Experimental Investigation of the Effect of Oil Injection Flow Rate on the Performance of Oil-Injected Twin-Screw Compressor

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ABSTRACT

One of the performance parameters to measure the efficiency of an oil-injected, twin-screw compressor is the volumetric efficiency and specific shaft power consumption. The volumetric efficiency is a measure of the fraction of theoretical volume flow delivered. The inefficiency in volume flow is observed because of the internal leakages during the compression of gas in the clearance gaps. These clearance gaps are maintained between the rotating elements and the rotating-stationary elements for assembly, operation, and reliability purposes. To compensate for the undesirable effect on volumetric efficiency because of relatively increased clearances, these clearance gaps can be filled with lubricating oil during operation. However, beyond a certain level of oil flow, the drag loss caused by the shearing of excess oil in the clearance gaps can lead to an increase in shaft power. So, a trade-off between higher volumetric efficiency and lower shaft power consumption needs to be investigated.

In this paper, an oil-injected, twin-screw air compressor used for a 75 kW input power is experimentally investigated to understand the effect of oil injection flow rate on the performance of the screw compressor. The oil injection flow rate, the compressor speed, and the discharge pressure are varied during the experimental investigation. To analyze the effect of these varied parameters on the performance, the compressor shaft power and volume flow rate are measured. The volumetric efficiency and compressor shaft power are calculated and plotted against injection oil flow, pressure ratio, and rotational speed. From the comparison, it is understood that with the increase in oil injection rate, the volumetric efficiency increases while the specific power consumption does not change much. The investigation confirms that an optimum oil injection rate is required for a particular operating condition, the rotational speed, and the pressure ratio. Although additional oil injection improves the volumetric efficiency, it adversely affects the shaft power.

Keywords: twin-screw compressor, oil injection flow rate, volumetric efficiency, specific shaft power

1. INTRODUCTION

The principle of a rotating positive-displacement compressor, the twin-screw form was developed during the 1930s when a rotating compressor with a high flow rate and stable flow under varying pressure conditions was required. A screw compressor is best described as a rotating positive-displacement volume reduction device. In a screw compressor, two helically grooved rotors rotate continuously in a tightly enclosed housing. With the successive rotation of the screw rotors in a particular direction, it creates suction at one end of the housing, and gas is trapped in the volume created between the rotors and the rotor and housing. As the rotors continue to rotate, the trapped volume is reduced thereby increasing the pressure of the gas before it is finally discharged into the other end of the housing. The clearances are maintained between the rotors and the rotor with the housing for assembly, operation, and reliability purposes. However, they adversely affect the compressor performance because of the internal leakages which reduce the volumetric efficiency of the compressor. With state-of-the-art manufacturing technology, it is possible to manufacture screw compressors with tight clearances and at a low cost. In the oil-flooded screw compressor, the oil is injected into it during the compression for mainly three reasons; cooling the compressed gas, lubricating the rotating elements, and sealing the clearance gaps. In-compression cooling enables the compression process to go near the isothermal process thereby reducing the power requirement for compression. It also lowers the discharge temperature of the compressed gas and because of this higher-pressure ratio can be achieved. Although the effect of the amount of oil injection rate on the performance of the compressor at different operating conditions is theoretically predicted by commercial tools, there are only a few references available for experimental investigation. Also, the available experimental investigations are limited with the number of parameters varied during the experiment. So, a comprehensive experimental investigation is needed to understand the overall effect of oil injection rate on the volumetric efficiency and on the shaft power for different rotational speeds and at different pressure ratios.

To check the effect of oil flow rate on screw compressor performance, many researchers have developed mathematical models based on the thermodynamics of the process.

Stosic *et al.* (2003) developed a numerical model to check the effect of oil injection on the working process of a twin-screw compressor. The effect of the different geometrical parameters of the rotors such as male and female tip radii on the specific power of the compressor is investigated.

Hsieh S. H. et al. (2011) developed a mathematical model to check the temperature distributions in the rotors of oil-injected screw compressors. The six empirical constants are determined by minimizing the difference between the calculated and measured temperature of the rotors. The heat transfer by convection, conduction, and radiation in the screw compressor and bearings is discussed and analyzed.

Fujiwara and Osada (1995) experimentally obtained the heat transfer coefficient and flow coefficient which are used to develop the mathematical model of the screw compressor performance. Fleming and Tang (1995) analyzed the six types of internal leakages in the screw compressors using the mathematical model. The leakage paths inside the screw compression chamber and their importance to improve the compressor performance are discussed. Wang *et al.* (2021) performed the transient CFD analysis of a twin-screw compressor with oil injection in the compression chamber. CFD simulation results found good agreement with the experimental results for air mass flow rate and indicated power. Temperature distribution in the screw compressor is well analyzed due to oil injection inside the chamber.

Stosic *et al.* (1990) presented the mathematical model of the oil injection on the screw compressor working process. The study further extended to investigate the results with experimentation and observed better results in lower oil consumption, better gas cooling, and an improvement in overall compressor performances. Valenti *et al.* (2013) have merely focused on energy saving by improving the isentropic efficiency during the compression process by considering heat transfer between the mixed flow of gas and lubricating oil, which also resulted in discharge temperature on lower sides. The effective oil distribution in the compressor results in the effective heat transfer which affects discharge temperature and efficiency, as an outcome discharge temperature was lowest for 100 μm oil droplet size.

Peng *et al.* (2003) presented the effect on volumetric efficiencies and adiabatic efficiencies of screw compressors at different speeds and discharge pressure. They have also recorded and analyzed p-V diagrams at different rotor speeds for a twin-screw air compressor.

The presented literature review shows that the effects of oil injection in the twin-screw compression chamber have been widely investigated. But very few investigations have observed the effect of oil flow rate at different speeds as well as at different pressure ratios of the screw compressor. Zhilong He *et al.* (2018) experimentally checked the effect of varying oil flow rates on the volumetric efficiencies, adiabatic efficiencies, and specific power of the oil-flooded screw compressor. This investigation also indicates the effect of rotational speed on compressor performance. The heat transfer model is also developed to calculate the heat exchange between oil droplets and air in the compression chamber. But it lacks a similar experimental investigation of the effect of oil flow rate linked with different pressure ratios.

In this paper, the experimental setup is developed to test the effect of different oil flow rates at different pressure ratios and speeds of the twin-screw compressor. The volumetric efficiencies and specific shaft power consumption were used to understand the effects of varied oil injection flow rates on the performance of the compressor. The effect on the discharge temperature is also recorded and presented.

2. EXPERIMENTAL SETUP

An oil-flooded, air screw compressor packaged unit of 75 kW input power rating designed and developed by Kirloskar Pneumatic Company Limited, Pune, India has been used for carrying out the experimental investigation. The detailed testing methodology is explained in this section. The screw compressor package has different circuits for the circulation of oil and the delivery of air. A schematic of the flow diagram is shown in Figure 1. The compressor package consists of a bare compressor block, a three-phase induction motor, an air-oil separator tank, and heat exchangers to cool air and oil. It also consists of the air and oil filters, and an intake valve to load and unload the compressor. A variable frequency drive is used to adjust the rotational speeds of the compressor.

The ambient air from the atmosphere is sucked into the compressor block via a micro-level air filter and an intake valve. As the compression of the air starts, oil is mixed with air and the air-oil mixture is pushed towards the discharge end. The compressed air-oil mixture is discharged from the compressor block and enters an air-oil separator. Inside the air-oil separator tank, oil and air are separated due to centrifugal action. The air flows to an air-cooled after-cooler and the volume flow rate of cooled air is measured before being discharged into the atmosphere.

The oil separated in the air-oil separator tank is cooled in an air-cooled heat exchanger and filtered before it is recirculated back into the compressor block.

The volume flow of air is measured using the nozzle designed according to an IS 10431:1994. The differential pressure across the nozzle is measured using a U-tube manometer and the flow of air is calculated and normalized to suction conditions using the relationship between the differential pressure, temperature, and the diameter of the nozzle given in IS 10431:1994. For the measurement of oil flow rate, an oval gear type flow meter is installed in the oil line between the oil filter outlet and compressor block inlet. The oil flow rate is controlled using a ball valve in the oil line.

The total power of the compressor package is measured on the energy meter. The power available at the electric motor input terminal is back-calculated after deducting the cooler fan power, control panel power, and VFD panel loss from the energy meter measurement. Upon multiplying the motor input power by the motor efficiency, the compressor block shaft power is calculated. The corrections to the suction air volume flow rate and the shaft power are done according to Annexure C of ISO 1217:2009.

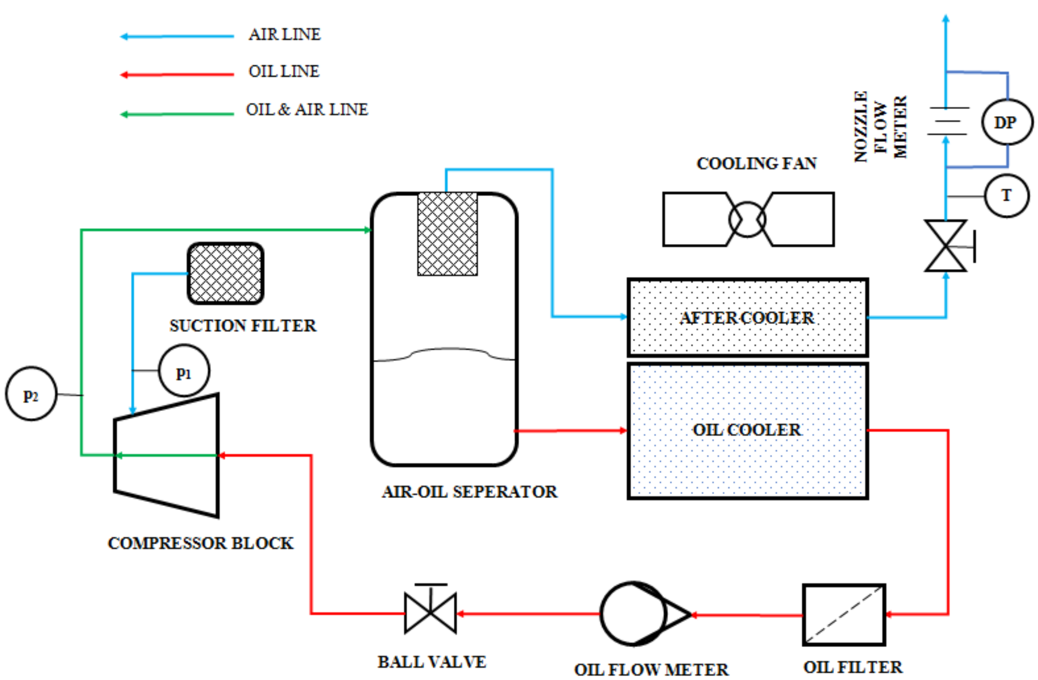

Figure 1. Schematic of the flow diagram

2.1 Instrumentation

For the measurement of the parameters, different types of instruments are used and are as listed in Table 1.

Table 1. List of instruments

Measured parameter	Instrument used	Specifications
Compressor Speed	Metravi- Digital Tachometer	RPM Test Range: 2 to 99,9999 RPM, Accuracy: ±0.05% ±1 Digit
Temperature	Fluke- 59 MAX Infrared Thermometer	Temperature Range: -30°C to 350°C Accuracy: ±2.0°C
Oil flow	Oil flow meter, Type: Oval gear flow	Flow Range: 10-333 lpm, Accuracy: 0.5%
Pressure	Danfoss-Pressure transmitter	Pressure Range: 0 to 16 bar, Output signal [mA]: 4 - 20, Accuracy: ±0.5%

2.2 Experimental parameters

Two sets of experiments are carried out to investigate the effect of varied oil injection flow rates. The first set is carried out by varying pressure ratios across the compressor block while during the second set, the rotational speeds are changed. Table 2 shows the experimental conditions of the first set at a constant rotational speed of 1,950 rpm and Table 3 shows the second set at a constant pressure ratio of 9.

Table 2. Experimental conditions (Set 1)

Pressure ratio, π	Oil injection flow rate, lpm				
7	68	78	88	98	105
8	68	78	88	98	105
9	68	78	88	98	105
10	68	78	88	98	105

Table 3. Experimental conditions (Set 2)

Rotational speed, rpm	Oil injection flow rate, lpm				
1,950	68	78	88	98	105
1,750	68	78	88	98	105
1,550	68	78	88	98	105

The performance parameters such as volumetric efficiency, specific power consumption, and discharge temperature are used to evaluate the compressor performance. The volume flow rate is normalized to 1 bar (a) and 35°C. The following equations 1 and 2 are used for calculating the volumetric efficiency and specific power. While the pressure ratio is calculated as the discharge pressure divided by the suction pressure of the compressor block and it is measured using a pressure transmitter.

Volumetric efficiency:

$$\eta_v = \frac{Q_m}{Q_{th}} \tag{1}$$

Specific Power Consumption:

$$\mathrm{SPC} = \frac{W_m}{Q_m} \tag{2}$$

3. RESULTS AND DISCUSSION

Two sets of experiments are carried out as indicated in the previous section. In the first set, the pressure ratios are varied from 7 to 10 while keeping a constant rotational speed of 1,950 rpm. In the second set, the compressor rotational speed is varied from 1,550 to 1,950 rpm while keeping a constant pressure ratio of 9. In both cases, the oil injection flow rate to the compressor block is varied from 68 to 105 lpm.

3.1 Effect of oil flow rate on compressor performance with pressure ratio

The oil injection flow rate is changed while changing the pressure ratios at a constant rotational speed. The effect on the performance with different oil injection flow rates is shown in Figure 2, Figure 3, and Figure 4. From the results, it is observed that as the oil flow rate increases, the volumetric efficiency increases. This is mainly due to a reduction in leakages in the clearance gaps within the compressor block. Increased oil injection flow rate enhances the filling of these clearance gaps with the oil and results in reduced air leakage thereby increasing the volumetric efficiency. A similar trend is observed across all pressure ratios as indicated in Figure 2. For the same oil injection flow rate, the volumetric efficiency decreases with the increase in pressure ratios. At higher pressure ratios, the air leakage across the clearance gaps increases for the portion of clearance gaps where oil is not completely filling.

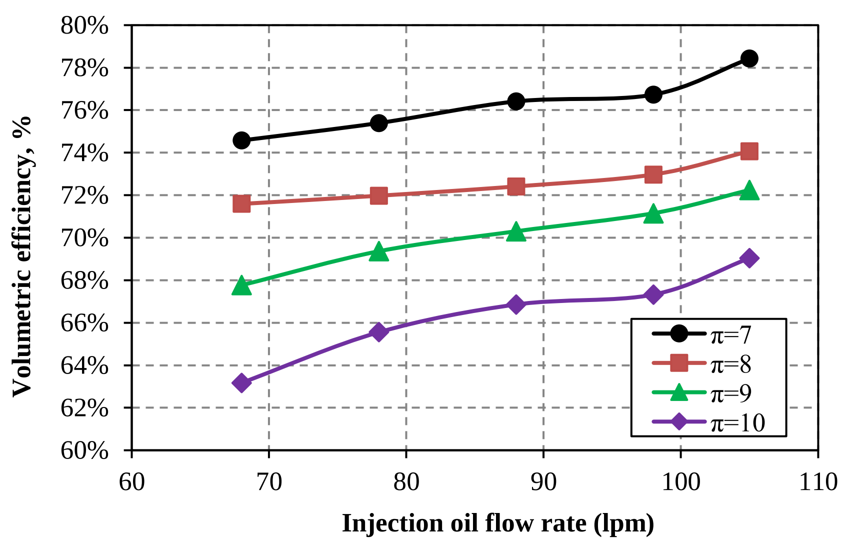

Figure 2. Volumetric efficiency at different pressure ratios vs. oil flow rate

The performance of the screw compressor can also be defined in terms of specific power consumption. It is nothing but the shaft power required to deliver the unit volume flow rate of the gas/air. The effect on the specific power consumption with variation in oil flow rate at different pressure ratios is shown in Figure 3. It is observed that the specific power consumption (SPC) of the compressor block is reduced with increasing the oil flow rate. This is mainly due to the marginal increase in the power with the increase in oil flow rate while the volume flow rate increases considerably. This leads to reduced specific power consumption. SPC is normalized with the lowest value measured at pressure ratio 7.

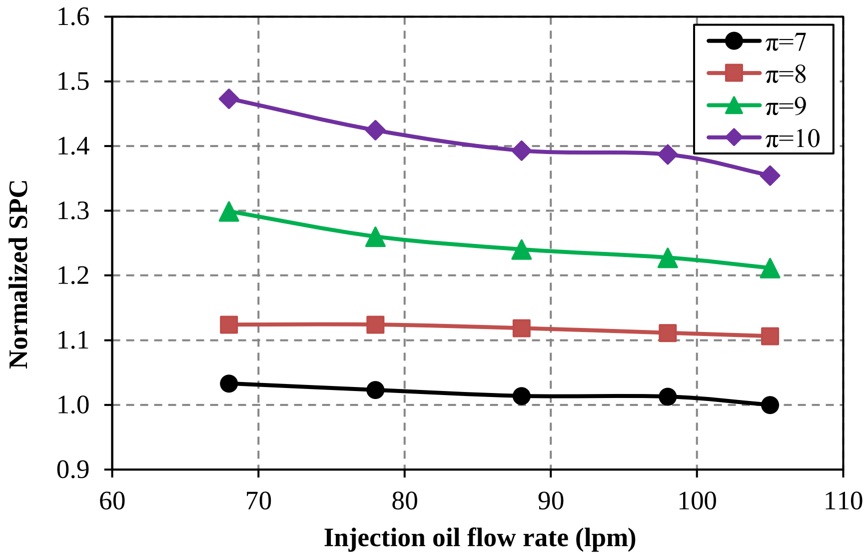

Figure 3. Normalized SPC at different pressure ratios vs. oil flow rate

Another important parameter that is recorded during the experiments is the discharge temperature of the compressor block. The variation in the discharge temperature under different pressure ratios is shown in Figure 4. It is measured right after the discharge port using the resistance temperature detector and it measures the air-oil mixture temperature. It is observed that the increase in the oil flow rate for the same pressure ratio reduces the discharge temperature of the compressor block. This is the effect of an improved heat transfer rate between compressed air and oil. Higher the oil flow rate better the heat transfer rate and more energy are absorbed by the oil which results in reduced discharge temperature.

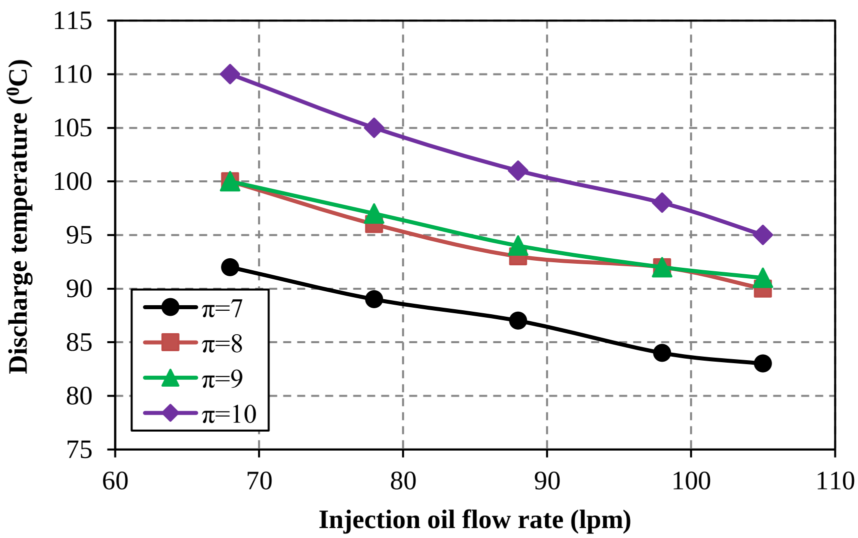

Figure 4. Discharge temperature at different pressure ratios vs. oil flow rate

3.2 Effect of oil flow rate on compressor performance with rotational speed

The effect of oil flow rate with changing the rotational speed has been studied and discussed in this section. Figure 5, Figure 6, and Figure 7 show the effect on volumetric efficiency, specific power consumption, and discharge temperature respectively.

The volumetric efficiency increases with increasing oil flow rate and rotational speed. It is observed that at low speeds of 1,750 & 1,550 rpm, the volumetric efficiency is increased up to 95 lpm while there is no significant improvement observed with a further increase in the oil injection flow rate. This may be because the oil injection flow rate is high enough to form sufficient sealing between the leakages and reduce the leakage paths. Hence additional oil might be contributing more to the increase in shaft power than to prevent leakages. While at higher speed volumetric efficiency increases with an increase in the oil flow rate.

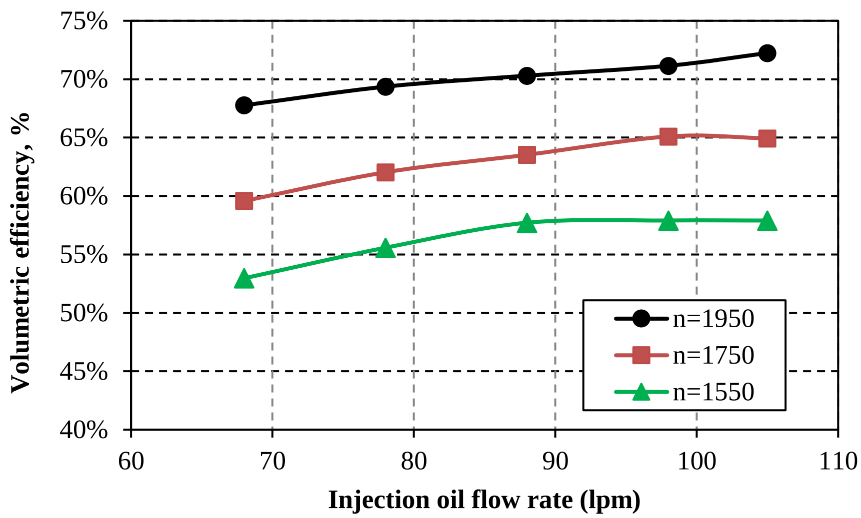

Figure 5. Volumetric efficiency at different speeds vs. oil flow rate

The effect on the specific power consumption with rotational speed is explained in this section. It is observed that with the increase in speed, the specific power consumption is decreased. This is mainly due to the reduction in the leakages and the formation of oil film between the rotors and housing gaps. SPC is normalized with the lowest value measured at pressure ratio 7 and 1,950 rpm in the previous set.

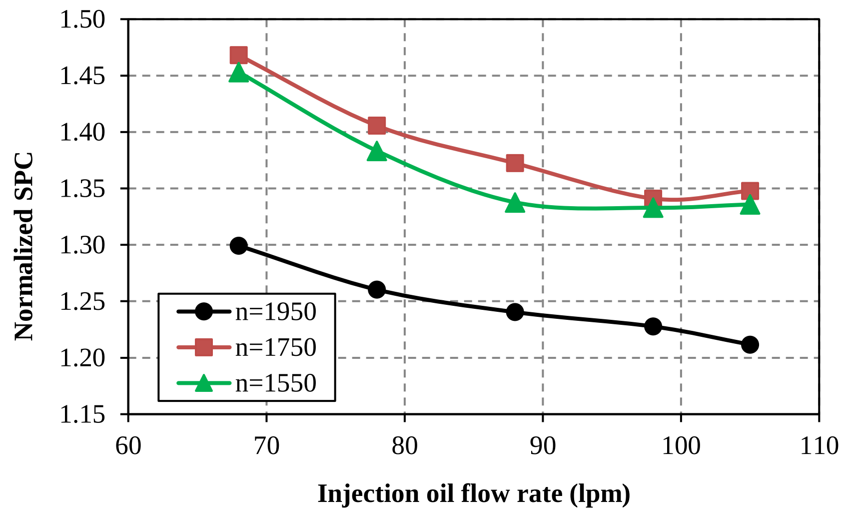

Figure 6. Normalized SPC at different speed vs. oil flow rate

The effect with respect to rotational speed on the compressor discharge temperature is shown below. It is observed that as the speed increases the discharge temperature increases for the same oil flow rate. The same trend is observed for all oil flow rates ranging from 68 to 105 lpm. At lower speeds, the discharge temperature is lower which is mainly due to the heat transfer time between air and oil in the compression chamber.

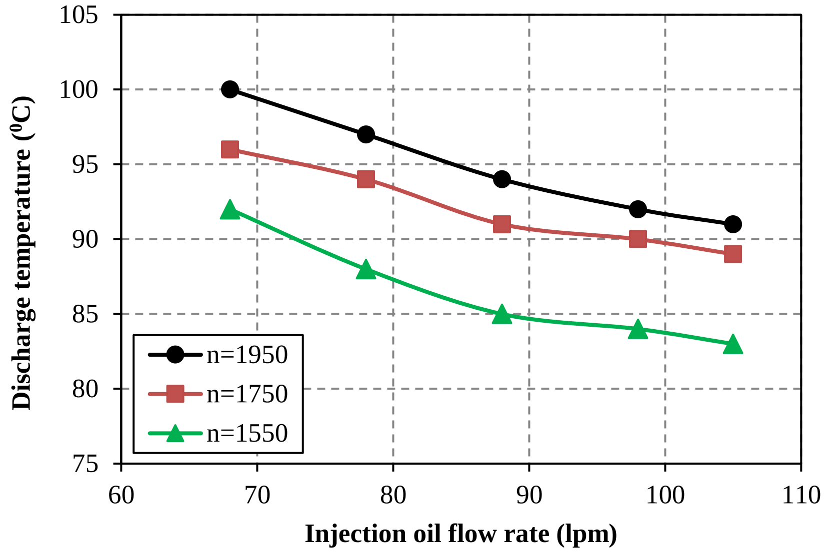

Figure 7. Discharge temperature at different pressure ratios vs. oil flow rate

4. CONCLUSIONS

In this paper, the effect of oil flow rate with variable pressure ratios and rotational speeds of the oil-injected twin-screw compressor is investigated experimentally on the 75 kW Kirloskar Pneumatic Company Limited compressor package.

It is observed that with the increase in oil flow rate the volumetric efficiency increases due to a reduction in leakages. The trend is the same for all pressure ratios but there is a difference in the improvements observed. For the lower pressure ratios (π=7 & π=8) the volumetric efficiency is improved by 2.5- 4 % with the increase in oil flow rate by 54%. While at higher pressure ratios (π=9 & π=10) the improvement observed is 4.5- 6 %. This indicates that at higher pressure ratios there are more leakages in the compression chamber which are reduced with an increase in oil flow rate. For the SPC, with the increase in oil flow rate with respect to pressure ratios the improvement variation is 1.5- 8 %. At lower pressure ratios the improvement is less while at higher pressure ratios the improvement is more. Another parameter observed is the reduction in the discharge temperature with an increase in oil flow rate at all pressure ratios.

The effect of the oil flow rate at different rotational speeds of the compressor block is also checked experimentally. At low speeds, 1,550 rpm and 1,750 rpm, the improvement in the volumetric efficiency was observed to be 4.5 % and 5.5 % respectively up to 95 lpm. Beyond this point, further, improvement is not observed with more oil quantity. Improvement in the specific power consumption is more at low rotational speed while it is slightly less at the high speed. This can be explained by the dominance of leakages on the compressor performance at lower speeds since leaking flows get more time between suction and discharge. The effect of oil film sealing the gaps and contributing to better performance is hence more visible at lower speeds.

So, in general, there is an improvement in all performance parameters of twin-screw oil-flooded screw compressors with the increase in the oil flow rate. But the optimum value needs to be identified because, after a certain point, the increased drag losses diminish the gain in performance with an increase in oil flow rate. The restrictions from the package side also need to be considered. The increase in oil flow rate directly affects the sizing of the air-oil separator and the oil carryover of the machine. Hence, increasing oil flow beyond a certain point is not recommended.

NOMENCLATURE

n	Rotational speed	rpm
P	Compressor package power	kW
p	Pressure	bar (a)
Q	Volume flow rate	cfm
T	Temperature	^{0}C
W	Compressor shaft power	kW
η	Efficiency	%
π	Pressure ratio	

Subscripts

1	Inlet
2	Outlet
v	Volumetric
m	Measured
th	Theoretical

Abbreviations

IS	Indian Standard
ISO	International Organization for Standardization
SPC	Specific Power Consumption
VFD	Variable Frequency Drive
CFD	Computational Fluid Dynamics
lpm	Liter per minute
rpm	Revolutions per minute
cfm	Cubic feet per minute

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