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Enhancing the Efficiency of Reciprocating Compressors by Incorporating with Quick Return Mechanism

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Abstract: *A reciprocating compressor is a positive displacement machine that uses a piston driven by a crankshaft to deliver gases at high pressure. Innovations in the field of compressors paved way for the invention of modified types of compressors like screw compressors and scroll compressors. They replaced the conventional reciprocating compressors in many fields like refrigeration due to their compact size and higher efficiencies. However, reciprocating compressors are still being used in some industrial applications due to their peculiar properties suited for these areas. One of the factors that affect the efficiency of compressor is the time taken for a complete cycle of process. If we can reduce the time, we can improve the efficiency. Although it is possible to reduce the time taken for suction stroke as well as compression stroke, it is not possible to reduce the time of compression stroke without increasing the power input. However, we can reduce the time taken for the suction stroke where less power is required as compared to compression stroke. Our fundamental aim is to reduce the overall cycle time of the compressor by incorporating quick return mechanism in it. The quick return mechanism can reduce the time for suction stroke thereby increasing its efficiency.*

Keywords: *Reciprocating compressors, Quick return mechanism, Slider crank mechanism, Slotted link, Fixed link.*

1. Introduction

A reciprocating compressor is an inevitable component in many machines as well as many household equipments. The piston traverses the cylinder, sucking in the atmospheric air at one end of its stroke, and then compressing the air when it reaches the other end of its stroke. Reciprocating compressors can be single stage or multi stage depending upon the number of cylinders involved. Some examples where reciprocating compressors are essential are gas pipelines, oil refineries, natural gas processing plants, huge refrigeration plants and chemical plants.

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The conscious efforts to improve the efficiency and performance in reciprocating mechanism itself were less known. In this project we are trying to find out the modifications that have to be made in the structure and working of the reciprocating compressor so as to improve its efficiency. The theory of reciprocating mechanism is very old and the reciprocating compressor that we use today was evolved from the research and development of the reciprocating steam engine.

The famous Anglo-Irish physicist and inventor Robert Boyle produced a pump using piston rings made up of leather, to pump water to higher altitudes. However, the first practical reciprocating pump was made by Thomas Savery in 1698, which was driven by steam. However, it did not have a piston as such, although it used a receiver which has a volume of water trapped in it which acts as a piston, with the help of steam to push the water out. The return stroke gets affected by wetting the receiver filled with water, which creates a fractional vacuum, which then again sucks in the water.

The French physicist Denis Papin (22 August 1647 – 26 August 1713) invented the steam digester, which acted as the forerunner of the pressure cooker and of the steam engine. By getting inspired from Thomas Savery and Denis Papin, Thomas Newcomen in 1712 made a design of reciprocating steam engine, which used a piston rod assembly along with a true piston. It was the first ever-practical steam engine, which was known as Newcomen atmospheric engine. In late 1700's James Watt made a piston with the help of brass rings. Watt got patent for his steam engine, which is single acting, in 1769 and he got another patent for his double acting steam engine in 1782.

G. M. Miller in 1860 fabricated a piston that used back vented piston rings. This technique resulted in the use of a single piston ring, which uses compressive pressure to press the ring against the wall of the cylinder. Modern reciprocating compressors made use of piston rings that can be acclimatized to the profile of the cylinder, with the help of special designs [1]. The discovery of the reciprocating compressor is not well distinguished, since there are various nations that used steam engines and the technology used for the production of reciprocating compressors. The idea of reciprocating compressors was taken one-step further during 1890's by a draughtsman working for a British steam engine manufacturer called Belliss and Morcom, which is now a compressor manufacturer.

Albert Charles Pain, another scientist made a design by drilling holes down the centre of crankshafts and connecting rods, which allowed the oil which is pressurized to push through the holes that are made straight into the centre of the bearings. These holes were called oil ways. The principle that was presented by Alfred Morcom was later described in a paper, which was published by the Institution of Mechanical Engineers in 1897[2].

There were several attempts to improve the efficiency of reciprocating compressors. Back vented piston rings were used to avoid air leakage. This allowed the use of a single piston ring, which used compressive pressure to clasp the ring against the wall of the cylinder [3]. Another attempt to improve the efficiency of reciprocating compressors was the discovery of multistage reciprocating compressors. In a multistage compressor there are many cylinders having varying diameters. The air that intakes in the first stage get compressed and then it gets passed over a cooler to accomplish a temperature that is very close to ambient air. The cooled air thus we get is passed to the next stage where it again compressed and then heated up. This air is again passed over a cooler to achieve a temperature that is as close as possible to ambient temperature. Then this compressed air is passed to the final or the third stage of the air compressor from which it gets compressed to the required pressure and delivered to the air receiver after cooling sufficiently in an after cooler [4].

Introduction of inter coolers also improved the efficiency. An intercooler is a mechanical device used to cool a fluid, which may be liquid or gas, incorporated between two stages of a multistage heating process. An intercooler usually consists of a heat exchanger that removes waste heat in a gas compressor [5]. They are used in many applications, including air compressors, air conditioners, refrigerators, and gas turbines, and are widely known in automotive use as an air-to-air or liquid-to-liquid cooler for forced induction(turbocharged or supercharged) internal combustion engines to improve their volumetric efficiency by increasing intake air charge density through nearly isobaric(constant pressure) cooling [6].

2. Experimental

2.1. Design

In a reciprocating compressor the intake gas enters the suction manifold, then flows into the compression cylinder where it gets compressed by a piston driven in a reciprocating motion via a crankshaft, and is then discharged. A reciprocating compressor is shown in Figure.1. Quick return mechanism converts a circular motion (rotating motion following a circular path) into a reciprocating motion. The mechanism consists of an arm attached to a rotating disc that moves at a controlled uniform speed. Unlike the crank, the arm of the mechanism runs at a different rate than the disc. By having the disc run at a different rate than the attached arm, productivity increases. The design of this mechanism specializes in vector calculus and the physical aspects of kinematics and dynamics. Powered by a motor, the disc rotates and the arm follows in the same direction (linear and left-to-right, typically) but at a different speed. A diagram of a quick return mechanism is shown in Figure. 2.

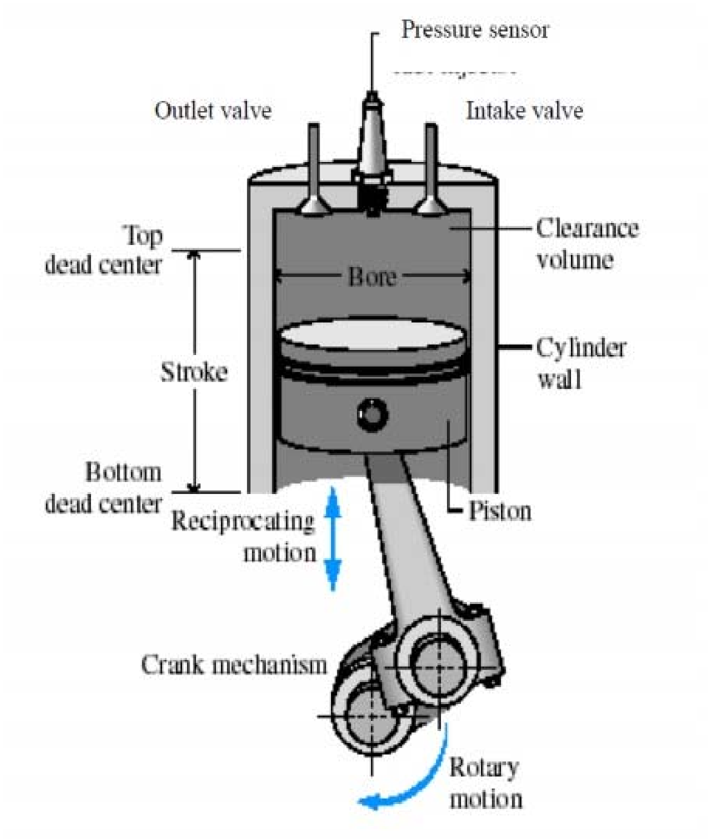

Figure 1: Reciprocating compressor[7]

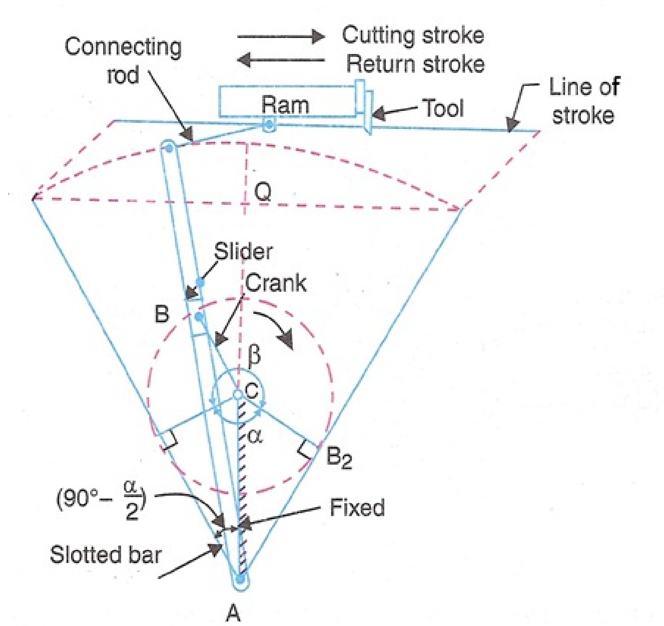

Figure 2: Quick return mechanism[8]

When the disc nears a full revolution, the arm reaches its farthest position and returns back to its initial position at a quicker rate, hence its name. Throughout the forward stroke, the arm has a constant velocity. Upon returning to its initial position after reaching its maximum horizontal displacement, the arm reaches its highest velocity. In this mechanism, the ram is actuated by gear drives associated with electric motor. First, the electric motor drives the pinion gear. Next, the pinion gear drives the bull gear, which rotates in opposite direction due to external gear meshing. A radial slide is provided on the bull gear. A sliding block is assembled on this slide. The block can be positioned in radial direction by rotating the stroke adjustment screw. The sliding block has a crank pin. A rocker arm is freely fitted to this crank pin. The rocker arm sliding block slides in the slot provided in the rocker arm called as slotted link. The upper end has fork, which is connected to the ram block by a pin while the bottom end of the rocker arm is pivoted.

The experimental setup is designed according to the working of a compressor incorported with quick return mechanism. The design of the proposed mechanism is shown in Figure. 3. The setup was fabricated with this design. The fabricated model is shown in Figure. 4. The compressor is the major part of our experimental set up. The compressor used for the experimental set up is a modified pedal pump. The modified pedal pump that is connected to the electric motor produces the required compressed air. It has a bore and stroke length of 8 cm each.

The motor gives the piston of the compressor the required reciprocating mechanism so that the processes of suction and compression happen. A dc high torque, low speed motor is required in our experimental set up. So we used a wiper motor of a four wheeler with a speed of 30 rpm, with an input voltage of 12V and a current of 1.5A. The power source gives the required input power for the working of the motor.

Since we need a dc power supply for the motor, an eliminator is used. The eliminator is made by a rectifier circuit along with a transformer. Two diodes and a capacitor connected in the right way constitute a rectifier. The transformer has the input voltage of 230V, an output voltage of 12V and an output current of 5A.

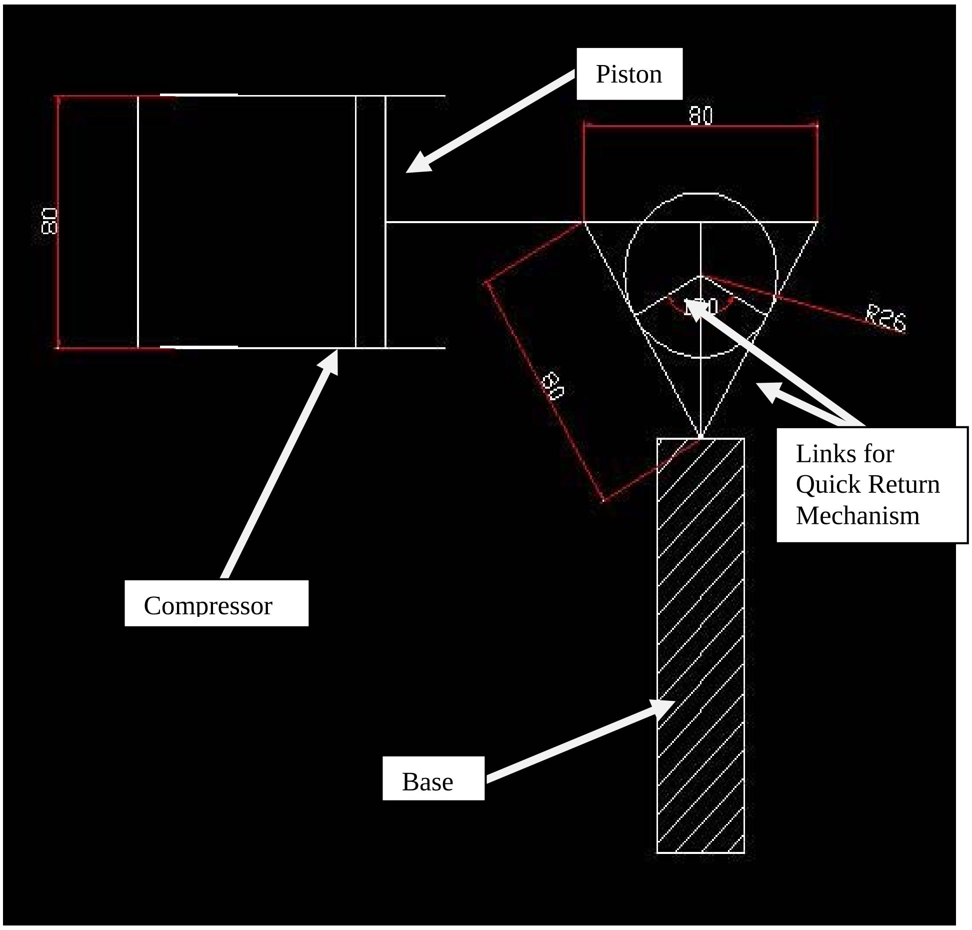

Figure 3: Design of experimental setup

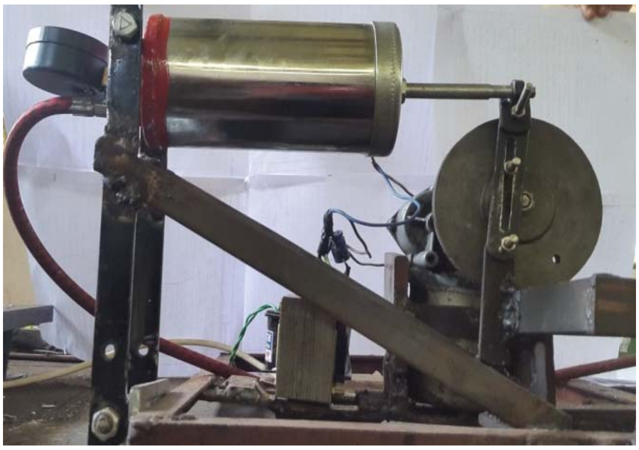

Figure 4: Fabricated setup

B. Testing

Experiments were conducted for the analysis of the performance of the reciprocating compressor incorporated with quick return mechanism, and the results obtained are compared with that of slider crank mechanism, conducted with the same test setup.

The experiment was conducted by connecting the transformer ends to an energy meter, whose ends are connected to a 230V main supply, and the equipment (which has quick return mechanism) ran for some time. The time for one revolution of energy meter disc and the speed of the motor are noted. The mechanism was shifted to slider crank, by connecting the motor directly to the compressor end, and the same was repeated for the slider crank mechanism. The experiment was repeated in three conditions- no load, with a load of 104 kPa, and with full load (106 kPa).

3. Results and Discussion

The tests were carried out in three conditions- without load, and with loads of 104 kPa and 106 kPa. The observations are given below:

Case 1: *No load*

The observations in no load condition is shown table 1

	Time for 1 revolution of energy meter	RPM
(a) Slider crank mechanism	41.1	24
(b) Quick return mechanism	43.29	24

Table 1: Observations for no load

$$\text{Input} = \frac{x}{t} \times \frac{1}{k} \times 3600 \text{ W} \qquad (3.1)$$

Where,

x = Number of revolutions of energy meter disc

t = Time for 1 revolution of energy meter disc

k = Energy meter constant

$$Discharge = \frac{LAN}{60} m^3/s \qquad (3.2)$$

Where,

L = Stroke length

A = Cross sectional area

N = Speed in RPM

Calculations:

1. Slider crank mechanism

$$\text{Input} = \frac{3600}{1800 \times 41.1} = 48.66\ \text{W}$$

$$\text{Discharge} = \frac{0.08^3 \times \pi \times 24}{4 \times 60} = 1.61 \times 10^{-4}\ m^3/s$$

2. Quick return mechanism

$$\text{Input} = \frac{3600}{1800 \times 43.29} = 46.2\ \text{W}$$

$$\text{Discharge} = \frac{0.08^3 \times \pi \times 26}{4 \times 60} = 1.74 \times 10^{-4}\ m^3/s$$

3.

i. % relative reduction in input

$$= \frac{48.66 - 46.29}{48.66} \times 100 = 5.3\ \%$$

ii. % relative increase in discharge

$$= \frac{1.74 - 1.61}{1.61} \times 100 = 8.1\ \%$$

Case 2: *Loaded (Pressure = 104kPa)*

The observations for a load of 104kPa is shown table 2

	Time for 1 revolution of energy meter	RPM
(a) Slider crank mechanism	37.1	21.5
(b) Quick return mechanism	40.05	23

Table 2: Observations for a load of 104kPa

$$Pressure = \rho g h \qquad (3.3)$$

Where,

ρ = Density of fluid (water)

g = Acceleration due to gravity

h = Water level height

$$Output = P_1 V_1 \ln \frac{P_2}{P_1} \qquad (3.4)$$

Where,

P_1 = Suction air pressure

P_2 = Compressed air pressure

V_1 = Volumetric discharge

$$Isothermal\ efficiency, \eta_{iso} = \frac{Output}{Input} \quad (3.5)$$

Calculations:

1. Pressure

$$\text{Pressure} = 100 \times 9.81 \times 0.41 = 4 \text{ kPa}$$
$$\text{Absolute pressure} = 100 + 4 = 104 \text{ kPa}$$

2. Slider crank mechanism

$$\text{Input} = \frac{3600}{1800 \times 37.1} = 53.9 \text{ W}$$

$$\text{Discharge} = \frac{0.08^3 \times \pi \times 21.5}{4 \times 60} = 1.44 \times 10^{-4}\, m^3/s$$

$$\text{Output} = 100 \times 0.65 \times 1.44 \times 10^{-4} \times \ln \frac{104}{100} = 3.67 \times 10^{-4} kW$$

$$Isothermal\ efficiency = \frac{3.67 \times 10^{-4}}{53.9 \times 10^{-3}} = 0.68\%$$

3. Quick return mechanism

$$\text{Input} = \frac{3600}{1800 \times 40.05} = 49.9 \text{ W}$$

$$\text{Discharge} = \frac{0.08^3 \times \pi \times 26}{4 \times 60} = 1.54 \times 10^{-4}\, m^3/s$$

$$\text{Output} = 100 \times 0.65 \times 1.54 \times 10^{-4} \times \ln \frac{104}{100} = 3.92 \times 10^{-4} kW$$

$$Isothermal\ efficiency = \frac{3.92 \times 10^{-4}}{49.9 \times 10^{-3}} = 0.785\%$$

4.

i. % relative reduction in input

$$= \frac{53.9 - 49.9}{53.9} \times 100 = 7.4\ \%$$

ii. % relative increase in discharge

$$= \frac{1.54 - 1.44}{1.44} \times 100 = 6.94\ \%$$

iii. Improvement in efficiency = 0.105%

iv. % relative increase in efficiency

$$= \frac{0.785 - 0.68}{0.68} \times 100 = 15.44\%$$

Case 3: Full Load (Pressure = 106kPa)

The observations for a load of 106kPa is shown table 3.

	Time for 1 revolution of energy meter	RPM
(c) Slider crank mechanism	33.5	19
(d) Quick return mechanism	37.01	20.5

Table 3: Observations for full load (106kPa)

1. Pressure

$$\text{Pressure} = 100 \times 9.81 \times 0.61 = 6 \text{ kPa}$$
$$\text{Absolute pressure} = 100 + 6 = 106 \text{ kPa}$$

2. Slider crank mechanism

$$\text{Input} = \frac{3600}{1800 \times 33.5} = 59.7 \text{ W}$$
$$\text{Discharge} = \frac{0.08^3 \times \pi \times 19}{4 \times 60} = 1.273 \times 10^{-4}\, m^3/s$$
$$\text{Output} = 100 \times 0.65 \times 1.273 \times 10^{-4} \times \ln\frac{106}{100} = 4.821 \times 10^{-4} kW$$
$$Isothermal\ efficiency = \frac{4.821 \times 10^{-4}}{59.7 \times 10^{-3}} = 0.8075\%$$

3. Quick return mechanism

$$\text{Input} = \frac{3600}{1800 \times 37.01} = 54.04 \text{ W}$$
$$\text{Discharge} = \frac{0.08^3 \times \pi \times 20.5}{4 \times 60} = 1.34 \times 10^{-4}\, m^3/s$$
$$\text{Output} = 100 \times 0.65 \times 1.34 \times 10^{-4} \times \ln\frac{106}{100} = 5.075 \times 10^{-4} kW$$
$$Isothermal\ efficiency = \frac{5.075 \times 10^{-4}}{54.04 \times 10^{-3}} = 0.939\%$$

4.

i. % relative reduction in input

$$= \frac{59.7 - 54.04}{59.7} \times 100 = 9.48\ \%$$

ii. % relative increase in discharge

$$= \frac{1.34 - 1.273}{1.273} \times 100 = 5.26\ \%$$

iii. Improvement in efficiency = 0.1315%

iv. % relative increase in efficiency

$$= \frac{0.939 - 0.8075}{0.8075} \times 100 = 16.3\%$$

The experimental results are tabulated in Table 4

Pressure (kPa)	Power Input			Discharge			Isothermal efficiency(%)		
	Slider crank (W)	Quick return (W)	Savings (% Relative reduction)	Slider crank (m^3/s)	Quick return (m^3/s)	Improvement (% Relative increase)	Slider Crank	Quick return	Improvement (% Relative increase)
100	48.6	46.2	5.3	1.61	1.74	8.1	0	0	_
104	53.9	49.9	7.42	1.44	1.54	7.42	0.68	0.785	15.44
106	59.7	54.04	9.48	1.273	1.34	5.26	0.807	0.939	16.3

Table 4: Experimental results

In the no load case, the power input was 48.6 watts in slider crank mechanism, whereas 46.2 watts in quick return mechanism. That is, there is a percentage relative reduction of 5.3% for the quick return case, as compared with slider crank case. The discharge for slider crank mechanism was 1.61 m^3/s, whereas 1.74 m^3/s for quick return mechanism. That is, there is a percentage relative improvement of 8.1% for the quick return case, as compared with slider crank case. The efficiency change has no significant role in this case, because the efficiency is zero as there is no load.

When a 104 kPa load was applied, the power input was 53.9 watts in slider crank mechanism, whereas 49.9 watts in quick return mechanism. That is, there is a percentage relative reduction of 7.42 % for the quick return case, as compared with slider crank case. The discharge for slider crank mechanism was 1.44 m^3/s, whereas 1.54 m^3/s for quick return mechanism. That is, there is a percentage relative reduction of 7.42 % for the quick return case, as compared with slider crank case. The isothermal efficiency, for slider crank mechanism was 0.68%, whereas an efficiency of 0.785% was obtained for quick return mechanism. That is, there is a percentage relative increase of 15.44 % for the quick return case, as compared with slider crank case.

When a 106 kPa load was applied, the power input was 59.7 watts in slider crank mechanism, whereas 54.04 watts in quick return mechanism. That is, there is a percentage relative reduction of 9.48 % for the quick return case, as compared with slider crank case. The discharge for slider crank mechanism was 1.273 m^3/s, whereas 1.34 m^3/s for quick return mechanism. That is, there is a percentage relative reduction of 5.26 % for the quick return case, as compared with slider crank case. The isothermal efficiency, for slider crank mechanism was 0.807%, whereas an efficiency of 0.939% was obtained for quick return mechanism. That is, there is a percentage relative increase of 16.3 % for the quick return case, as compared with slider crank case.

From these observations, we can conclude that incorporating quick return mechanism in reciprocating compressors can result in significant reduction in input power required for the operation and increase in discharge. Furthermore, it can improve the efficiency considerably.

4. Conclusion

Incorporating quick return mechanism in reciprocating compressors can result in significant reduction in the input power required for the operation and increase in discharge. Furthermore, it can improve the efficiency considerably. The cost for implementing the mechanism can be retrieved easily from the savings by the mechanism, in a short span of time. The decreased input power and increased discharge can lead to the requirement of smaller components, and hence smaller equipment. It has a large scope in the fields of oil refineries, gas pipelines, chemical plants, refrigeration plants, etc., where reciprocating compressors are the only used compressors.

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