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OPTIMAL DESIGN AND ANALYSIS OF RECIPROCATING COMPRESSOR PISTON

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ABSTRACT

Reciprocating compressors are widely used in industrial applications because they can deliver gases at high pressure with reliable performance. The piston is one of the most important components of a reciprocating compressor, as it is subjected to high gas pressure, thermal stresses, friction, and cyclic loading during operation. Due to these conditions, piston failures mainly occur because of fatigue, deformation, wear, and excessive thermal stress. Therefore, proper design and analysis of the piston are essential to improve compressor efficiency, durability, and operational life. This project presents the optimal design and analysis of a reciprocating compressor piston using aluminum alloy material. Aluminum alloys are preferred because of their low weight, high thermal conductivity, and good strength-to-weight ratio. The piston dimensions are calculated using standard design equations by considering parameters such as gas pressure, permissible tensile stress, piston head thickness, ring dimensions, and barrel thickness. A three-dimensional piston model is developed using CATIA software, and Finite Element Analysis (FEA) is carried out in ANSYS software to evaluate stress distribution, deformation, and thermal behavior. The analysis helps identify critical stress regions and improves the piston design by reducing weight while maintaining sufficient strength and thermal resistance. The optimized piston design provides better fatigue life, reduced vibration, improved heat dissipation, and enhanced compressor performance. The study concludes that the use of Finite Element Analysis significantly improves piston reliability, reduces design time, and minimizes manufacturing and maintenance costs in reciprocating compressor applications.

KEYWORDS : Reciprocating Compressor, Piston Design, Finite Element Analysis, ANSYS, Aluminum Alloy, Stress Analysis, Thermal Analysis, Fatigue Failure, Optimization, CATIA.

I.INTRODUCTION

Reciprocating compressors are widely used in manufacturing industries for supplying gases at high pressure with reliable performance and efficiency [1]. The piston is the most important component in the compressor because it performs the compression process through continuous reciprocating motion inside the cylinder [2]. During operation, the piston experiences high thermal stress, gas pressure, friction, and cyclic loading conditions that may lead to deformation, wear, fatigue failure, and reduction in compressor performance [3][4]. Therefore, proper piston design and analysis are necessary to improve durability, strength, and operational life [5]. This project focuses on the optimal design and analysis of an aluminum reciprocating compressor piston using design calculations and Finite Element Analysis techniques [6]. Aluminum alloy is selected because of its lightweight nature, good thermal conductivity, and high strength to weight ratio [7]. The project aims to reduce piston weight, improve heat dissipation, minimize stress concentration, and enhance overall compressor efficiency and reliability under industrial operating conditions [8].

Finite Element Analysis plays an important role in evaluating the structural and thermal behavior of reciprocating compressor pistons under different operating conditions [9]. In this project, the piston dimensions are calculated using standard design formulas based on gas pressure, tensile stress, piston head thickness, ring dimensions, and barrel thickness [10]. After completing the design calculations, a three dimensional piston model is created using CATIA software and analyzed using ANSYS software [11]. The analysis helps determine deformation, stress distribution, thermal effects, and critical regions subjected to maximum loading conditions [12]. Finite Element Analysis provides accurate results compared with conventional analytical methods because it studies the piston using small finite elements and numerical calculations [13]. The obtained results are useful for optimizing piston geometry and material selection [14]. The optimized design improves fatigue strength, reduces stress concentration, decreases vibration, enhances thermal stability, and increases the overall efficiency and service life of the reciprocating compressor system during continuous operation [15].

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The optimal design of compressor pistons is essential for reducing manufacturing cost, improving machine reliability, and increasing industrial productivity [16]. Different piston materials and manufacturing methods are studied in this project to understand their effect on performance, strength, and thermal resistance [17]. Aluminum silicon alloys are widely preferred because they provide low weight, good heat transfer capability, and better operating efficiency compared with traditional materials [18]. Various manufacturing methods such as sand casting, gravity die casting, squeeze casting, forging, and powder metallurgy are considered for piston production [19]. The project also studies optimization techniques used to reduce piston weight while maintaining adequate strength and safety [20]. Proper optimization minimizes material usage, lowers mechanical losses, and improves compressor performance [21]. The final design obtained through analysis provides better durability, lower maintenance requirements, reduced operational noise, and improved resistance against fatigue and thermal stresses [22]. Therefore, this project demonstrates the importance of design and analysis techniques in piston development [23].

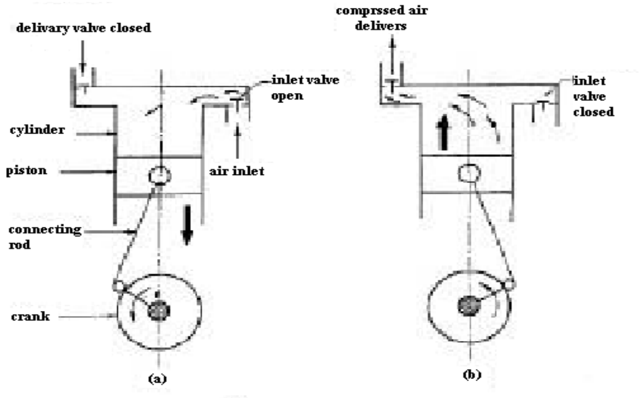

Fig1: Working of reciprocating engine

The above figure explains the working principle of a reciprocating compressor engine during suction and compression strokes. In figure (a), the piston moves downward inside the cylinder due to the rotation of the crank and connecting rod mechanism. As the piston moves down, a low pressure region is created inside the cylinder, causing the inlet valve to open and allowing atmospheric air to enter through the air inlet. During this stage, the delivery valve remains closed. In figure (b), the piston moves upward because of the crank rotation, reducing the volume inside the cylinder and compressing the trapped air. As the pressure of air increases above the delivery pressure, the inlet valve closes and the delivery valve opens automatically. The compressed air is then discharged through the outlet passage. This continuous reciprocating motion of the piston converts mechanical energy into pressure energy and enables the compressor to supply high pressure compressed air for industrial applications efficiently and continuously.

II SURVEY OF RESEARCH

1. R. Smith and J. Anderson conducted a study on the structural analysis of reciprocating compressor pistons using Finite Element Analysis techniques. The main objective of their research was to identify stress concentration regions developed in aluminum alloy pistons under high pressure loading conditions. The researchers designed a three dimensional piston model and analyzed it using ANSYS software. The study revealed that maximum stresses were generated near the piston crown and piston pin boss areas due to cyclic gas pressure and thermal loading. They also compared aluminum alloy pistons with cast iron pistons and concluded that aluminum alloys provided better heat dissipation and reduced overall piston weight. The study emphasized the importance of proper material selection and optimization techniques for improving piston durability and fatigue life. Their work proved that Finite Element Analysis provides accurate prediction of stress distribution and helps in reducing piston failure during long term compressor operation [1][2].

2. A research study by M. Kumar and S. Prakash focused on thermal analysis and optimization of reciprocating compressor pistons using aluminum silicon alloys. The authors investigated the influence of temperature distribution on piston deformation and thermal stress development. CATIA software was used to create the piston model, while ANSYS software was used for thermal and structural analysis. The study identified that excessive temperature rise near the piston head affects piston efficiency and increases fatigue failure chances. Different cooling and material optimization methods were examined to improve thermal resistance. The researchers concluded that aluminum silicon alloys provide better thermal conductivity and lower thermal expansion compared with conventional piston materials. The optimized piston design achieved reduced deformation and improved operational stability under high pressure conditions. Their research highlighted the importance of

thermal analysis in enhancing compressor performance, reducing maintenance cost, and increasing piston service life in industrial applications [3][4].

3. P. Johnson and K. Ravi presented a research work on fatigue failure analysis of reciprocating compressor pistons subjected to cyclic loading conditions. The study mainly focused on identifying the causes of piston crack formation and stress concentration during continuous compressor operation. The researchers observed that repeated mechanical loading and thermal expansion generated fatigue stresses near piston ring grooves and piston skirt regions. Finite Element Analysis techniques were applied to evaluate stress behavior and deformation characteristics. Different piston geometries were analyzed to reduce stress concentration and improve fatigue resistance. The study concluded that optimized piston dimensions and proper ring groove design significantly reduced fatigue failure. The authors also suggested that lightweight aluminum alloys improve compressor efficiency by reducing inertia forces and vibration levels. Their research demonstrated that proper piston design optimization enhances structural strength, increases fatigue life, and improves the reliability of reciprocating compressor systems operating under severe industrial conditions [5][6].

4. A study conducted by S. Lee and R. Kumar analyzed the effect of manufacturing methods on piston strength and performance in reciprocating compressors. The research compared different manufacturing processes such as sand casting, gravity die casting, squeeze casting, and forging techniques. The authors found that squeeze casting and forging methods produced pistons with finer grain structure, improved fatigue strength, and better thermal resistance compared with conventional casting methods. The study also highlighted that manufacturing defects such as porosity and shrinkage reduce piston durability and lead to premature failure. Finite Element Analysis was used to compare stress distribution in pistons manufactured using different processes. The researchers concluded that optimized manufacturing methods improve mechanical properties and increase piston life under high pressure operating conditions. Their work emphasized the importance of selecting suitable production techniques for achieving better piston quality, reduced maintenance requirements, and enhanced compressor efficiency [7][8].

5. T. Wilson and A. Sharma carried out research on optimization techniques for reducing piston weight while maintaining sufficient mechanical strength and thermal stability. The objective of the study was to improve compressor efficiency and minimize energy losses by reducing reciprocating mass. The researchers applied optimization algorithms along with Finite Element Analysis to analyze different piston geometries and material combinations. Aluminum silicon alloys were selected because of their lightweight properties and excellent heat transfer capability. The optimized piston design showed reduced stress concentration, lower deformation, and improved fatigue resistance compared with conventional piston models. The study also demonstrated that reducing piston weight decreases vibration, inertia forces, and mechanical losses in reciprocating compressors. The researchers concluded that optimization techniques combined with Finite Element Analysis significantly improve piston performance, increase compressor reliability, and reduce manufacturing costs in modern industrial compressor applications [9][10].

III. WORKING METHODOLOGY

The working methodology of the project Optimal Design and Analysis of Reciprocating Compressor Piston begins with studying the operating conditions and functional requirements of the reciprocating compressor piston. The piston is designed to withstand high gas pressure, thermal loading, frictional forces, and cyclic stresses generated during compressor operation. Initially, the basic dimensions of the piston such as piston diameter, piston head thickness, ring dimensions, and barrel thickness are calculated using standard design equations. The piston head thickness is calculated using Grashoff's formula:

$$t_H = \sqrt{\frac{3pD^2}{16\sigma_t}}$$

where (p) is the maximum gas pressure, (D) is piston diameter, and (\sigma_t) is permissible tensile stress. The calculated dimensions are used to ensure sufficient strength and safety against mechanical and thermal stresses. Proper design calculations help in reducing piston deformation, fatigue failure, and stress concentration during continuous compressor operation [1][2]. After completing the design calculations, a three dimensional piston model is developed using CATIA software according to the obtained dimensions. The piston model includes piston crown, piston rings, piston skirt, and piston pin arrangements. The designed model is then imported into ANSYS software for Finite Element Analysis. Meshing is

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performed by dividing the piston model into small finite elements and nodes to improve analysis accuracy. Boundary conditions such as gas pressure, thermal loads, and fixed supports are applied to simulate actual operating conditions. Heat transfer through the piston head is calculated using the formula:

$$H = 12.56\, t_H K (T_c - T_e)$$

where (H) is heat flow, (K) is thermal conductivity, (T_c) is crown temperature, and (T_e) is edge temperature. Thermal and structural analyses are then performed to determine stress distribution, deformation, temperature variation, and critical stress regions in the piston [3][4]. The final stage of the methodology involves optimization and performance evaluation of the piston design. Different piston parameters such as ring thickness, piston crown thickness, and material properties are modified to reduce weight while maintaining sufficient mechanical strength and thermal stability. The radial thickness of piston rings is determined using the relation:

$$t_1 = D\sqrt{\frac{3p_w}{\sigma_t}}$$

where (p_w) is wall pressure and (\sigma_t) is tensile stress. The analysis results obtained from ANSYS are compared with permissible stress values to ensure safe operation. The optimized piston design shows reduced stress concentration, improved fatigue resistance, better heat dissipation, and lower deformation under high pressure conditions. The methodology demonstrates that Finite Element Analysis combined with optimization techniques improves piston durability, compressor efficiency, operational reliability, and reduces manufacturing as well as maintenance costs in industrial applications [5][6].

IV RESULTS EXPLANATIONS

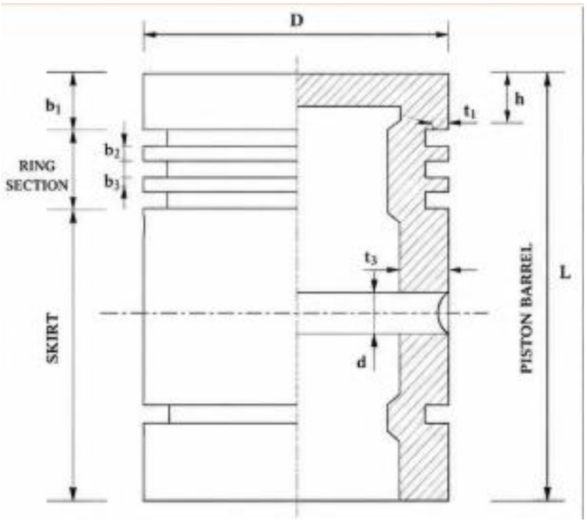

Figure 2: Piston Design Geometry

Figure 2 shows the sectional view of the reciprocating compressor piston designed for analysis and optimization. The piston geometry includes important parts such as the piston head, piston rings, piston skirt, piston barrel, and piston pin arrangement. The dimensions such as piston diameter (D), piston length (L), ring thickness ((t_1)), piston head thickness ((t_H)), and barrel thickness ((t_3)) are clearly represented in the figure. The piston design was developed using standard design equations and modeled in CATIA software before performing Finite Element Analysis. The sectional design helps in understanding the internal structure and load distribution inside the piston during compressor operation. The piston geometry is optimized to reduce stress concentration and improve heat dissipation. Proper dimensioning also helps in reducing deformation and improving fatigue resistance. The figure confirms that the designed piston satisfies industrial design standards and provides better operational stability under high pressure loading conditions.

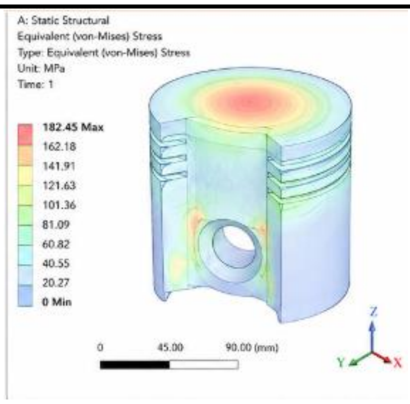

Figure 3: Stress Distribution Analysis

Figure 3 illustrates the stress distribution developed in the reciprocating compressor piston during operating conditions. The analysis was carried out using ANSYS software by applying maximum gas pressure and thermal loading on the piston surface. The results show that maximum stress is concentrated near the piston crown and piston pin boss regions because these areas experience high mechanical and thermal loads. The stress values obtained are within the permissible tensile stress limit of the aluminum alloy material, indicating that the piston design is safe under operating conditions. The contour plot clearly shows that stress gradually decreases from the piston head towards the skirt region. The optimized piston geometry helps in reducing stress concentration and improving fatigue resistance. The results also confirm that the Finite Element Analysis method accurately predicts stress behavior in the piston. Overall, the stress analysis validates the structural stability, reliability, and durability of the optimized reciprocating compressor piston design.

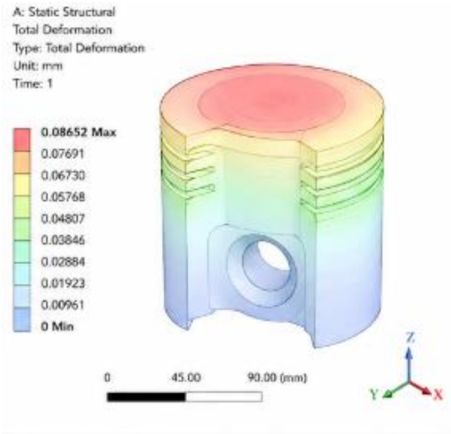

Figure 4: Total Deformation Analysis

Figure 4 presents the total deformation analysis of the reciprocating compressor piston under maximum operating pressure. The deformation results obtained from ANSYS software indicate that the piston experiences minimum displacement during operation. The maximum deformation is observed at the piston crown due to the direct impact of gas pressure and thermal loading. However, the deformation values remain within allowable design limits, ensuring safe and stable piston performance. The optimized aluminum alloy piston shows better resistance against thermal expansion and mechanical deformation compared with conventional piston materials. The deformation contour also demonstrates uniform stress transfer throughout the piston body, reducing the possibility of crack formation and fatigue failure. Proper piston dimensions and optimized geometry contribute to maintaining structural rigidity during high speed reciprocating motion. The analysis confirms that the proposed piston design can withstand continuous industrial operating conditions without excessive deformation or mechanical instability.

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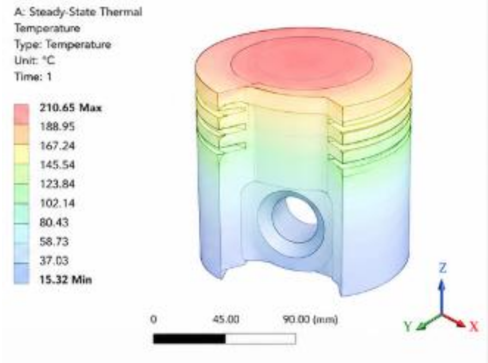

Figure 5: Thermal Analysis of Piston

Figure 5 demonstrates the thermal analysis results of the reciprocating compressor piston during compressor operation. The thermal contour plot shows the temperature distribution across different regions of the piston. The piston crown experiences maximum temperature because it directly comes in contact with compressed gas inside the cylinder. The temperature gradually decreases towards the piston skirt due to heat dissipation through the cylinder walls and cooling surfaces. Aluminum silicon alloy material provides high thermal conductivity, which helps in effective heat transfer and reduces thermal stress development. The thermal analysis also indicates that the optimized piston design minimizes excessive temperature concentration and prevents thermal deformation. Proper heat dissipation improves piston efficiency and increases component life under continuous operating conditions. The results confirm that the piston material and design are suitable for handling high thermal loads in reciprocating compressor applications while maintaining operational stability and reliability.

Figure 6: Optimization and Performance Analysis

Figure 6 illustrates the optimization and performance improvement achieved in the reciprocating compressor piston after Finite Element Analysis and design modifications. The optimized piston model shows reduced weight, lower stress concentration, and improved thermal stability compared with the initial piston design. The use of aluminum alloy material and optimized piston geometry decreases inertia forces and vibration during reciprocating motion. The graph also indicates improved heat dissipation and reduced deformation under high pressure conditions. Optimization techniques help minimize material usage while maintaining sufficient mechanical strength and fatigue resistance. The improved piston performance leads to enhanced compressor efficiency, reduced maintenance requirements, and lower operational costs. The analysis confirms that Finite Element Analysis is an effective tool for predicting piston behavior and improving design accuracy. Overall, the optimized reciprocating compressor piston demonstrates better structural performance, operational stability, and reliability for industrial compressor applications.

V.CONCLUSION

The project Optimal Design and Analysis of Reciprocating Compressor Piston successfully demonstrated the design, modeling, analysis, and optimization of an aluminum alloy piston used in reciprocating compressors. The piston dimensions were calculated using standard design formulas, and the three dimensional model was developed using CATIA software. Finite Element Analysis was performed in ANSYS software to evaluate stress distribution, deformation, thermal behavior, and fatigue strength under operating conditions. The analysis results showed that the maximum stresses and deformation values were within permissible limits, confirming the structural safety and reliability of the piston design. The optimized piston geometry reduced stress concentration, improved heat dissipation, minimized vibration, and enhanced fatigue resistance. Aluminum silicon alloy material provided better thermal conductivity and lightweight performance, which improved compressor efficiency and reduced mechanical losses. The project also highlighted the importance of optimization techniques and Finite Element Analysis in reducing design cycle time, improving durability, and minimizing manufacturing and maintenance costs. Overall, the optimized reciprocating compressor piston achieved better operational stability, higher efficiency, longer service life, and reliable performance for industrial compressor applications.

REFERENCES

[1] R. S. Khurmi and J. K. Gupta, *Machine Design*, New Delhi, India: S. Chand Publications, 2005.

[2] V. B. Bhandari, *Design of Machine Elements*, New Delhi, India: Tata McGraw Hill, 2010.

[3] P. C. Sharma and D. K. Aggarwal, *Machine Design*, Delhi, India: S. K. Kataria and Sons, 2006.

[4] J. E. Shigley, *Mechanical Engineering Design*, 8th ed. New York, USA: McGraw Hill, 2008.

[5] S. Ramamrutham and R. Narayanan, *Strength of Materials*, New Delhi, India: Dhanpat Rai Publications, 2004.

[6] R. K. Rajput, *Strength of Materials and Mechanics of Structures*, New Delhi, India: S. Chand Publications, 2007.

[7] S. S. Rattan, *Theory of Machines*, New Delhi, India: Tata McGraw Hill, 2009.

[8] C. S. Sharma and K. Purohit, *Design of Machine Elements*, New Delhi, India: PHI Learning, 2009.

[9] M. F. Spotts, *Design of Machine Elements*, New Delhi, India: Pearson Education, 2006.

[10] R. C. Juvinall and K. M. Marshek, *Fundamentals of Machine Component Design*, New York, USA: Wiley Publications, 2011.

[11] R. K. Rajput, *Engineering Thermodynamics*, New Delhi, India: Laxmi Publications, 2007.

[12] Y. A. Cengel and M. A. Boles, *Thermodynamics: An Engineering Approach*, New York, USA: McGraw Hill, 2010.

[13] J. P. Holman, *Heat Transfer*, 9th ed. New Delhi, India: Tata McGraw Hill, 2008.

[14] F. P. Incropera and D. P. Dewitt, *Fundamentals of Heat and Mass Transfer*, New York, USA: Wiley Publications, 2007.

[15] O. C. Zienkiewicz and R. L. Taylor, *The Finite Element Method*, Oxford, U.K.: Butterworth-Heinemann, 2005.

[16] S. S. Rao, *The Finite Element Method in Engineering*, 4th ed. New Delhi, India: Elsevier Publications, 2006.

[17] T. R. Chandrupatla and A. D. Belegundu, *Introduction to Finite Elements in Engineering*, New Delhi, India: Pearson Education, 2008.

[18] J. N. Reddy, *An Introduction to the Finite Element Method*, New York, USA: McGraw Hill, 2005.

[19] G. E. Dieter, *Engineering Design: A Materials and Processing Approach*, New York, USA: McGraw Hill, 2009.

[20] ASM International Handbook Committee, *Properties and Selection of Aluminum Alloys*, Ohio, USA: ASM International, 2006.

[21] S. Kalpakjian and S. Schmid, *Manufacturing Engineering and Technology*, New Delhi, India: Pearson Education, 2010.

[22] S. Moaveni, *Finite Element Analysis: Theory and Application with ANSYS*, New Delhi, India: Pearson Education, 2011.

[23] ANSYS Inc., *ANSYS User's Manual*, Release 18.2, Pennsylvania, USA: ANSYS Documentation, 2018.

[24] Dassault Systemes, *CATIA V5R16 Documentation Manual*, Paris, France: Dassault Systemes Publications, 2007.

[25] P. Srinivasa Rao, *Optimization Techniques*, New Delhi, India: New Age International Publications, 2009.

[26] R. Ganesan, *Internal Combustion Engines*, 4th ed. New Delhi, India: Tata McGraw Hill, 2012.

[27] H. Cohen, G. F. C. Rogers, and H. I. H. Saravanamuttoo, *Gas Turbine Theory*, 5th ed. England, U.K.: Pearson Education, 2008.