineers to predict and manage component temperatures, thereby improving the efficiency, reliability, and longevity of reciprocating compressor systems in various industrial applications. Reciprocating compressors are essential components in many industrial applications, including refrigeration, air conditioning, and gas compression systems. However, they are prone to temperature rise due to the compression process, friction, and other factors, which can affect their performance and reliability.

Wang Y et al. [32] the primary focus of the study is to develop a comprehensive compression model that can accurately simulate the compression process in open reciprocating compressors while considering the effects of cylinder wall cooling. The main objective of the research is to study the effectiveness of various cylinder wall-cooling strategies in mitigating temperature rise and improving the performance and reliability of reciprocating compressors. This work contributes to the advancement of compressor technology by providing valuable insights into the thermal behavior of reciprocating compressors and the effectiveness of cylinder wall cooling strategies in optimizing their performance.

Liu. G et al. [33] focused on the fin by implementing the design. It looks at how well fins with different augmentations—that is, without extensions—perform in terms of heat exchange. With these different sorts of fin expansions, one may anticipate obtaining between 5% and 13% more heat exchange when weighed against the same-shaped fin without these augmentations. We used Autodesk Simulation to analyze Fin's performance. This heat transfer experiment looks at surface temperature fluctuations in connection to heat loss rate.

Mou. B et al. [34] the enlarged area of a rectangular structure transferred heat more effectively than alternative fin forms. In comparison to fins with other sorts of layouts, the temperature at the free end of a fin with a rectangular extension is lower. Compared to alternative layouts, the fin efficiency with rectangular expansions is greater.

Pichler K et al [35] is to operate a four-stroke cycle with compressed air. The bike will attempt to reach a speed of 50 km/h, and the range of compressed air recharging is after running 70–80 km. Both Minicabs and City Cats will come with single-energy engines. These engines are designed for usage in cities, where the top speed limit is 50 km/h. According to Motor Development International, using compressed air technology, which emits no pollution, will soon make it illegal to pollute in these areas. Conversely, the dual energy engine, which is offered in all MDI cars, was designed with both urban and rural driving in mind.

Ramezanizadeh M et al. [36] describe the many reciprocating compressor failure types across a range of operating situations and provide advice on how to detect and address frequently recurring issues. A crucial first step in keeping operational equipment in good condition is to use condition-monitoring techniques. It assists in identifying the early and catastrophic failures that cause a sharp decline in production and system degradation. In a case, study a locomotive is a reciprocating air compressor.

Roskosch D et al. [37] highlight the related issues, diagnoses, and workable fixes backed by suitable maintenance plans for overhauling and repairing that result from parts failing frequently.

Ren T et al [38] examine how temperature affects a compressor's filter performance or the pressure drop over it and the filter's efficiency. The performance of the filter has been studied at different temperatures in the range of 10^0 to 35 ^{0}C using both experimental and CFD analysis.

Baakeem S et al. [39] on the design, manufacturing, and management of an intercooler for a three-phase digitalized reciprocating air- compressor test rig with an automated control drive unit. The purpose of the air-compressor test rig is to investigate the properties of compressed airflow through flow arrangement and a two-stage reciprocating air compressor. This self-contained, fully instrumented device has an air stabilization tank, air receivers, an intercooler, and a mild steel frame set on an elevated base. An AC Moor powers the compressor. The intercooler's job is to cool the system down to a suitable level, and it has temperature and pressure sensors at the intake and exit. The volumetric efficiency has risen to 100% with the addition of an intercooler. An air-stabilizing tank is required for this job in order to steady the airflow in order to determine the airflow rate. The test result showed that the compressor's actual free air delivery volume was 0.020 m3/sec and that it had completed 77 N-m of work. Additionally, it was discovered that, at a compressor's isothermal efficiency of 45%, the compressor's air delivery capacity is around 1.02 kg/minute. An intercooler with a specific design can reject heat with a capacity of 2.049 kilojoules/kg.

Kassai M et al. [40], compressed air utilization is rising swiftly these days. However, there are other factors that contribute to a compressor's low efficiency, including its location, height, pipeline length, intercooler performance, and even the environment, all of which raise the compressor's power consumption. The most effective way to lower the coolant is by intercooling. By adjusting the water's temperature and varying the ratios at which we mix the various coolant kinds into the water, we are expanding our investigation in this study. The selection of coolants is contingent upon several features, including but not limited to miscibility, boiling point, self-ignition temperature, and explosion range.

Park C et al. [41], air compressor intercooling is required to boost efficiency. A heat exchanger with a shell and tube design works especially well as an intercooler between a compressor's two compression stages. The process of defining a design, heat transfer area, pressure drops, and determining whether the assumed design fulfills all criteria is a feature of heat exchanger design. This study work aims to present a simple and effective method for air compressor intercooler design. This study presents heat exchanger modeling, which is centered on minimizing the heat transfer area. A flow chart outlining the process of designing is also included.

3. Methodology

The testing was performed in a two-stage reciprocating air compressor with two independent tubes, positioned in a V form with two separated cylinders specifications are listed in Table 2 Compressor manufactured by private company Coimbatore Compressor Engineering. Fig. 4 shows a two-stage air compressor so, that after the completion of the first stage the compressed air passes through an intercooler, it is a device used to reduce the heat from the first stage compressed air. This heat reduction method works by a different method and all electric and electronic components are used to measure the data from the setup. Increasing the fin length in an intercooler is one method to enhance its performance. Here is how increasing fin length can improve intercooler efficiency:

Figure:4 Photographic view of two-stage reciprocating compressor

3.1 Enhanced Heat Transfer Area: Longer fins increase the surface area available for heat transfer between the compressed air or fluid and the surrounding cooling medium (such as air or coolant). With more surface

(Model type ELT 600), can generate a maximum output pressure of about 13 kg / cm2 and 4.4 kg / cm2. The compressor was a dynamic duo assembled, driving the second stage directly from the first stage’s rear. The inlet of the compressor sucked the air from the atmosphere as the required amount by using the sensor. After the compression, compressed air is stored in the reservoir at the bottom of the compressor setup. A pressure transducer is mounted on the air compressor, and it indicates the pressure level in the tank area available, there's a greater opportunity for heat to dissipate from the compressed air or fluid, resulting in better cooling efficiency.

3.2 Improved Heat Transfer Coefficients: Longer fins may promote better airflow or coolant flow over the intercooler surface, increasing the heat transfer coefficients between the fluid and the intercooler material. This improvement in heat transfer coefficients enhances the overall heat transfer rate and reduces the temperature rise of the compressed fluid passing through the intercooler.

3.3 Reduced Thermal Resistance: Longer fins can reduce thermal resistance within the intercooler, allowing for more effective heat dissipation. Lower thermal resistance means that the intercooler can cool the compressed air or fluid more efficiently, resulting in lower outlet temperatures and improved performance.

3.4 Optimized Cooling Efficiency: By increasing fin length, you optimize the intercooler's ability to transfer heat from the compressed air or fluid to the surrounding cooling medium. This optimization leads to improved cooling efficiency and lower overall temperatures, which can enhance the performance and reliability of the entire system.

However, it is important to note that simply increasing fin length may also lead to higher pressure drop and increased airflow resistance across the intercooler. Therefore, it is essential to balance the benefits of increased heat transfer area with the potential drawbacks of a higher-pressure drop to achieve optimal intercooler performance for your specific application. Additionally, other factors such as fin density, thickness, and material properties are considered in conjunction with fin length to maximize intercooler performance.

3.5 Fin Density and Thickness: Increase fin density (number of fins per unit area) to maximize the surface area available for heat transfer. However, higher fin density may also increase pressure drop. Optimize fin thickness to balance between structural integrity and heat transfer efficiency. Thicker fins provide support that is more robust but may impede airflow or coolant flow.

3.6 Fin Shape and Profile: Experiment with different fin shapes (e.g., flat, corrugated, serrated) to enhance heat transfer characteristics. For example, corrugated fins can increase surface area and disrupt boundary layers, improving heat transfer. Consider using tapered fins, where the fin thickness varies along its length, to distribute airflow or coolant more evenly and reduce pressure drop.

3.7 Fin Spacing: Optimize fin spacing to balance between maximizing surface area and minimizing pressure drop. Closer fin spacing increases heat transfer area but may lead to higher pressure drop. Use computational fluid dynamics (CFD) simulations or experimental testing to determine the optimal fin spacing for your specific application.

3.8 Material Selection: Choose fin materials with high thermal conductivity to improve heat transfer efficiency. Aluminum alloys are commonly used due to their lightweight nature and good thermal properties. Consider coating the fins with heat-conductive materials or using composite materials to further enhance thermal conductivity and corrosion resistance.

3.9 Enhanced Surface Treatments: Apply surface treatments such as coatings or textures to the fins to promote better heat transfer. For example, thermal spray coatings or micro-grooved surfaces can increase heat transfer coefficients and reduce fouling.

3.10 Fin Alignment and Orientation: Optimize the orientation and alignment of the fins to ensure uniform airflow or coolant flow distribution across the intercooler surface. Consider using staggered or offset fin arrangements to minimize flow resistance and improve heat transfer effectiveness.

3.11 Multi-Stage Intercoolers: Explore multi-stage intercooler configurations with different fin characteristics in each stage to maximize cooling efficiency. Use computational modeling or experimental testing to optimize the design of each stage for the best overall performance.

3.12 Integrated Heat Exchanger Design: Integrate the intercooler fins with the overall heat exchanger design to ensure efficient heat transfer and minimal thermal losses. Consider the interaction between fins and other components (such as tubes or headers) to optimize overall system performance.

By carefully optimizing the characteristics of the fins in an intercooler, you can significantly enhance its heat transfer efficiency, reduce pressure drop, and improve overall performance in various applications. Experimentation, simulation, and iterative design refinement are essential steps in achieving the optimal fin design for your specific intercooler application.

The different sets of readings are taken in various conditions of the compressor. Table 1 listed the parameters changed compared with the existing compressor rig to the newly adapted one. Table 2 shows the two-stage reciprocating air compressor specification

Fig. 5 shows the investigation of the annular fin characteristic of the intercooler revealing that there are 16 fins and 152 mm of conventional length. The heat dissipation level of this fin intercooler might vary. The area variation notion states that there is a high heat dissipation level. Fig. 6 shows, as a result, there are 21 fins and 159mm in length variations. Both the length and quantity of fins grew with the increment. Therefore, adding a fin and enlarging the cylinder's diameter makes it easier to find.

Table 1. Parameter variation

Conventional intercooler	In mm	Modified intercooler	In mm
Fins diameter	73	Fins diameter	86
Length	152	Length	159
Number of fins	16	Number of fins	21

Table 2. Two-stage reciprocating air compressor specification

S.No	Compressor type	Two stages air cooled reciprocating compressor
1	Number of cylinders	2
2	High-pressure cylinder diameter	0.06 m
3	High-pressure cylinder stroke	0.085 m
4	Low-pressure cylinder diameter	0.1 m
5	Low-pressure cylinder stroke	0.085 m
6	Gas constant	0.287 kJ/kg
7	Air density	1.17 kg/m3
8	Water density	1000 kg/m3
9	Motor efficiency	0.60%

Figure:5 Conventional intercooler

Figure:6. Modified intercooler

4. Calculation

Consider the working fluid to be a perfect gas, and we can use the equation of state to determine P-V-T. Calculating the working fluid's pressure (P), volume (V), and temperature (T) requires making these assumptions.

$$\mathrm{P} \times \mathrm{v} = m \times R \times T \qquad (1)$$

P = Pressure in (N/m²); K = Gas Constant in (J/mol·K); m = Molar Mass in (g/mol); V = Volume in (m^3); T = Temperature (K) R = Molar Ratio.

The cylinder's clearance is disregarded, the compression process is polytrophic, and the polytrophic index (n), as determined by the law of compression as presented in the equation, is taken to be 1.35.

$$PV\,n = C \text{ or } P1Vn\,1 = p2Vn2 \qquad (2)$$

Temperature delivered upon compression (T2) the following formula may be used to get the temperature delivered at the conclusion of the compression:

The real efficiency in volume the ratio of displacement volume (m3/min) to free air delivery (FAD) indicates the real volumetric efficiency.

For a single-acting compressor

$$Vd = (\frac{\pi}{4}) \times D2 \times L \times N \qquad (3)$$

$$F.A.D = (\frac{m\times R\times T1}{P1}) \qquad (4)$$

Hence, Volumetric efficiency

$$nvol = (\frac{F.A.D}{Vd}) \qquad (5)$$

Indicated work (I.W)

The indicated work of compression is given as:

$$W = \frac{n}{(N-1))\times m\times R(T2-T1)}\ in\ (kJ/min) \qquad (6)$$

Indicated power (I.P)

The indicated power of the compressor is given as:

$$I.P = \frac{(Indicated\ Work)}{60} \qquad (7)$$

Work done by a reciprocating compressor.

A compressor's job is to take in enough fluid and boost its pressure. With respect to a single-acting reciprocating compressor in the absence of a clearing volume, we have that.

$$W = (\frac{n}{(n-1))\times m\times R\times T1((\frac{P2}{P1})^{\wedge(\frac{n}{(n-1)})-1)}}) \qquad (8)$$

Alternatively, we can also use.

$$W = (\frac{n}{(n-1))\times P1V1((\frac{P2}{P1})^{(n/(n-1))-1)}}) \qquad (9)$$

Where: m is the mass per minute and given by:

$$m = \left(\frac{P1V1}{RT1}\right) \qquad (10)$$

Where P2, V2, and T2 represent the pressure, volume, and temperature of the fluid after compression, and P1, V1, and T1 represent the pressure, volume, and temperature of the fluid before compression.

Heat is transferred during compression.

Heat transfer is given by.

$$Q = W + \nabla U \qquad (11)$$

$$Q = [\frac{(P1V1-P2V2)}{n-1}] - Cv \times (T2 - T1) \qquad (12)$$

$$Q = [R \times \frac{(T1-T2)}{n-1}] + Cv \times (T2 - T1) \qquad (13)$$

$$Q = (T2 - T1) \times [\,Cv - (\frac{R}{n-1})] \qquad (14)$$

Mechanical Efficiency The mechanical efficiency (η_{mech}.) given by.

$$nmech = \frac{indicated\ power}{shaft\ power} * 100 \qquad (15)$$

Isothermal Efficiency (η_{iso}.) The isothermal efficiency is given by first analyzing the isothermal power, which is given as

$$Isothermal\ power = mRT1\ ln(\frac{P2}{P1}) \qquad (16)$$

Therefore

$$niso = \frac{isothermal\ power}{shaft\ power} * 100 \qquad (17)$$

Overall efficiency isothermal efficiency ($\eta_{overall\ iso}$)

Overall, isothermal efficiency is given by:

$$overall\ \ s = \frac{isothermal\ power}{shaft\ power} * 100 \qquad (18)$$

Swept volume is defined as the Volume displaced by each piston moving from the bottom dead center to the top dead center

$$\text{Swept volume (Vs)} = \frac{\pi \text{ x } D2\text{x } L\text{x } N}{4 \text{ x } 60} \qquad (19)$$

Where D = Bore diameter, L = Stroke length, N = Number of revolutions

Volumetric efficiency is the ratio between the actual volumes and to swept volume of the compressor.

$$(\eta_v) = \frac{\text{Actual volume}}{\text{swept volume}} \qquad (20)$$

Isothermal Work. When no heat flows into or out of the gas because its container is at the same temperature, and then there is no work done.

$$Isothermal\ Work\ done = P1 \times Q\ actual \times ln\,\frac{P3}{P1} \qquad (21)$$

Where P_1 = Inlet pressure in (N/m^2), P_3 = Delivery pressure in (N/m^2), Shaft power = Motor power *Motor efficiency (η_m)

$$Re_d = \frac{4 \text{ x } m}{\pi \text{ x } D \text{ x } \mu} \qquad (22)$$

Re_d = Reynolds number, m = Mass flow rate. μ = Absolute viscosity

$$Nu = 0.023 \text{ x } Re_d^n \text{ x } Pr^n \text{ (or)} \qquad (23)$$

$$Nu = \frac{h \text{ x } D}{k}$$

Nu = Nusselt number, Pr = Prandtl number

$$Q = h \times A \times \Delta T \qquad (24)$$

h = Heat transfer coefficient in (W/m²·K)

A = Fins Area in (m^2)

ΔT = Temperature difference in K

5. Result and Discussion

The reports of the two-stage reciprocating compressor experimental set-up were discussed. Firstly, the working conditions in the background are investigated before the compressor begins. The stable temperature is dependent on the performance of the absorption chiller and on the air, temperature placed in the intercooler from the first stages t1 t2, and t4. Increase rapidly with time. These indicate the existing intercooler performance compressor rig. The inlet temperature (T_2) of the intercooler is always higher than the outlet temperature (T_3) of the intercooler. Those parameters are measured at normal conditions.

5.1 Graphs

All the graphs were drawn between delivery pressure to volumetric efficiency, isothermal efficiency, and amount of heat rejection. Fig. 7 shows that overall, achieving high volumetric efficiency in a reciprocating air compressor under normal conditions requires careful consideration of these factors and optimization of the compressor design, operating parameters, and maintenance practices.

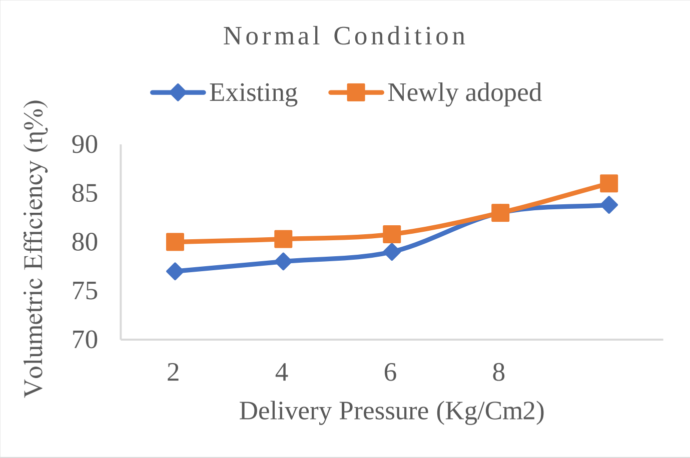

Figure: 7 Volumetric efficiency of normal condition

The modified intercooler has increased the volumetric efficiency by about 84% but the conventional intercoolers have 83% volumetric efficiency.

Fig.8 shows that altitude variation can significantly affect the volumetric efficiency of a reciprocating air compressor by reducing air density and mass flow rate. Understanding and managing these effects are essential for optimizing compressor performance at different altitudes and ensuring reliable operation across varying operating conditions. In conditions when altitude varies, the newly modified intercooler has a better volumetric efficiency (85%). The earlier type's volumetric efficiency is lower, at 80.5%.

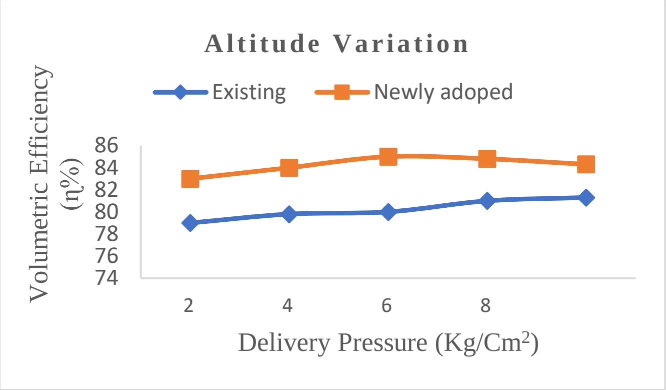

Figure:8 Volumetric efficiency of altitude variation

Fig. 9 shows the volumetric efficiency of a reciprocating air compressor refers to its ability to deliver a volume of compressed air compared to the theoretical maximum volume it could deliver under ideal conditions. Higher motor efficiency in a reciprocating air compressor can positively affect its volumetric efficiency by improving energy transfer, reducing heat generation, enabling higher compression ratios, optimizing control systems, and minimizing air leakage. These improvements result in more effective compression of air and a higher delivery of compressed air compared to the theoretical maximum, leading to enhanced overall compressor performance.

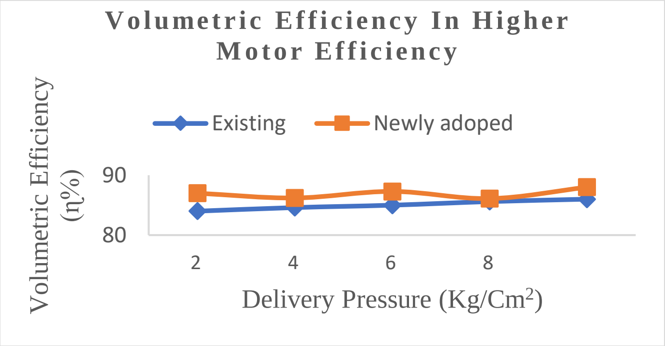

Figure: 9 Volumetric efficiency of higher motor efficiency

When comparing the new kind to the old, the new one's isothermal efficiency was greater. Fig. 10 shows the isothermal efficiency of a reciprocating air compressor under normal conditions refers to its efficiency in compressing air while minimizing heat generation and maintaining a relatively constant temperature during the compression process. While achieving true isothermal compression is not possible in practice, isothermal efficiency provides a measure of how closely the compression process approaches ideal isothermal conditions. The isothermal efficiency of the new modified intercooler compared with conventional intercooler modified intercooler got higher efficiency (56.5%).

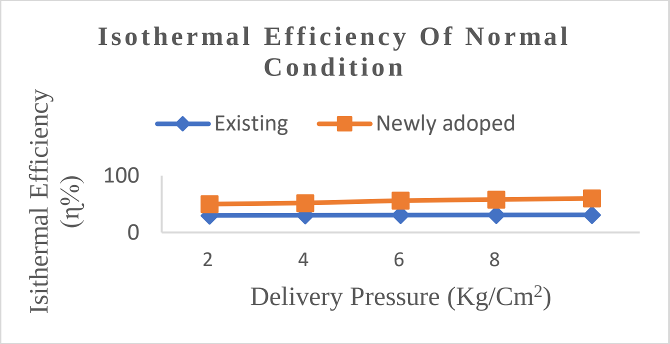

Figure: 10 Isothermal efficiency of normal condition

Fig.11 shows that altitude variation can affect the isothermal efficiency of a reciprocating air compressor by affecting air density, temperature, compression ratio, and cooling effectiveness. Maintaining optimal operating conditions, adjusting compression parameters as needed, and implementing effective cooling strategies are essential for maximizing isothermal efficiency across different altitudes.

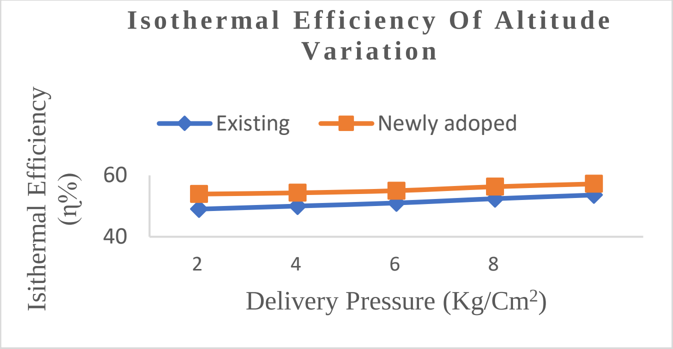

Figure:11 Isothermal efficiency of altitude variation

Fig. 12 shows that higher motor efficiency implies less wasted energy and lower heat generation during compressor operation. This reduction in heat generation contributes to a closer approximation to isothermal compression conditions, as less energy is lost as heat to the surroundings. With higher motor efficiency, more of the electrical energy input is converted into useful mechanical work for compressing the air. This increased efficiency means that a larger proportion of the energy input contributes to the compression process, enhancing energy transfer efficiency and approaching closer to isothermal conditions. Higher motor efficiency can positively influence the isothermal efficiency of a reciprocating air compressor by reducing heat generation, improving energy transfer efficiency, and potentially allowing for higher compression ratios. While achieving true isothermal compression may not be feasible, improvements in motor efficiency contribute to more efficient and reliable compressor operation. Heat rejection of the new intercooler compared with conventional; the modified intercooler has increased heat transfer rate cause of higher diameter.

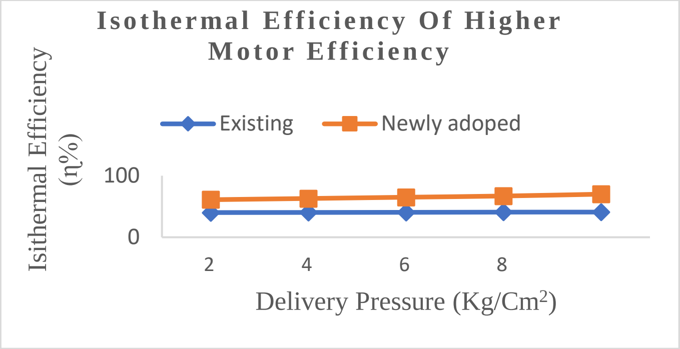

Figure: 12 Isothermal efficiency of higher motor efficiency

Fig. 13 shows that in a reciprocating air compressor operating under normal conditions, heat rejection is a critical aspect of maintaining optimal performance and preventing overheating. Let us look at how heat rejection works and how important it is in the context of a reciprocating air compressor.

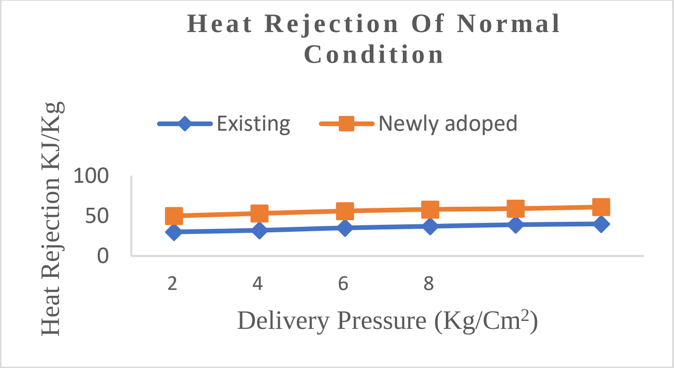

Figure:13 Heat rejection of a normal condition

Efficient heat rejection is essential for maintaining the compressor's operating temperature within safe limits. If heat is not effectively dissipated from the compressor, it can lead to overheating, reduced efficiency, and potential damage to the compressor components. Heat rejection requirements may vary depending on factors such as ambient temperature, compressor load, and operating environment. It is essential to monitor operating conditions and adjust heat rejection mechanisms as needed to maintain optimal performance. Heat rejection is a critical aspect of reciprocating air compressor operation under normal conditions. Effective heat rejection mechanisms, including cooling systems, airflow management, and component design, are essential for preventing overheating and ensuring reliable compressor performance. Heat rejection was higher (61%) in newly adapted intercoolers in higher altitudes heat rejection of the older type had lesser efficiency 57 %.

Fig. 14 shows the variation in altitude can significantly affect the operation of a reciprocating air compressor, including its heat rejection characteristics. Here is how altitude variation affects heat rejection in a reciprocating air compressor.

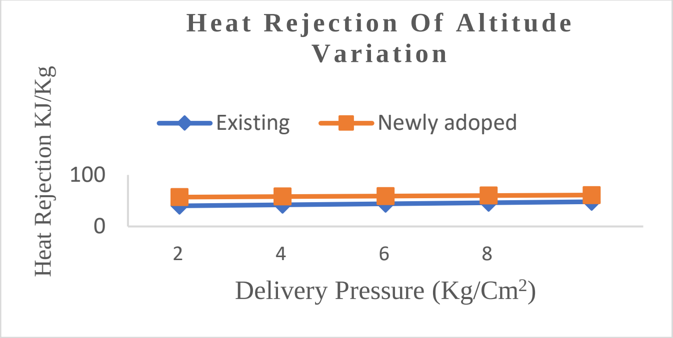

Figure: 14 Heat rejection of altitude variation

The compression process in a reciprocating air compressor generates heat due to mechanical friction and adiabatic heating of the compressed air. At higher altitudes, where the air is less dense, the compressor may experience increased mechanical friction as it works harder to compress the thinner air. This can result in higher heat generation within the compressor. Elevated operating temperatures can negatively affect the performance and reliability of a reciprocating air compressor. At higher altitudes, where ambient temperatures may also be lower, the compressor may be more susceptible to temperature fluctuations and thermal stress. Effective heat rejection mechanisms are essential to manage operating temperatures and ensure reliable compressor operation. Altitude variation can affect heat rejection in a reciprocating air compressor by affecting air density, compressor performance, and cooling system effectiveness. Proper system design, adjustment, and maintenance are essential to manage heat rejection and ensure reliable compressor operation at higher altitudes.

When the delivery pressure of the compressor increases, the compression process becomes more demanding, resulting in greater temperatures within the compressor. Fig. 15 shows the results of increased heat generation. With higher delivery pressures, the compressor requires more extensive heat rejection mechanisms to dissipate the additional heat generated during compression. This may involve more robust cooling systems, such as air or water cooling, to maintain safe operating temperatures.

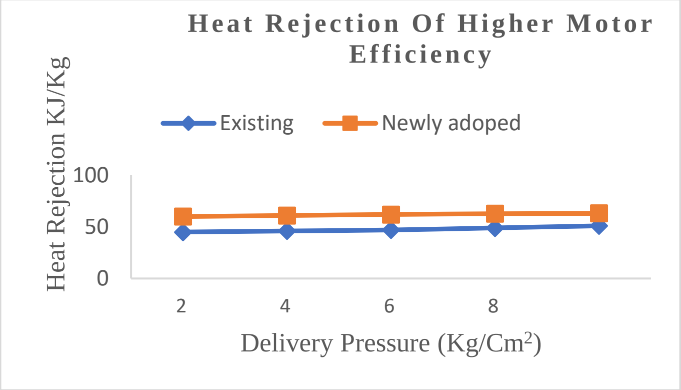

Figure:15 Heat rejection of higher motor efficiency

Higher delivery pressures can also affect the efficiency of the compressor. While increasing pressure typically improves the compressor's performance in terms of output pressure and flow rate, it may also lead to increased energy consumption and operating costs due to higher heat generation and the need for more extensive cooling. When designing or operating a reciprocating air compressor system, it is essential to consider the relationship between delivery pressure, heat generation, and heat rejection. While higher motor efficiency can help reduce heat generation within the motor itself, variations in delivery pressure can still influence the overall heat rejection requirements of a reciprocating air compressor system. Effective heat rejection management involves optimizing both motor efficiency and heat dissipation mechanisms to ensure efficient and reliable operation across different operating conditions Heat rejection is higher (65%) in newly adapted Intercooler with higher motor efficiency heat rejection of the older type has lesser efficiency 53.5 %

6. Conclusion

Numerous significant discoveries have been made when improving the reciprocating air compressor with different intercooler fin widths. Initially, there has been a noticeable increase in overall performance as the newly redesigned intercooler, with its remarkable 84% volumetric efficiency, surpasses the earlier 83% volumetric efficiency model. Furthermore, the recently added intercooler has isothermal efficiency—, which reached an astounding 56.5% significantly, outperformed the earlier unit. This serves to highlight how well the intercooler design was modified. Notable findings were obtained while comparing the heat rejection of the new and traditional intercoolers. Due to the larger fin diameter of the upgraded intercooler, it demonstrated a better rate of heat transfer. As a result, there was a noticeable improvement in heat rejection, especially at higher altitudes. The newly modified intercooler outperformed the older model in terms of efficiency; heat rejection rates were as high as 61% and 65%, respectively, demonstrating the advantages of the improvements made to improve motor efficiency. To sum up, the experimentation with different intercooler fin diameters to optimize the reciprocating air compressor has shown to be successful. The enhanced performance and efficiency in compressor operations are made possible by the improvements in heat rejection, volumetric efficiency, and isothermal efficiency, which highlight the efficacy of the modified intercooler design.

7. Challenges and Opportunities for Future Studies

Even though positive displacement compressors have been the subject of several research projects, more effort is still required to understand a few important concerns. For instance, because most studies are carried out under certain working conditions, the compressor performance and operating characteristics provided in the literature might not be adequate to direct the selection process. To give a deeper understanding of positive displacement compressors, particularly the latest technology, further experimental research is required. It's also important to note that compressor performance maps are helpful resources that help choose the right machine based on the needs of the application. Nevertheless, there was no discussion of performance mapping for positive displacement compressors in the available literature.

. More significantly, the mapping approach's current standard only covers a small number of applications. Consequently, it advised that more study be on this subject.

Lubricating oil application improves machine performance in a number of ways. However, the presence of the fluid-oil combination and the severe conditions (high temperature and pressure) at the compressor discharge have a substantial impact on the oil's viscosity, which deteriorates the lubricating performance. Thus, more research on lubricating systems is necessary. Applying materials with extreme condition functionality, such as nanoparticle additives, is one way to solve this kind of problem. This may need multidisciplinary work between material and mechanical engineers.

Even though there has been considerable growth in research interest in two-phase flow, the discontinuity of the flow's characteristics remains a difficult problem, necessitating the creation of two-phase flow modeling. Compressor models based on CFD have become more accessible with the use of sophisticated simulation resources, providing further insights into complex processes like heat transport. But Multi-physics modeling issues are still hard to solve, and finding a balance between computing cost and model fidelity is still a challenging task. The use of machine learning techniques in the modeling and optimization of positive displacement compressors has grown in popularity. The main advantage of machine learning techniques is that they do not always require a mathematical connection between parameters. Thus, it makes sense that if machine-learning techniques are extensively used, modeling and optimization efforts in the future will likely be more successful.

Thermo-economic and energy analysis are useful tools for determining irreversibility and related system costs. Scholars, particularly those in the sector, ought to focus more on this approach as it might yield valuable data on possible enhancements and financial savings for the compressor and its system. One possible way to reuse the thermal energy generated during fluid compression is waste heat recovery. This method's improved energy use because of waste heat recovery is one obvious benefit. Nevertheless, the present difficulty with this approach is the expense and technology required to recover low-grade waste heat, which deters small-scale applications like home refrigerators from using it. Thus, it would be advantageous for future studies to address this issue in order to improve compressor systems' sustainability and energy efficiency.

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Conflicts of Interest:

The authors disclose no conflicts of interest.

Author Contribution Statement:

Kirubadurai B: Conceptualization, Methodology, Data curation, Writing – original draft. Dr Jaganraj R: Writing – review & editing. Dr. Jegadeeswari. G: Supervision, Project administration. Jayabalan. C: Resources and Formal Analysis.

Notations

N-Number of revolutions, V_η-Volumetric Efficiency, **P_1**- Inlet pressure, **P_3**- Delivery pressure, **η_m**-Motor efficiency, **Re_d**- Reynolds number, **m-** Mass flow rate, **μ-** Absolute viscosity, **Nu-** Nusselt number, **Pr-** Prandtl number, **h-** Heat transfer coefficient, **A-** Fins Area, **ΔT** -Temperature difference, **V_η**- Volumetric Efficiency, **Vs-** Swept volume, **D-** Bore diameter, **L**-Stroke length, **TEMA**-Tubular Exchanger Manufacturers Association, **T**-temperature, **P**-pressure

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