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Performance Analysis of a Single-acting Reciprocating Compressor Using Thermodynamic Concepts

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Abstract
This paper presents the application of thermodynamic concepts in the analysis of the performance of a Single-acting Reciprocating Compressor. Reciprocating Compressor, is a positive-displacement compressor with applications in automotive industries, gas pipeline processes, oil refinery industries, chemical and gas processing plants among others, hence it is essential to apply the thermodynamics concepts in the study of the specific physical quantities of temperature, energy, work, power and heat transferred; for the overall improvement of the efficiencies of the system. The use of compressed air in our day to day activities either at homes for cleaning, workshops for inflating tyres, industries for controlling equipment and laboratories for experiments cannot be over emphasized. In industries, compressed air has gone a long way in getting jobs done in a faster, reliable and at a more convenient way owing to the fact that most industrial machines and implements are now pneumatically controlled (uses air). So there is a need to maintain the use of this compressed air. This study is the analysis of the performance of a single–acting reciprocating compressor, whose prime mover rating is a 1.5 HP electric motor running at 2100 r.p.m. Other designed parameters are 2.0m^3/min of air, intake pressure (P_1) of 1.0 bars and the discharge pressure (P_2) of 5.0 bars. The single-acting reciprocating compressor was designed and manufactured; employing the working principle, it was observed to be in good agreement with other existing compressors. Thermodynamic concepts such as the application of the perfect gas law were employed for the analysis of the mass of air delivered per minute, delivery temperature at the end of compression. Other thermodynamics concepts analysed were the indicated work, indicated power, isothermal compression, and polytropic compression. The heat transferred during compression, work done by a reciprocating compressor, isothermal efficiency and overall isothermal efficiency of the compressor were also computed. The results show that as the compression pressure increases, there is a corresponding increase in efficiency of the compressor and vice versa; giving the overall efficiency of the compressor as 84.3%. Consequently the thermodynamic parameters are economically adequate and useful in analysing cycle performance for the single-acting reciprocating compressor operations.

Keywords: *Single-acting, reciprocating, compressor, compression, air, thermodynamics concepts.*

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I. INTRODUCTION

A reciprocating compressor is a positive-displacement air compressor that converts power into potential energy stored as compressed air using electric motors, diesel or gasoline engine, among others as it’s prime-mover. It uses piston driven by a crankshaft to deliver fluid (gases or air) at high pressure. The intake atmospheric air enters through the suction valve, then flows into the compression chamber where it is compressed by a piston driven in a reciprocating motion by means of a crankshaft. The compressed air, then, is held in the tank until when it is required. During the delivery process, the compressed air that was held in the tank is then discharged at high pressure through a discharge valve, therefore depressurizing the tank. It is essential to emphasise that the main function of a compressor is to take a definite quantity of fluid (typically gas, and most often air) and deliver it at a required pressure Salem (2005) and Rajput (2015). The compressed air contains energy which can be employed for a variety of applications such as operating tools in factories, operating drill and hammers in road building, excavating, inflating of tyre, drying, spray painting among other by utilizing the kinetic energy of the air as it is released and the tank depressurizes.

Reciprocating air compressors can be classified into single-acting and double-acting reciprocating air compressors. This paper focuses on the single-acting reciprocating compressor where the air that is compressed in the cylinder is on one side of the piston only. Figure 1.1 shows the AutoCAD 3D Model of the single-acting reciprocating compressor with a handle and belt guard used in this study.

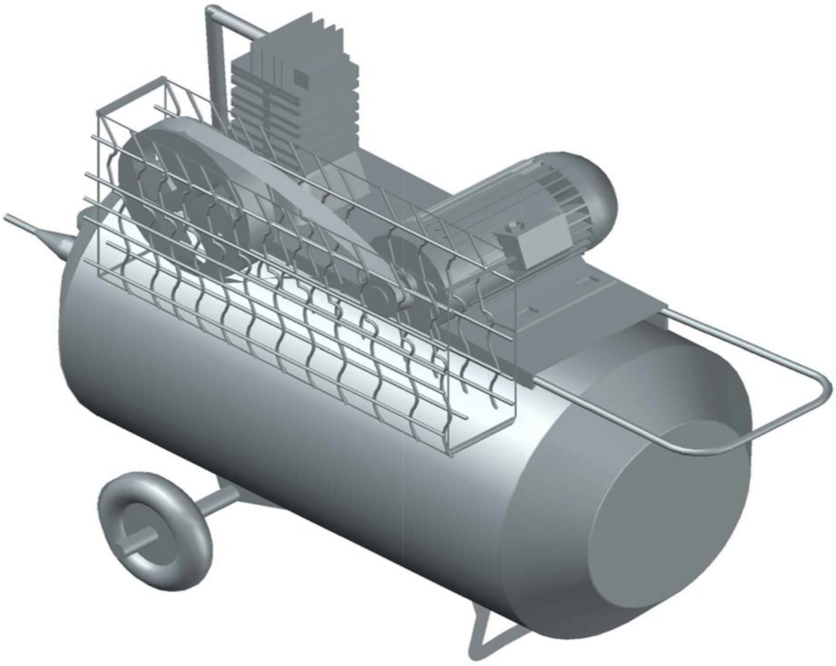

Figure 1.1: AutoCAD 3D Model of the single-acting reciprocating compressor with a handle and belt guard.

The aim of this study is to employ thermodynamic concepts in the analysis of the performance of a single –acting reciprocating air compressor design and manufactured using locally available materials. The reciprocating compressor is to be used for practical demonstration in the mechanical engineering laboratory during Fluid Machinery, Applied Fluid Mechanics and Thermodynamics classes. The compressor will also be employed in workshops and places where pressurized air is required such as for tyre inflation, dust cleaning and spray-painting among others. It will assist the department of mechanical engineering in AKSU during accreditation visitation by the Nigerian University Commission (NUC) since it a compulsory requirement for accreditation; hence the urgent need for this project. Figure 1.2 shows the manufactured single-acting reciprocating compressor used in this study.

Figure 1.2: A Single-acting Reciprocating Compressor

II. BACKGROUND AND REVIEW OF PREVIOUS WORK ON COMPRESSION USING RECIPROCATING COMPRESSOR

This section presents the review of air compression using the reciprocating compressor and the thermodynamic operational sequence of the single-acting reciprocating compressor using a p-V diagram. A review of previous work relating to air or gas compression using reciprocating compressors has been extensively discussed in Wieberdink (2014), Shaw (2015), Alhelal (2016), Zhao (2014), Ribas *et al.* (2008), Diniz *et al.* (2016), Willingham (2009), Guerra (2013), Patil *et al.* (2017), Rahman *et al.* (2011), MacLaren and Tramschek, (1972), An *et al.* (2002). For details, the reader is referred to the work of the mentioned authors. But it is imperative to note that compression by reciprocating compressor is accomplished by the reciprocating movement of a piston within a cylinder.

The piston in the compressor moves downwards, reducing pressure in its cylinder by creating a vacuum. This difference in pressure forces the cylinder gate to open and air is drawn in. When the cylinder returned, it increases pressure, thus forcing the air out. To improve the efficiency of a reciprocating compressor, priority should be given to the improvement of the quality of the air intake, accurate matching of the air compressor controls, an improvement on the system design, minimizing pressure drop and routine maintenance of the compressor among others for optimum result. Air compression finds applications in the following areas; automobile industries, environmental cleaning, oil refineries, gas pipelines, chemical plants, natural gas processing plants and refrigeration plants.

In summary, an air compressor normally takes in atmospheric air, compresses it and delivers the high-pressure air to a storage container from which it may be conveyed by the pipeline to wherever the supply of compressed air is required Rajput (2015). During the process of compression, work is done upon it; hence compressor must be driven by prime-mover. The total energy received by the compressor from the prime-mover is used to perform different task, some will be employed for work done against friction; while others will be maintained within the air itself. The prime-mover used converts a fraction of the heat it receives from the source into work Khurmi and Gupta (2005).

The relevance of the thermodynamic concepts to this analysis was the need for new forms of solutions to the design problem at a reduced cost of production of the machine; considering the fact that thermodynamics is the science of the relations between heat and other forms of energy. This involves heat and temperature, and their relation to energy and work of the air compressor. The thermodynamic concepts allow for the easy computation of the overall efficiency of the compressor. The thermodynamic cycle of a reciprocating compressor is shown graphically on the p-V diagram of Figure 2.1.

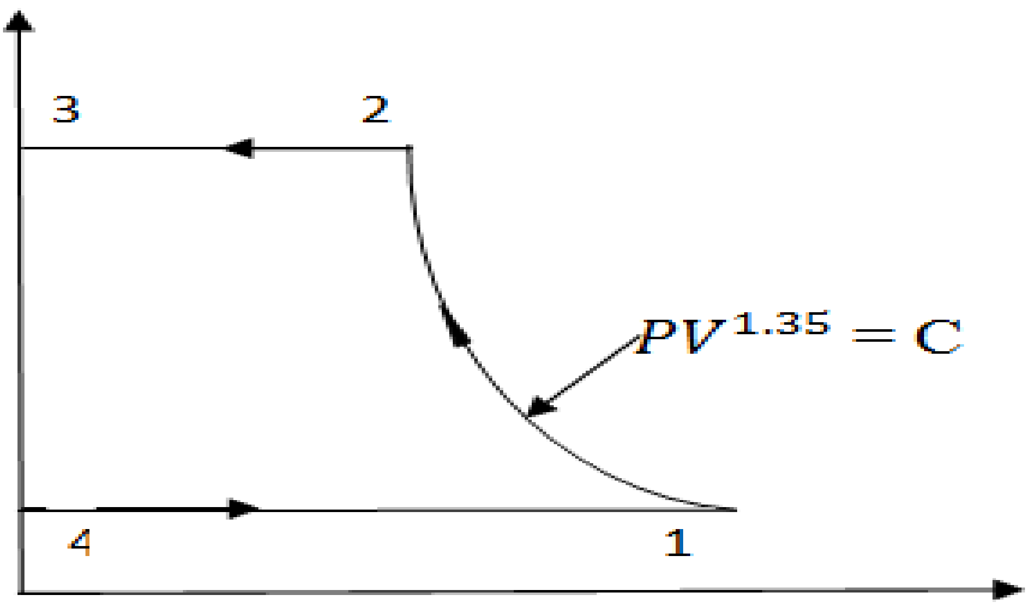

Figure 2.1: p-V diagram of the single-acting reciprocating compressor

The p-V diagram is employed to analysis the sequence of operations of a single-acting reciprocating compressor. The sequence operations indicate that the route 4 - 1 is Induction/intake process where the piston travels from top dead center (TDC) to bottom top center (BDC), the induction valve opens and air is induced into the cylinder, the volume and mass increases but pressure and temperature are constant during this process at P1, T1. Route 1 – 2 is the compression process where the piston travel from BDC to TDC, Inlet valve closes, and then the piston compresses air, leading to the reduction in the air volume, but increasing the pressure until it reaches P2 at point (2), with an increase in temperature. And finally, route 2 – 3 is the delivery process where the delivery valve opens at the point (2) and a high pressure air is delivered. The pressure and temperature is constant during this process at P2.

III. METHODOLOGY USING THERMODYNAMICS CONCEPTS FOR SINGLE-ACTING RECIPROCATING COMPRESSORS

The design principle of reciprocating compressor is based on the principle of compression. Compression is accomplished by the reciprocating movement of a piston within a cylinder. A connecting rod transforms the rotary motion of the crankshaft into the reciprocating motion of the piston in the cylinder. This motion makes ease the filling of the cylinder and the compression of air in the cylinder. Figure 3.1 shows the block diagram of the working sequence of a reciprocating compressor.

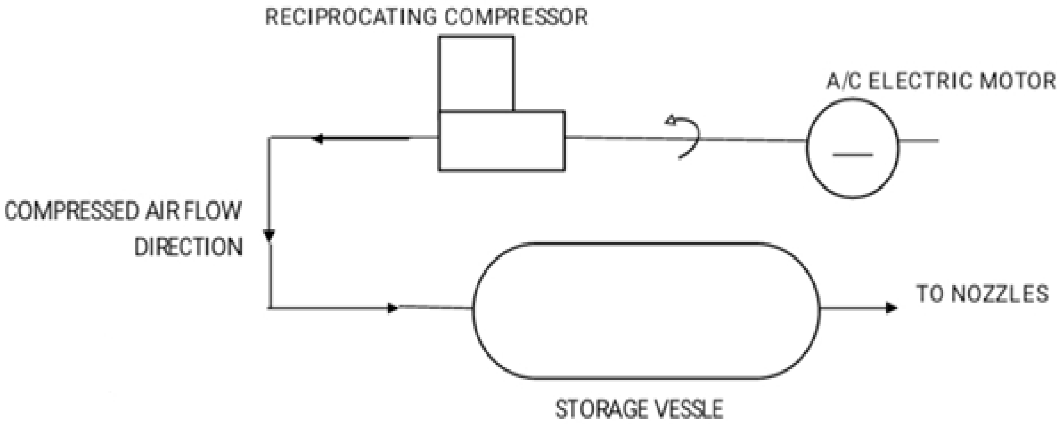

Figure 3.1: Block diagram showing the working principle of reciprocating compressor

In this study, the performance characteristics of a reciprocating compressor are determined with reference to the research assumptions. For example, torque and power are to be presented as a function of compressor speed. Applying the thermodynamics concepts and according to Rajput (2015);

a) **The working fluid is assumed as a perfect gas and *P-V-T*** can be calculated by using the equation of state. These assumptions are used to estimate pressure, *P, volume, V, and temperature, T, of the working* fluid.

$$PV = mRT \tag{3.1}$$

Where: **P** = Pressure; K **=** Gas Constant; **m** = Molar Mass; **V** = Volume; **T** = Temperature **R** = Molar Ratio.

b) Clearance in the cylinder is neglected

The compression process is polytropic and the polytropic index (n) is assumed to be 1.35 using the law of compression as shown in Equation 3.2.

$$PV^n = C, hence, PV^{1.35} = C \tag{3.2}$$

3.6 Delivered temperature at the end of the compression (T_2)

The temperature delivered at the end of the compression can be determined using the equation below:

$$T_2 = T_1 (\frac{P_2}{P_1})^{\frac{n-1}{n}} \tag{3.3}$$

3.6.1 The actual volumetric efficiency, η_{vol}:

The actual volumetric efficiency is given as the ratio of free air delivery (FAD) to the displacement volume in $\frac{m^3}{min}$

Where; $V_d = \frac{\pi}{4} D^2 LN$ for a single-acting compressor (3.4)

$$F.A.D = \frac{mRT_1}{P_1} \tag{3.5}$$

Hence, $\eta_{vol} = \frac{F.A.D}{V_d}$ (3.6)

3.6.1 Indicated work (I.W)

The indicated work of compression is given as:

$$I.W = \frac{n}{n-1} mR(T_2 - T_1) kJ/min \quad (3.7)$$

3.6.2 Indicated power (I.P)

Indicated power of the compressor is given as:

$$I.P = \frac{Indicated\ Work}{60} \quad (3.8)$$

3.4.4 Work done by a reciprocating compressor

The function of a compressor is to take a sufficient amount of fluid and to increase its pressure. Considering a single acting reciprocating compressor without clearance volume, we have that,

$$W = \frac{n}{n-1} mRT_1 \ [(\frac{P_2}{P_1})^{\frac{n}{n-1}} - 1] \quad (3.9)$$

Or we can also use,

$$W = \frac{n}{n-1} p_1 V_1 \ [(\frac{P_2}{P_1})^{\frac{n}{n-1}} - 1] \quad (3.10)$$

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

$$m = \frac{P_1 V_1}{RT_1} \quad (3.11)$$

where: p_1, V_1, T_1 are pressure, volume, and Temperature of the fluid before compression while p_2, V_2, T_2 are pressure, volume and temperature of the fluid after compression. The work done by a reciprocating compressor can further be analyzed in different ways depending on the type of compression. Since the compression may be isothermal, isentropic or polytropic.

3.4.5 Heat transferred during compression

Heat transfer is given by

$$Q = W + \Delta U \quad (3.12)$$

$$Q = \frac{P_1V_1 - P_2V_2}{n-1} - c_v(T_2 - T_1) \quad (3.13)$$

$$Q = \frac{R(T_1 - T_2)}{n-1} + c_v(T_2 - T_1) \quad (3.14)$$

$$Q = (T_2 - T_1) * \left[C_v - \left(\frac{R}{n-1}\right)\right]$$

(3.15)

3.5.2 Mechanical Efficiency

The mechanical efficiency ($\eta_{mech.}$) is given by;

$$\eta_{mech.} = \frac{indicated\ power}{shaft\ power} \times 100 \quad (3.16)$$

3.5.3 Isothermal Efficiency ($\eta_{iso.}$)

The isothermal efficiency is given by first analysing the isothermal power which is given as:

$$Isothermal\ power = mRT_1 In\ (\frac{P_2}{P_1}) \quad (3.17)$$

Therefore, $\eta_{iso} = \frac{isothermal\ power}{indicated\ power}\ x\ 100$ (3.18)

3.5.4 Overall efficiency isothermal efficiency ($\eta_{overall\ (iso)}$)
Overall isothermal efficiency is given by:

$$\eta overall\ (iso) = \frac{isothermal\ power}{shaft\ power}\ x100 \quad (3.19)$$

IV. RESULTS AND DISCUSSION

This section presents the results and discussion of this work. Performance evaluation of the reciprocating compressor using some thermodynamics concepts as stated in section 3 are presented. In this study, the following concepts were analysis:

- Mass of air delivered
- Temperature at the end of compression
- Work done during compression
- Heat transferred during compression
- Indicated work
- Indicated power
- The isothermal efficiency
- The overall isothermal efficiency

4.1 Designed parameters of the compressor

- Volume of air taken per minute (V_1) = 2.0m^3/min
- Intake pressure (P_1) = 1.0bar = 14.5psi
- Discharge pressure (P_2) = 5.0bar = 72.5psi

4.2 Electric motor rating

- Shaft power = 6.37kw
- Speed = 2100 r.p.m
- 50Hz/3phase

4.3 Performance analysis using Thermodynamic concepts

4.3.1 The mass of the air delivered per minute,
Assuming that the clearance in the cylinder is neglected, that the compression process is polytropic and the polytropic index (n) is given as 1.35 using the law of compression of Equation 3.2 and taking the initial room temperature (T_1) of 25^{O}C as the intake air,

$$T_1 = 25 + 273 = 298K$$
$$P_1 = 1\ bar = 1.0\ x\ 10^5\ N/M^2$$

Referring to Equation (3.4) which is given as: $m = \frac{P_1 V_1}{RT_1}$

$$m = \frac{1.0\ \times 10^5 \times 2}{287\ \times 298} = 2.340\ kg/min$$

4.3.2 Delivered temperature at the end of the compression (T_2)
From the p-V diagram for the single-acting reciprocating compressor shown as Figure 2.1, the delivery temperature is analysis using Equation 3.3 given as,

$$T_2 = T_1 (\frac{P_2}{P_1})^{\frac{n-1}{n}}$$

$$T_2 = 298\left(\frac{5}{1}\right)\frac{1.35-1}{1.35} = 452.3K$$

4.3.3 Indicated work (I.W)
Using Equation (3.22),

$$I.W = \frac{n}{n-1}MR(T_2 - T_1)kJ/min$$

$$I.W = \frac{1.35}{1.35-1} \times 2.340 \times 0.287(452.3 - 298)$$

$$I.W = 399.70kJ/min$$

4.3.4 **Indicated power (I.P)**

As given in Equation (3.23),

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

$$I.P = \frac{399.70}{60} = 6.70kW$$

Indicated power (I.P) can also be analysis using the equation;

$$I.P = \frac{n}{n-1}x\ mRT_1\left[\left(\frac{p_2}{p_1}\right)^{\frac{n}{n-1}} - 1\right]$$

Hence, $I.P = \frac{1.35}{1.35-1}x\ \frac{2.340}{60}x\ 0.287\ x\ 298\ x\left[\left(\frac{5}{1}\right)^{(1.35-1)/1.35} - 1\right] = 6.70kW$

4.3.5 **Work done by a reciprocating compressor**
The work done by the reciprocating compressor during compression per kg of air is analysis using Equation 3.10, which is given as,

$$W = \frac{n}{n-1}mRT_1\ \left[\left(\frac{P_2}{P_1}\right)^{\frac{n}{n-1}} - 1\right]$$

$$W = \frac{1.35}{1.35-1}\ x\ 2.34\ x\ 0.287\ x\ 298\ x\ \left[\left(\frac{5}{1}\right)^{(1.35-1)/1.35} - 1\right] =$$

$$399.18\frac{kJ}{kg}\ \ of\ air$$

4.3.6 Heat transferred during compression
The heat transferred during compression is analysis using Equation 3.12 which is given as,

$$Q = (T_2 - T_1) * \left[C_v - \left(\frac{R}{n-1}\right)\right]$$

Assuming,

$C_p = 1.005 \frac{kJ}{kgK} and\ R = 0.\frac{287kJ}{kgK}, then\ C_v = C_p - R = 1.005 - 0.287 = 0.718\ kJ/kgK$

Hence, $Q = (452.3 - 298) * \left[0.718 - \left(\frac{0.287}{1.35-1}\right)\right] - 15.739\ kJ/kg$

The negative sign indicates that heat rejection from the system

4.4 Efficiency of the compressor

There are three main reciprocating compressor efficiencies, which are mechanical efficiency, isothermal efficiency and overall efficiency. Isothermal efficiency and overall efficiency are the main focus of this work. Considering that the shaft power rating is 6.37kW, hence, the efficiencies are analysis as follows,

4.4.1 Isothermal Efficiency ($\eta_{iso.}$)

The isothermal efficiency is analysis using Equation (3.18) as:

$$Isothermal\ efficiency = \frac{Isothermal\ power}{\text{Indicated power}} x\ 100$$

But, $\text{Isothermal power} = mRT_1 In\ (\frac{P_2}{P_1})$

$$= \frac{2.340}{60} \times 0.287 \times 298\ In\left(\frac{5}{1}\right) = 5.368 \frac{kJ}{s} or\ kW$$

$$\eta_{iso} = \frac{5.368}{6.70}\ x\ 100 = 80.12\%$$

4.4.2 Overall efficiency ($\eta_{overall}$)

Overall efficiency from equation (3.20) is given by:

$$\eta_{overall} = \frac{isothermal\ power}{shaft\ power}\ x\ 100$$

$$\eta_{overall} = \frac{5.368}{6.37}\ x\ 100 = 84.3\ \%$$

4.5 Discussion

This involves the evaluation of the performance of the Single-acting reciprocating compressor. Performance characteristics data of a single-acting reciprocating compressor comprising of the designed parameters of the compressor and electric motor rating were presented in section 4.1 and 4.2 respectively. The performance of the compressor was investigated during operation and were analyzed using a graph and a chart. This graph and chart show the performance of the machine in terms of efficiency at different operating pressures. Table 4.1 shows the operational details of the reciprocating compressor.

Table: 4.1: A Table showing the operating pressure and the corresponding efficiencies

S/N	Operating Pressure reading (bar)	Efficiency (η)
1	1	0
2	1.5	21.23
3	2	36.30
4	2.5	47.98
5	3	57.53
6	3.5	65.60
7	4	72.60
8	4.5	78.76
9	5	84.28

From the Table 4.1, it is observed that as the compression pressure increases, there is also an increase in efficiency of the compressor up to the point that the overall efficiency of 84.3% is obtained. This can further be illustrated using charts and graph shown as Figure 4.1 and Figure 4.2 respectively.

4.5.1 Bar chart of efficiency against the discharge pressure: The main characteristics, positions of the efficiency of the compressor with respect to the discharge pressure can be illustrated comprehensively using bar chart of Figure 4.1 and graphically, using Figure 4.2.

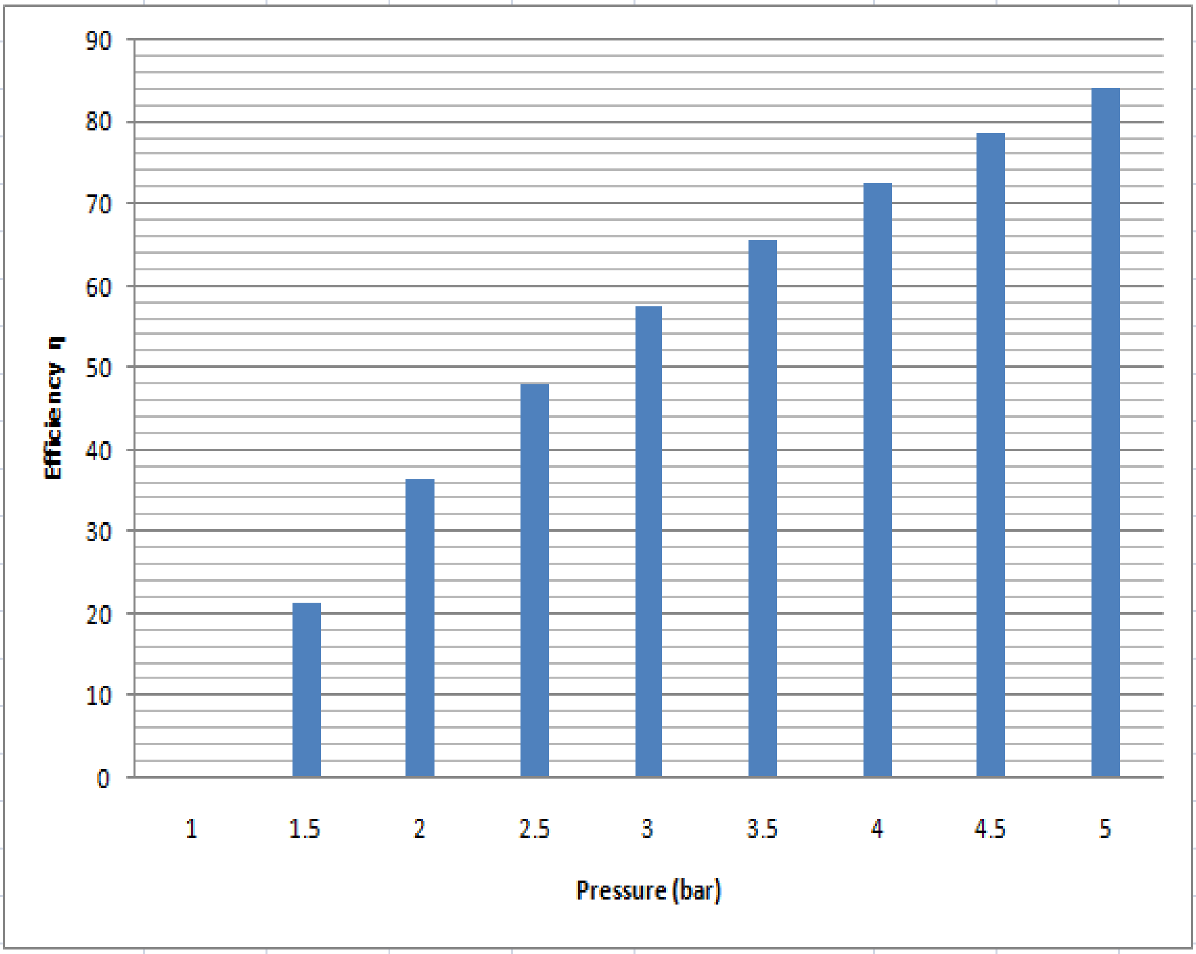

Figure 4.1: Bar chart showing the relationship between efficiency and pressure of the single-acting reciprocating compressor

4.5.2 Graph of efficiency against the discharge pressure

The graph of pressure discharge from the compressor with respect to the generated overall efficiency was also plotted to further illustrate the relationship between the two parameters Figure 4.2.

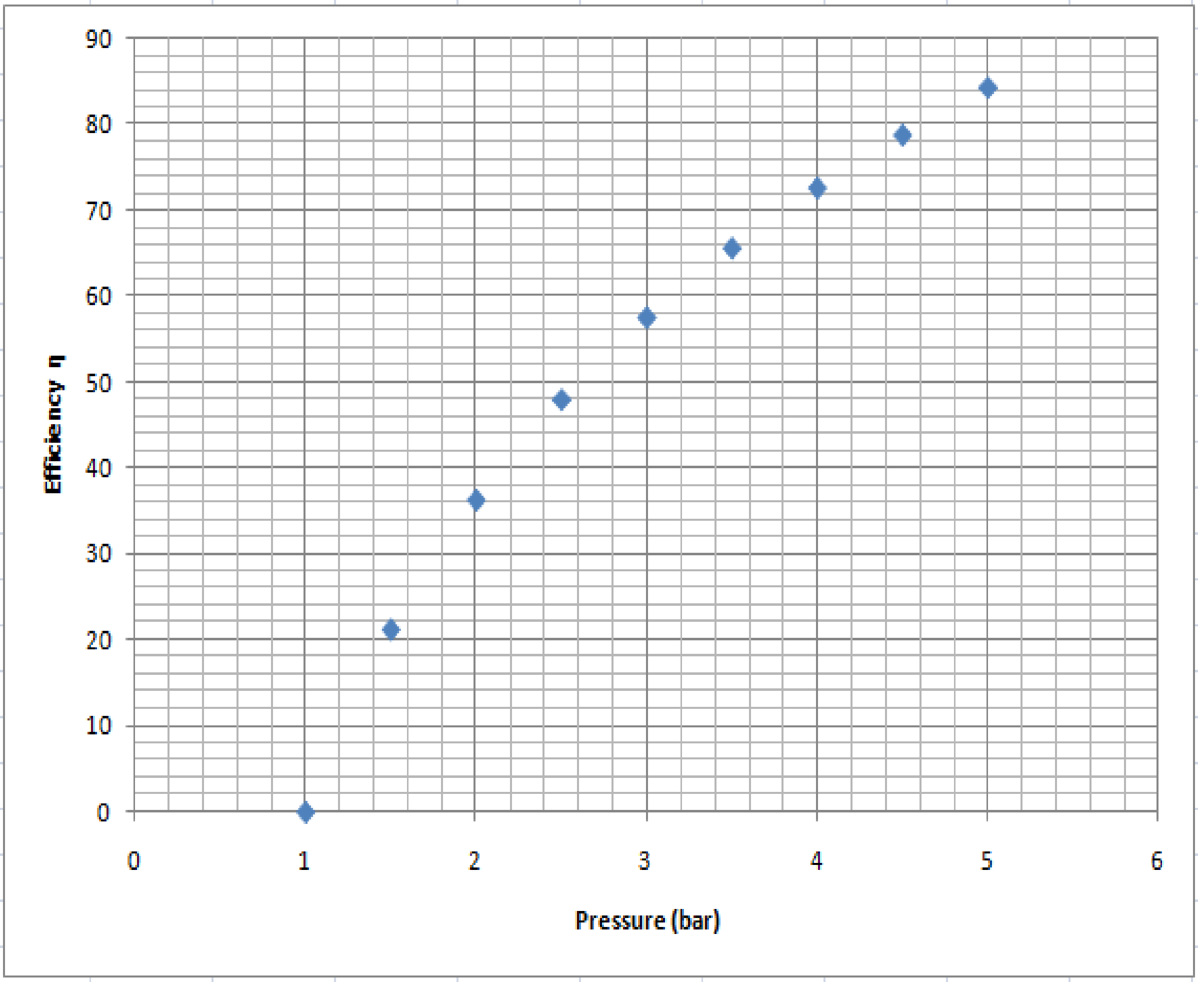

Figure: 4.2: Graph of efficiency against discharge pressure of the single-acting reciprocating compressor

From Figure 4.2, it can be observed that as the pressure of the compressor increases, the generated overall efficiency increases, the piston inside the cylinder can be said to undergo movement from the Top Dead Center (TDC) to the Bottom Dead Center (BDC) at a faster rate. The crankshaft and connecting rods which facilitates the movement of the piston can also be said to undergo reciprocating and to and fro motions respectively.

4.5.3 Validation of the Performance analysis against the Standard Rajput Performance test of a single-acting reciprocating compressor

The result is validated against a standard Rajput performance test of a single-acting reciprocating compressor with the following data: Suction pressure of 1 bar, suction temperature of 20C, discharge pressure of 6 bars, discharge temperature of 180C, speed of compressor of 1200 r.p.m, the mass of air delivered of 1.7kg/min and a shaft power of 6.25kW Rajput (2015). Let EIB data represent the result of this study while RAJPUT represents the result of the Rajput performance test. The results of the computed isothermal efficiencies for both EIB and RAJPUT are presented in Table 4.2. The RAJPUT data are plotted as shown in Figure 4.3 and the validation of EIB data against RAJPUT data is presented as Figure 4.4.

Table: 4.2: A Table showing the Performance Validation of EIB Efficiencies against the RAJPUT Performance Efficiencies

S/N	Operating Pressure reading (bar)	EIB Isothermal Efficiency (η)	RAJPUT Isothermal Efficiency (η)
1	1	0	0
2	1.5	21.23	15.46
3	2	36.30	26.42
4	2.5	47.98	34.93
5	3	57.53	41.88
6	3.5	65.60	47.76
7	4	72.60	52.85

8	4.5	78.76	57.34
9	5	84.28	61.35

Figure 4.3 shows the graph of the Isothermal efficiencies of RAJPUT data against the operating pressures. The analyses indicate that as the discharge pressure increases, the efficiency increases. The results of the EIB reciprocating compressor were compared to the standard R. K. Rajput results and they were in good agreement since the trend (efficiencies profiles) is the same. In each case, as the pressure increases, there was an increase in efficiency in both results as shown in Table 4.2. This indicated that the higher the discharge pressure, the higher the efficiency as shown graphically in Figure 4.4. Hence, the results of this single-acting reciprocating compressor are in good agreement with other existing single-acting reciprocating compressors.

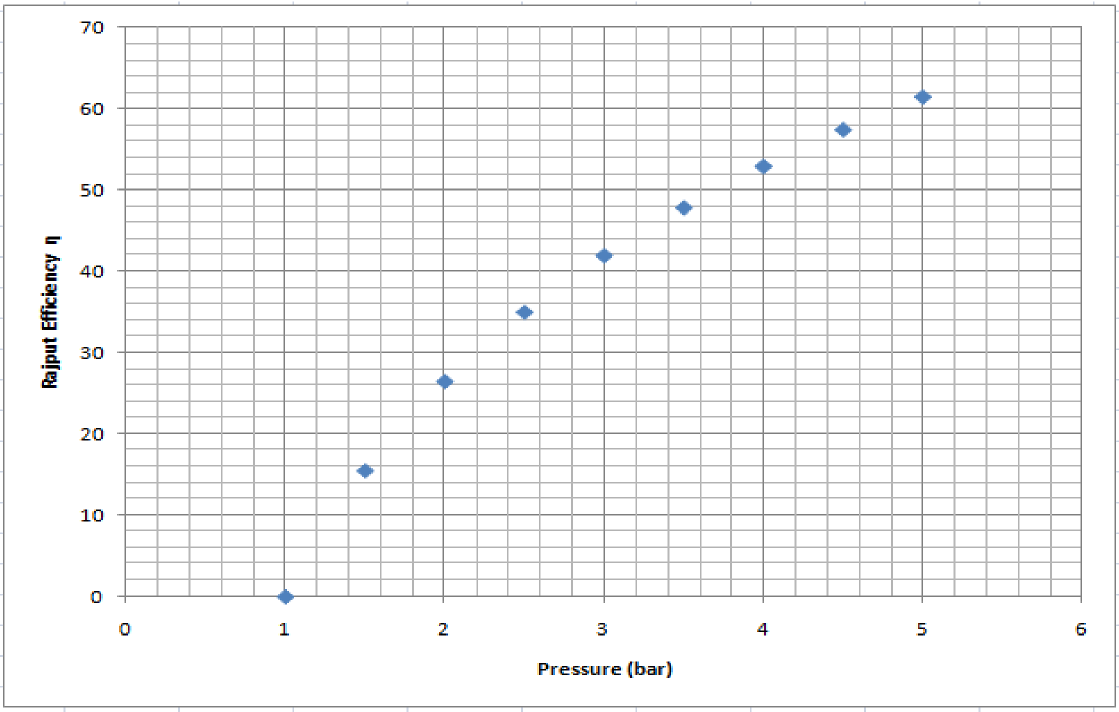

Figure 4.3: Shows a graph of Isothermal efficiencies of the RAJPUT Performance test

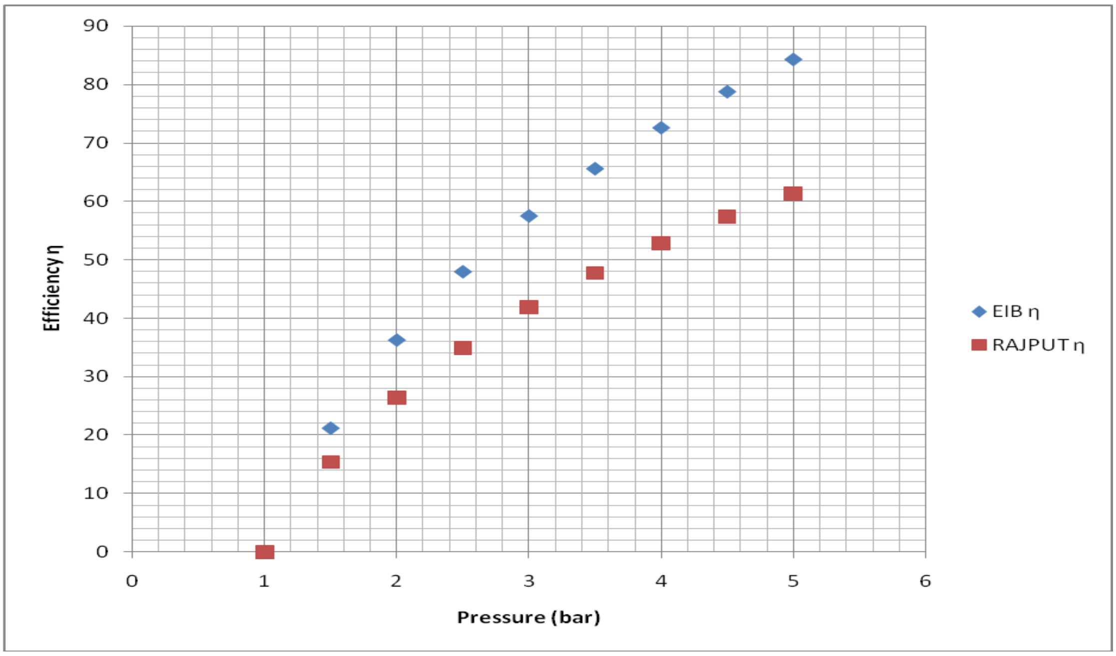

Figure 4.4: Validation of Isothermal Efficiencies of EIB against the RAJPUT Isothermal Efficiencies at different operating pressures

V. CONCLUSION

The single-acting reciprocating compressor was designed and manufactured. The project was successfully completed and the aims achieved. Thermodynamic concepts were employed for the analysis of the mass of air delivered per minute, delivery temperature at the end of compression. The indicated work, indicated power, heat transferred during compression. The work done by a reciprocating compressor, isothermal efficiency and overall isothermal efficiency of the compressor was also computed.

The results were analysed and compared with a standard R. K. Rajput performance test of a single-acting reciprocating compressor using thermodynamic concepts. The results were in good agreement; confirming the usefulness of applying thermodynamics concepts in the analysis of the performance of this compressor. Hence, the results of this single-acting reciprocating compressor are in good agreement with other existing single-acting reciprocating compressors.

The overall results show that as the pressure increases, there is a corresponding increase in isothermal efficiency of the compressor, giving the overall isothermal efficiency of the compressor of 84.3%.

The equipment is in used in the Department of Mechanical Engineering of Akwa Ibom State University, Nigeria's workshop for demonstration and teaching during Fluid Machinery, Applied Fluid Mechanics and Thermodynamics classes. It is also being employed for domestic purpose, such as cleaning. Other applications include, but not limited to the operation of small tools in the workshop, operating drill and hammers in road work within the university, excavating, inflating of tyres and spray painting among others.

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