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Experimental analysis of a hermetic reciprocating compressor to improve starting characteristics.

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Abstract*— Better starting performance of the hermetic compressor has become one of the primary development targets due to variation in operating pressures of refrigerants. Reciprocating mechanism subjected to pressure transients in suction and discharge lines and critical conditions occurred during on-off cycling which imposes greater forces on piston this causes requirement of high starting torque. For reducing torque demand and improving starting ability, various methods were studied but offset cylinder method is implemented which reduces torque demand due to the reduction of forces on the crank by reducing the angularity of connecting rod. The paper deals with the evaluation of torque demand for better operation of compressor and Excel program have been successfully developed for the same. Experimental validation of mathematical results was done on offset cylinder type compressor prototype to overcome startability issues also effect of some refrigerants on torque requirement is discussed.

***Keywords*— Torque, Startability, On-Off cycling, Hermetic reciprocating compressor, Offset mechanism**

I. INTRODUCTION

Small-scale hermetic reciprocating compressors are widely used to compress refrigerant in household refrigerators and air-conditioners. In hermetic reciprocating compressors, the crankcase and motor are mounted on same shaft inside the housing. When compressor is started, it is subjected to critical operational conditions such as sudden decrease in pressure at suction line and increase in pressure at discharge would increase pressure difference in suction and discharge.Frequent on-off creates redistribution of refrigerant within the system promotes pressure differential also large quantity of liquid refrigerant is suddenly dumped into the compressor this causes more torque requirement also during startup motor has to overcome the inertia of rotating components [1]. Startability issues takes place due to over pressure during starting and running condition so it is necessary to evaluate the total load torque for motor selection based on gas force, inertia of component and frictional resistance of bearing. Evaluation of the total load torque, need to consider summation of these parameters which actively contributes to starting resistance.
The compressor is an important component of the refrigeration system.Whether compressor will start under certain conditions or not is the most important task for the manufacturer.It is required that the compressor must start in these conditions without any problem. Startability test is performed in order to verify whether the compressor will start or not. The induction motor is used to drives the crankshaft. The torque produced by motor must overcome high pressures, Inertia of rotating components and bearing friction. Choice of refrigerant is also influenced starting ability. Upcoming refrigerants may have unexceptional pressures so it is very important to study starting characteristics. Torque leverage can be obtained by replacing the inline slider crank mechanism by offset slider crank mechanism. This will help to improve starting characteristics also it will reduce side thrust on the cylinder wall.

II. PROBLEM DESCRIPTION

When the compressor is started after a prolonged period, pressures on suction and discharge sides are equal.So, the starting process is relatively easier.But if the compressor is in running condition and electric supply is switched off and restarted, unequal pressure differential is develope due unequal distribution of refrigerant, which causes very high starting resistance on the motor.Time required to equalize the pressures is about one or two minutes.But sudden on-off is takes place in fraction of second. When compressor operates during the sudden on-off situation, unequal pressures create a tremendous force on the piston and electric motor is unable to overcome these forces to maintain the compression process.So,compressor model was not have good start ability.Starting characteristics are improved by employing offset cylinder mechanism to current model. Therefore, Forces due to pressure differential is reduced by offset cylinder mechnism. The objective of the analysis was to identify correct torque demand and provide improvements to the current model so as to reduce torque requirement.

III. LOAD TORQUE CALCULATION FOR INLINE COMPRESSOR

First step to improve starting characteristics of compressor is to find out accurate load torque which is going to act during suction and discharge strokes. Following equations can be utilise to find torque demand due to gas force, inertia and friction [2].

Compression torque by assuming volumetric efficiency 100% is given by,

$$T_C = F_C \cdot R \sin \emptyset \cdot \left(1 + \frac{R \cos \emptyset}{L \cos \psi}\right), \quad F_p = \frac{\pi \cdot dp^2}{4}(p_c - p_s). \tag{1}$$

Inertia torque is given by,

$$T_i = \frac{m_b}{2} R^2 \omega^2 \left(\frac{R}{2L} \sin \Theta - \sin 2\Theta - \frac{3R}{2L} \sin 3\Theta\right). \tag{2}$$

Power losses in bearing given by Petroff's Equation,

$$T_F = \frac{2\pi\mu r^3 b\omega}{h}. \tag{3}$$

Using these above equations, one can find out torque at each crank angle position. Addition of above torque gives resultant load torque for operation.

IV. MOTOR PARAMETERS SELECTION

Industry professionals face the challenge of choosing the most efficient system for a particular application. Achieving a quick start is simple – just apply a very large motor to the pump assembly. This is impractical because of the costs associated with a large motor and a drive train must be strong enough to withstand the strain of a high torque start-up. Selection of motor includes defining break down torque, locked rotor torque, and efficiency.

For defining starting torque of the motor to start satisfactorily at given voltage range, depends on unequal pressure on suction and discharge side. It is observed that refrigeration reciprocating compressors have a tendency to stop at specific crank angle position near the bottom dead center. After taking the start-stop test at various pressure conditions and at various line voltages for various refrigerants, the position where compressor stops during on-off cycling is determined. Torque at this position will be used to define starting torque. The manufacturer can perform these simple tests on its compressor model. This will help to define starting torque and other motor selection parameters for new developments.

It is experimentally identified that 220° to 230° crank angle is most favorable stopping position. Every time compressor stops at this position. Obviously, it will start from where it stops. This will give a estimation of starting torque value. Usually, the manufacturer does a lot of iterations to define this value and it takes a lot of time. This simple methodology can be of great help to the motor designer.

Starting Torque Program

Select test condition

Refrigerent	Groups	Ps	Pd
R 404A	LBP	127	368

Input Parameters

Input Parameters	m	inch	Input Parameters	Value	Units
Length of CR	0.04953	1.95	ω	366.5191	Rad/s
R(Ecc.)	0.011684	0.46	Displacement	2.24E-05	m^3
R/L=	0.235897436		Mass of Con Rod	0.111207	Kg
Dia. Piston	0.03493516	1.3754	Mass of piston	0.060328	Kg
D^2	0.001220465		Reciprocating mass	0.097397	Kg
Area Piston	0.000958551	m^2	Rotating mass	0.037069	Kg

Test Condition

R404A/LBP	PSI	Bar
Suction	127	8.75634176
Discharge	368	25.3727068

Output

	Nm	Kg-cm
Starting Torque	11.1588124	113.788219

Ø	Pc	Crank angle R	Connecting	Time	cos(Ø)	sin(Ø)	sin(2Ø)	cos(2Ø)	sin(Ψ)	cos(Ψ)	Pc-Ps	Fc	cosØ/sinΨ	Torque(Nm)
0.01	25.37270684	0.000174533	4.12E-05	4.76E-07	0.999999985	0.000175	0.0003	1	4.24249E-05	1	16.6163651	1592.76381	1	-0.00401423
1	25.37270684	0.017453293	0.004117	4.76E-05	0.999847695	0.017452	0.0349	0.99939	0.004242279	0.999991	16.6163651	1592.76381	0.9998567	-0.40139208
2	25.37270684	0.034906585	0.008233	9.52E-05	0.999390827	0.034899	0.0698	0.99756	0.008483265	0.99996402	16.6163651	1592.76381	0.9994268	-0.80259603
3	25.37270684	0.052359878	0.012346	0.000143	0.998629535	0.052336	0.1045	0.99452	0.012721667	0.99991908	16.6163651	1592.76381	0.9987104	-1.20342383
4	25.37270684	0.06981317	0.016456	0.00019	0.99756405	0.069756	0.1392	0.99027	0.016956194	0.99985623	16.6163651	1592.76381	0.9977075	-1.60368771
5	25.37270684	0.087266463	0.020561	0.000238	0.996194698	0.087156	0.1736	0.98481	0.021185556	0.99977556	16.6163651	1592.76381	0.9964183	-2.00320025
6	25.37270684	0.104719755	0.02466	0.000286	0.994521895	0.104528	0.2079	0.97815	0.025408465	0.99967715	16.6163651	1592.76381	0.9948431	-2.40177453
7	25.37270684	0.122173048	0.028753	0.000333	0.992546152	0.121869	0.2419	0.9703	0.029623634	0.99956112	16.6163651	1592.76381	0.9929819	-2.7992242
8	25.37270684	0.13962634	0.032836	0.000381	0.990268069	0.139173	0.2756	0.96126	0.03382978	0.99942761	16.6163651	1592.76381	0.9908352	-3.19536364

Fig. 1 Excel program

High operating system pressure results in starting problems. In next section offset type arrangement is discussed to reduce torque requirement.

V. OFFSET TYPE COMPRESSOR-SOLUTION TO SOLVE THE STARTABILITY PROBLEM

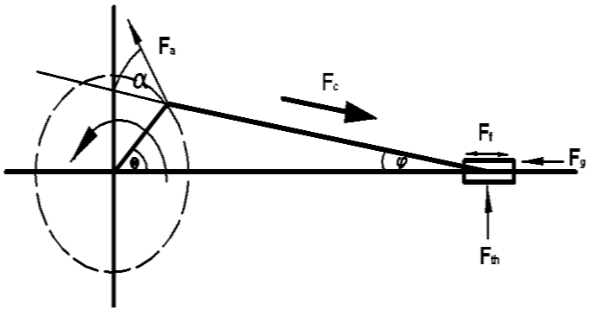

Fig. 2 Inline Slider Mechanism

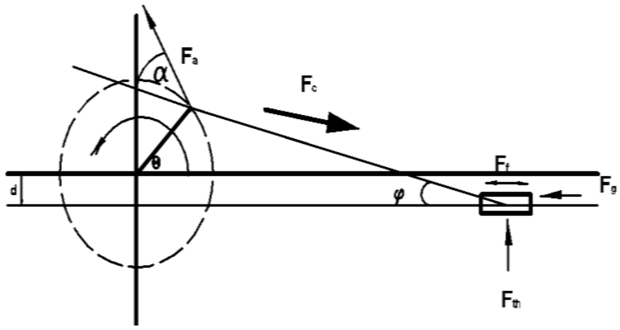

Fig. 3 Offset Slider Crank Mechanism

It is common practice in the industry to mount standard sized motor for a compressor. There are several reasons for this: (1) to save manufacturing costs, (2) to standardize installation, and (3) to enable the use of equipment for a different application. Sometimes the problem of startability arises due to insufficient motor torque. Using a bigger motor is not a solution because it will affect superheat losses and power consumption. To handle such situations offset mechanism is of great help. But offsetting causes an increase in stroke length. This can be restored by reducing crank length.
Conventional (figure 2) reciprocating compressor are built with the axis of the piston cylinder and the axis of rotation of the crankshaft is the same. But offsetting (figure 3) the axis of rotation of the crankshaft from the axis of piston-cylinder benefits in less torque demand due to change in position of connecting rod angularity when the piston reaches to top dead center. To maximize benefit in torque; iterations can be done to find out offset distance at which more torque reduction is possible.

Advantages of Offset mechanism-

1. It can be done with little modifications in existing model.
2. Reduction in load due to reduction in reaction force on crankshaft.
3. Increase in working volume. Compact arrangement as compared to inline mechanism
4. As load on crankshaft reduces, require less strong components.
5. Mechanism accelerate faster to rated speed causes faster development of hydrodynamic lubrication regime would reduce frictional losses

But more offset creates imbalance of mechanism which increases side thrust on cylinder wall and shaking forces but this can be manage by better balancing.
Following equations are worked out to find torque demand of offset slider crank mechanism [3].
Slider acceleration is given by,

$$a = R\omega^2 \cos\Theta + \frac{(R\sin\Theta + d)^2 R^2\omega^2 \cos^2\Theta}{\left[\sqrt{L^2 - (R\sin\Theta + d)^2}\right]^3} - \frac{(R\sin\Theta + d)R\omega^2 \sin\Theta + R^2\omega^2\cos^2\Theta}{\sqrt{L^2 - (R\sin\Theta + d)^2}} \tag{4}$$

Force in connecting rod,

$$F_C = \frac{(P * A - m * a)}{\cos\varphi} \tag{5}$$

Fa, vertical component of Fc,

$$F_a = F_c\,.\cos\left(90 - \sin^{-1}\left(\frac{R\sin\theta + d}{L}\right)\right) \tag{6}$$

Combined Gas load and inertia torque,

$$T = F_a.R \tag{7}$$

Calculations are performed by varying offset distance from 0 to 3 mm in steps of 0.6 mm. Fig 4 shows torque reduction before and after the offset. It shows that torque is decreases suddenly at 0.6 mm by 27.15%, later as the offset distance is increases; torque is also increasing. Another parameter on which offset is selected is thrust force. It is the horizontal force on cylinder wall exerted due to floating motion of connecting rod responsible for friction. Fig 5 shows maximum side thrust in a cycle after offset of 0.6 mm but after it is increases gradually. Therefore 0.6 mm is best value to achieve maximum benefit in terms of torque and side thrust.

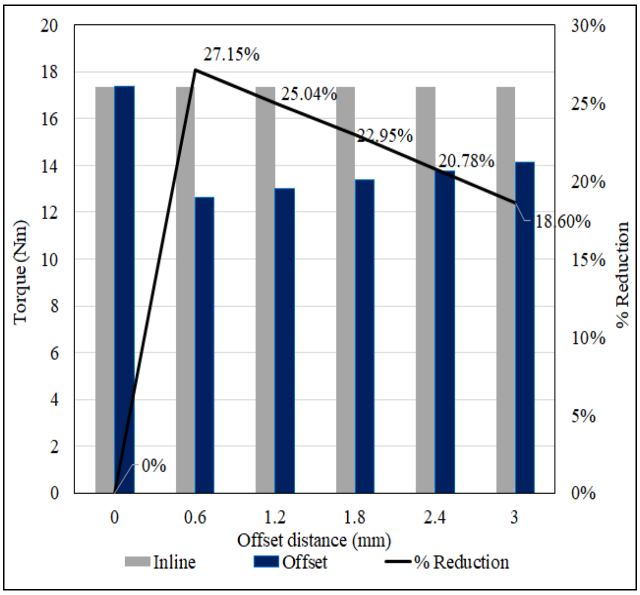

Fig. 4 Torque vs offset

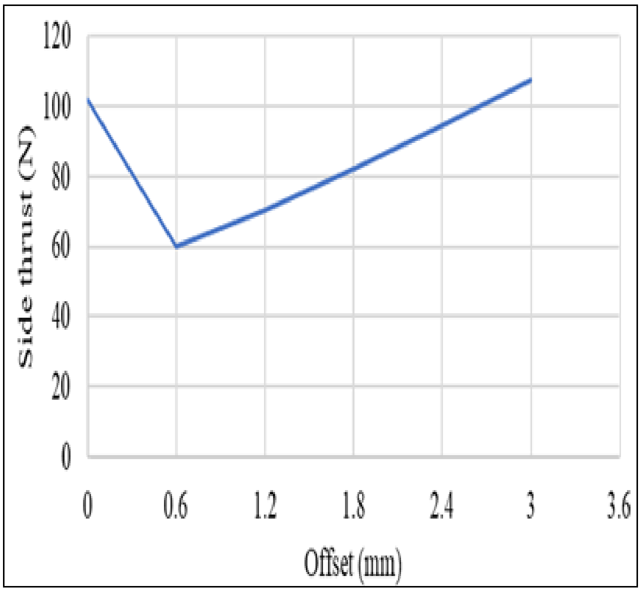

Fig. 5 Torque vs Crank angle

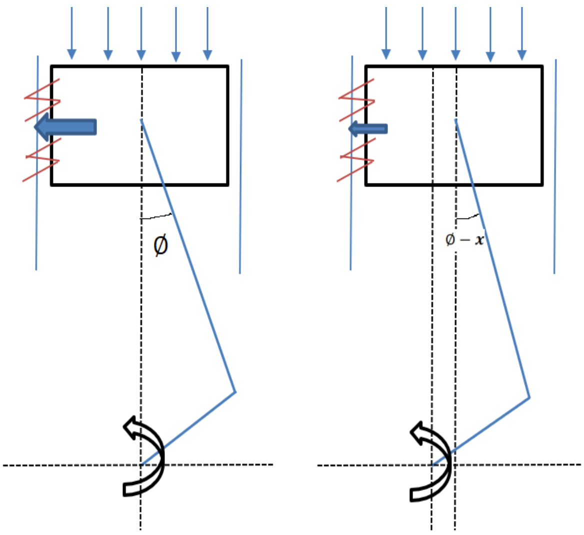

Fig. 6 Offset position for friction reduction

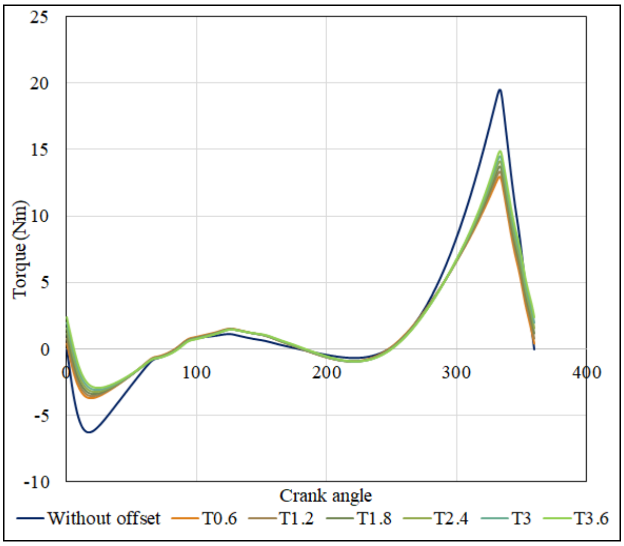

Fig. 7 Comparison of Crank angle vs torque for inline and offset mechanism.

Figure 7 shows the torque comparison between inline (conventional) and offset slider crank mechanism. The curve for offset mechanism lies below the conventional mechanism. This is the indication of reduction of torque demand. The requirement of compressor with refrigerant choice as R-404A impose very large starting a resistance. So, pressure and inertia of rotating components are not controllable parameters but friction can be reduced, due to reduction of side thrust force. So, this additional benefit can be achieved by offset slider crank arrangement. Fig 6 represents inline and after offset position. By offsetting cylinder to right hand side, the mechanism becomes an offset slider crank also angularity of connecting rod is reduces by few degrees angle. This results in reduction in side thrust on cylinder which is responsible friction between piston skirt and cylinder wall.

VI. EXPERIMENTAL ANALYSIS

An experimental unit is used to study single stage VCRS system. This unit has been designed to validate offset cylinder arrangement based on mathematical calculations. During the development of compressor, various iterations were performed such as downsized displacement with inline cylinder and offset cylinder arrangement and tested on calorimeter for startability test. It is found that improvement is seen in starting performance of offset cylinder arrangement compressor. Offset cylinder is done by shifting the cylinder bore as shown in figure 9, relative to the cross bore keeping all geometrical parameters as it is.

Table 1.
SPECIFICATIONS OF HERMETIC COMPRESSOR

Parameters	Dimension
Cooling Capacity	3630 Btu/hr.
Power Consumption	864 W
EER	4.2
Shaft eccentricity	0.460 inch
Connecting rod length	1.968 inch
Piston diameter	1.375 inch
Displacement	22.4 CC
Frequency	60 Hz

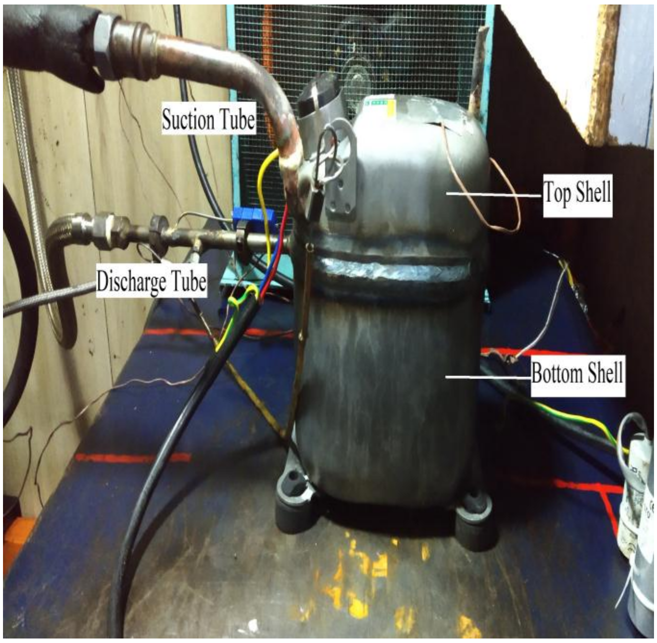

Fig. 8 Experimental setup

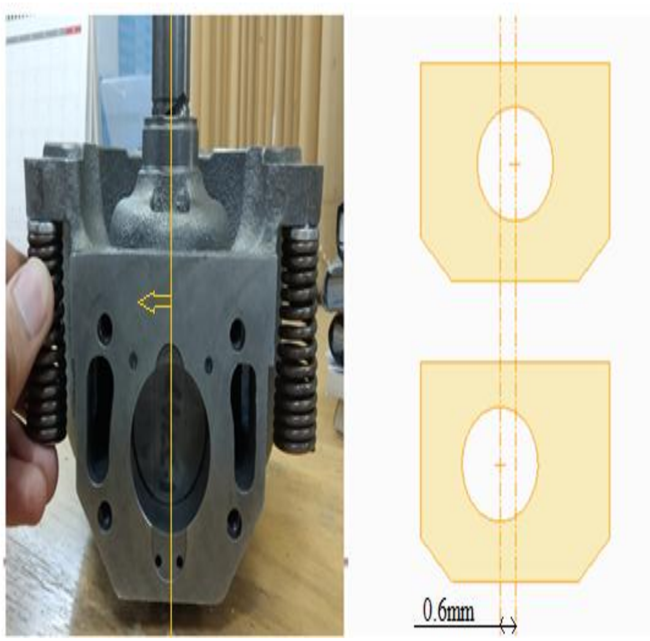

Fig. 9 Modifications in crankcase

Fig.8 shows experimental prototype equipped and necessary connections with test facility. Startability tests were performed successfully on this setup. Instruments for pressure, mass flow, temperature measurement are connected and values are show on control panel of calorimeter. Test were performed as per industry standard conditions for low back pressure appliances.

VII. EFFECT OF REFRIGERANTS ON THE STARTABILITY

Startability test is performed according to application group such as LBP, MBP, CBP. Figure 5 shows comparison of differential pressure for R-134a, R-404A, R-22, R-290 at standard ASHRAE conditions.

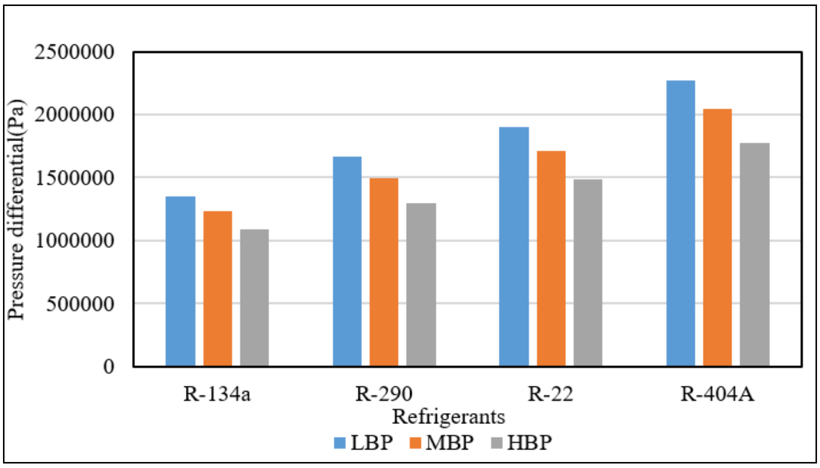

Fig. 10 Pressure differential Comparison of different refrigerants

It shows that pressures differential of R-404A is about 40% higher than R-134a for LBP group. Therefore, the compressor operating on R-404A has more chances of occurring starting problem as compared to R-134a. Startability is greatly depend on type of refrigerant used in the system. It is better to use low operating pressure refrigerant in the system.

For LBP application group compression ratio is much higher because temperature inside the evaporator is to be maintain between -30℃ to -10℃ and condensing temperature is mostly depending on ambient temperature. Therefore, Chances of occurring startability issues are higher in these applications due to large pressure differential.

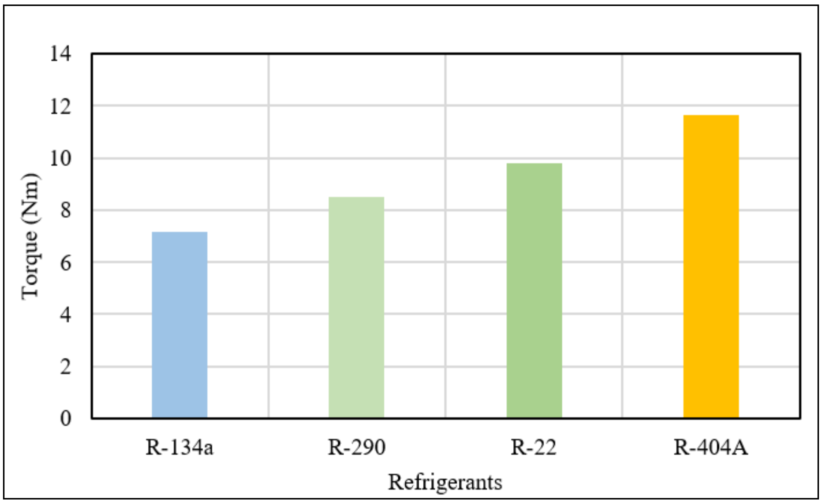

Fig. 11 Torque demand comparison for different refrigerants

Figure 6 shows comparison of torque demand of similar compressor model for various refrigerants. This graph indicates that greater the pressure differential, greater will be the torque demand of compressor for that refrigerant. R-404A would require high torque producing motor as compared to other refrigerants.

Offset crankshaft mechanism reduces force on crank which reduce torque demand during operation. Also, there is a significant reduction in thrust forces and torque at particular offset value improves the starting ability. According to new regulations for environmental protection, new refrigerants are introduced in the market which are either natural or environment friendly substances. These next generation refrigerants may have very high operating pressures, so it is necessary to design and systems with reduced load on motor to have a better starting ability.

VIII. RESULTS AND DISCUSSION

It is observed that most favorable stopping position is near to bottom dead center, also sometimes direction of rotation reverted due to the inertia of rotating compressors. This imposes larger torque demand on the motor. Interesting is that, when the compressor tries to start from this position motor must produce high starting torque. Length of connecting rod and eccentricity is managed in order to restore stroke length for offset cylinder mechanism by keeping the L/d_p ratio as the original. The optimum combination of these parameters leads to better results. Simulation results show that for a reciprocating refrigerant compressor with a displacement of 23 cc, the optimal combination of the crank length(R) =0.47 inch and the connecting rod length L =1.96 inch to minimize the torque demand by 27.15% with an offset distance of 0.6 mm. Startability tests are performed on inline and offset type compressor of similar configuration and it is observed that offset cylinder compressor exhibits better start as compared to inline compressor.

IX. CONCLUSION

In this work, torque comparison of conventional & offset cylinder compressor is studied both analytically and experimentally. an approach to find starting torque of a single cylinder reciprocating compressor is proposed. Calculations also performed on lower displacement models and compared with test results are in good agreement. The aim of the offset slider crank mechanism is to lower torque demand by changing the position of connecting rod angle. Compressor with offset cylinder arrangement is tested successfully for start ability and it is found that compressor is started satisfactory even at lowest specified voltage.

Nomenclature

R	Crank length	m
dp	Diameter of piston	m
A	Area of piston	m^2
L	Length of connecting rod	m
d	Offset distance	m
Fp	Force on piston	N
pc	Cylinder pressure	Bar
ps	Suction pressure	Bar
ω	Angular velocity	rad/s
r	Radius of bearing	m
b	Width of bearing	m
Θ	Crank angle	degrees
Φ	Connecting rod angle	degrees
α	Angle between the force Fa and extension of force Fc	N
μ	Dynamic viscosity of oil	Ns/m^2
Fa	Vertical component of Fc	N
Fc	Connecting rod force	N
Fg	Gas pressure force	N
Fth	Side thrust force	N
mb	Reciprocating Mass	Kg

LBP	Low back pressure
MBP	Medium back pressure
CBP	High back pressure

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