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Performance evaluation of a rotating sleeve vane compressor

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Abstract. This paper presents the performance study of a new designed rotating sleeve vane (RSV) compressor. The aim of this study was to develop a more compact semi-hermetic refrigerant compressor for refrigeration and air-conditioning systems, which will improve the conventional design in terms of sizing and operating mechanism. Experimental study was carried out on the prototype of a single and multi-vane (three and five-vane) RSV compressor prototypes with identical size of rotor and sleeve and tested the in a test bench of R134a refrigeration system. Each test was carried out in a steady state of refrigeration thermodynamic cycle at operating speed varied between 1000 rpm to 1500 rpm to obtain the mechanical and volumetric efficiencies. The experimental results on the three of the new prototypes were analyzed and found that that the single vane compressor prototype has a similar volumetric efficiency of about 90% with that of rolling piston compressor of equivalent capacity. A double increment in capacity to about 48 cc was observed in the five vane prototype models with the same overall dimension and configuration of the rotating components to that of the single vane. The volumetric efficiency was also comparable of about 70% to an existing multi vane rotary compressor.

1. Introduction

In the original model of a conventional multi-vane rotary (MVR) compressor, the tip of each vane rubs against the cylinder wall, creating friction and wear to the rubbing surfaces. A brilliant idea came out to change the cylinder wall to a new concept of a compressor called Rotating Sleeve Vane Rotary (RSVR) compressor. Two types of concepts have identified based on number of vanes. The compressor is known as Rotating Sleeve Single Vane Rotary (RSSVR) compressor [1] and Rotating Sleeve Multi Vane Rotary (RSMVR) compressor as shown in Figure 1. The design of the semi-hermatic compressor comprises of components, which are rotating and stationary. Rotating components are rotor, sleeve, vane and shaft, while stationary components are upper plate, lower plate, mechanical bearing and external casing. There are also standard components such as bearing, oil seal, O-ring, c-clip, bolt and nut. All these standard components selected have to comply with engineering practice and standard. All components designed follow ISO and BS standards. Critical components such as external casing and internal compression chamber required the safety factor to be checked according to an engineering standard. The prototypes design of the new developed compressor was adapted from conceptual design and prototype of RSSVR compressor are made by Yusof [2].

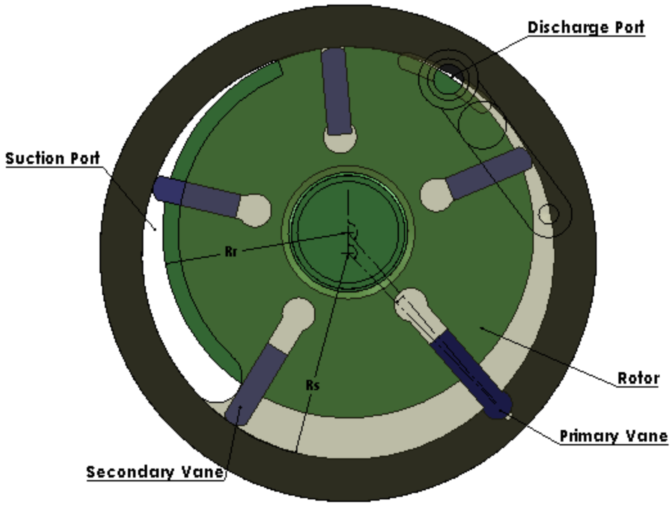


Figure 1. Sectional View of RSMVR compressor.

1.1 Development of the compressor

The developed mathematical model is incorporated into a computer program as tool in designing the compressor. The mathematical model of this compressor has discussed in detail by Sarip and Musa [3]. Through this process the compressor parameters such as pressure, temperature, friction force, mass flow rate and efficiency can be predicted and serves as a guide and tools in the designing process. The analysis of a rotating vane rotary sleeve (RSVR) compressor generally involves a variety of mechanical principles and the list are as follows:

- Geometrical – to determine the relationship between the component geometry of the compressor to the compressor cell volume.
- Thermodynamics – to determine the relationship between the density, pressure, and temperature of the gas during a thermodynamic process involving factors that influence the internal leakage, the effects of heat and oil lubrication.
- Kinematics and Dynamics - to analyze the action of the forces acting on the vane, sleeve and rotor.
- Performance – to determine the power and efficiency of the compressor.

1.2 Operation of RSVR compressor

The current vane rotary compressors, such as that of MVR compressor and rolling piston rotary types, have disadvantages at low speed and high speed of rotation, respectively. For MVR compressor, at low speed of rotation, each vane has not developed sufficient enough centrifugal force to pull itself out of the slot in the rotor for the vane tip to be always in contact with and to rub against the stationary cylinder wall, hence fails to create a compression chamber. While at high rotating speeds, high centrifugal force produces negative effect by creating high rubbing friction between the vane tip and the inner cylinder surface. For the rolling piston compressor on the other hand, at high speed of piston rotation the linear motion of the vane cannot synchronize with the fast rolling movement of the piston, creating a gap between the vane tip and surface of the rolling piston. This causes the gas to leak from the high pressure (compression) chamber to the low pressure (suction) chamber, thus reduces the volumetric efficiency of the compressor.

The new RSVR compressor concept can simultaneously address the weaknesses posed by the two respective existing rotary compressor models. In an RSVR compressor, as the rotor rotates, the sleeve will pull the primary vane out of the slot thus creating the gas suction chamber. As soon as suction mode ends a compression mode begins. This happens when the sleeve begins to push the primary vane back into the slot in the rotor. At certain high speed, both centrifugal force and the force exerted by the sleeve on each secondary vane tip begin to serve the secondary vanes, thus creating the multi suction/compression chambers, respectively. The friction on tip of secondary vane is estimated to be small due to rotor and sleeve rotates. The arc angle rubbed by tip of vanes is about 15^o to 25^o for one complete rotation as shown in Figure 2. The primary vane is one of the most important components in this compressor on which the rotation of the sleeve is totally dependent on it. In this concept, the primary vane ensures that suction, compression and discharge of the gas occur at all speeds of rotation. The thermodynamic process of a RSSVR and RSMVR are similar to that rolling piston and MVR compressor, respectively.

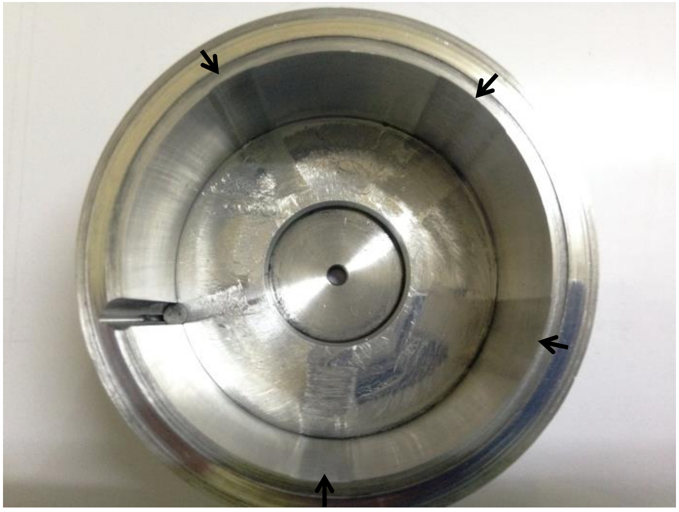


Figure 2. Rubbing surfaces between vane tip secondary and inner surface sleeve (Five Vane)

2. Design concept

The RSMVR compressor has a unique arrangement of the shaft that is connected to a motor to drive the compressor. The rotor or sleeve can be selected, either one to become a driver and/or the other as a follower. The conventional MVR compressor is rotated by a rotor that is connected by a mechanical shaft to an external motor. Figure 3 shows the possibility of such an arrangement of rotor-shaft and sleeve-shaft in designing the compressor. The analysis of the performance of either the sleeve or the rotor as driver was carried out based on same speed and dimension and the presence of both bearings was neglected. Three designs of semi hermetic horizontal prototype have been developed with different number of vanes. Three shaft rotor driven prototypes have been developed with the respective number of vanes: single, three and five. The physical dimensions of vane, rotor, sleeve and casing and locations of suction and discharge ports, remain unchanged. With this design approach, the total fabrication cost of the prototypes is reduced significantly. Three designs of semi hermetic horizontal prototype have been developed with different number of vanes. Three shaft rotor driven prototypes have been developed with the respective number of vanes: single, three and five. The physical dimensions of vane, rotor, sleeve and casing and locations of suction and discharge ports, remain unchanged. With this design approach, the total fabrication cost of the prototypes is reduced significantly.

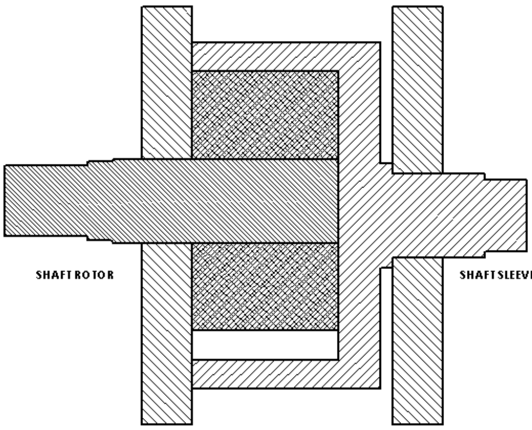


Figure 3. Shaft driven type of RSVR compressor

The design of all parts in the RSMVR compressor is completely new. At the initial stage the design is close to RSSVR compressor which has been designed by Yusof [2]. Based on this design many changes were done for example the locations of bearing, upper plate, suction and discharge ports and its casing. The material selection is compared to that of existing compressor established in the market. The material used commonly is a group of high carbon steel and aluminium alloy. The other components are designed by following a standard engineering practice. British Standard (BS) is a referral in designing and the arrangement of each component.

2.1. Design parameter

The design of the compressor is based on an automotive refrigeration plant of an air conditioning system of a vehicle car. The cooling capacity of the plant is set at maximum about 14,000 BTU/h and the size is about 200 mm height and 200 mm length. Table 1 shows the design parameters of operating condition for each prototype.

Table 1. Design of parameters of operating condition

Compressor size	200 (Dia) x 200 (L) mm	Suction temperature, T_s	278 K
Cooling capacity max, Q_{evap}	14,000 BTU/h	Discharge temperature,T_d	353 K
Operational speed max,N	2800 rpm	Suction pressure, p_s	3 bar a
Working fluid	R134a	Discharge Pressure, p_d	11 bar a

2.2. Main Dimension of component

The dimension of each component of developed compressor is calculated based on an ideal swept volume, $V_{swept} = 50cc$, number of vane, $N_v = 5$ and angle of end of suction at $\theta = 144°$ and assumed $\Gamma = \frac{L_c}{R_s} = 1.0$ and $\Omega = \frac{R_r}{R_s} = 0.9$. Using derived a cell volume equation, the dimensions of rotor, inner sleeve and length of chamber can be determined by equation (1) is expressed as below:

$$\frac{V_{swept}}{N_v} = \frac{\Gamma R_s^3}{4}[2(\sigma - \psi_a + \psi_b) + \zeta^2(sin(2\theta) - sin(2\theta - 2\sigma)) + (sin(2\psi_b) - sin(2\psi_a)) - 2\Omega^2\sigma] \quad (1)$$

where, ,$\sigma = \frac{2\pi}{N_v}$,$\psi_a = \zeta\, sin(\theta - \sigma)$,$\psi_b = \zeta sin\theta$,$\zeta = \frac{R_s - R_r}{R_s}$

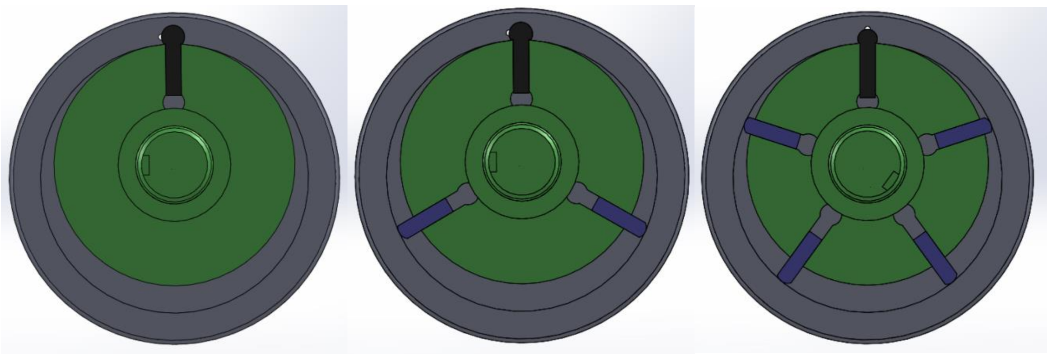
From the equation dimension parameters of inner sleeve radius, rotor radius and axial length can be determined. Table 2 shows the dimensions of the main components and others.

Table 2. Dimension of main component

Rotor radius, R_r	31.0 mm	Axial Length, L_c	36.0 mm
Inner sleeve radius, R_s	34.5 mm	Vane Height, H_v	14.0 mm
Outer sleeve radius, R_{st}	40.5 mm	Number of vane, N_v	1,3 5 no.

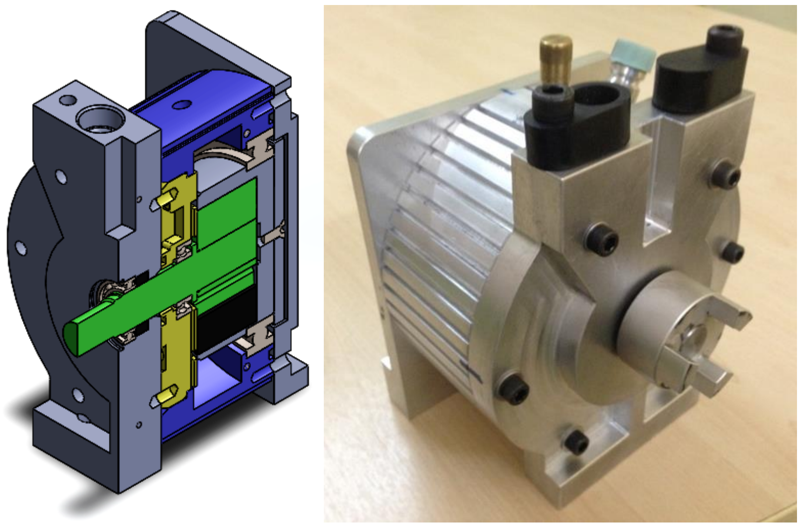
3. Prototyping development

Three semi-hermetic compressor design variations have developed for horizontal type prototypes with shaft connected to an external electric motor. The design is shaft rotor driven and horizontal type. Dimension of sleeve and rotor is unchanged except on the rotor where slots are made equivalent to the number of vanes added as shown in Figure 4. The figure represents the drawing of the single (17.6 cc), three-vane (44 cc) and five-vane (48 cc) RSVR compressor with. The total swept volume is taking the effects of thickness of vane and width of slot. Figure 5 show the isometric sectional drawing view and the actual and fully assembled photo of compressor prototype model.



(a) (b) (c)

Figure 4. Three different designs of RSVR compressor (Single (a), three (b) and five-vane (c))



(a) (b)

Figure 5. Isometric Sectioned drawing (a) and actual prototype model (b) of RSVR compressor

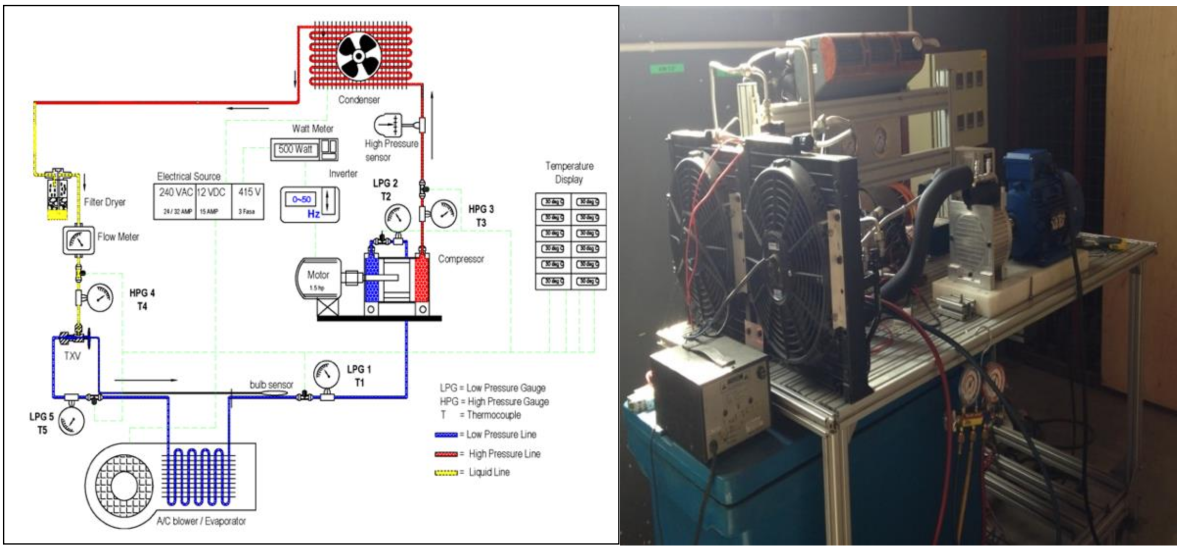
3.1 Test-bed of refrigeration System

The experimental work was carried out to test the performance of RSVR compressor. The experiments were carried out on the refrigeration test-bed of car air conditioning system. The test-bed is developed according to standards ISO 917: 1989 and using R-134a as a working fluid. Layout of cooling system components and measuring instruments are shown in the schematic and photo test-bed in Figure 6. The test-bed is equipped with measurement instruments ranging from analog and digital measurement instruments as shown in Table 3f. Experiment conditions have set-up to meet actual condition in car compartment, which is changing the cooling load in calorimeter and compressor speed. Mechanical efficiency is related to the loss incurred due to friction and other physical effects during the thermodynamic cycle of the compressor, where P_{poly} is polytropic compressor power and P_{shaft} is shaft compressor power. Relationship of mechanical efficiency,η_m is written as:

$$\eta_m = \frac{P_{poly}}{P_{shaft}} \tag{2}$$

Maximum swept volume is the cell volume at the end of suction (or beginning of compression) times the number of cells (or number of vanes). Volumetric efficiency, η_v is very much related to the actual mass flow rate of fluid, $\dot{V}_a$ through out of the compressor compare to design volumetric of compressor, $\dot{V}_s$. The relationship mathematically is given as:

$$\eta_v = \frac{\dot{V}_a}{\dot{V}_s} \tag{3}$$



(a) (b)

Figure 6. Schematic diagram (a) and photo (b) of experimental test-bed

Table 3. Air-conditioning parts and measuring instruments of test bed

Part	Specification
Compressor	**RSV Compressor (single, three and five-vane)**
Condenser, Txv and Evaporator	**Auto Air**, Car Air Conditioning
Thermocouple	Type k (-200 - 1250 'C)
Inverter	**TECO**, Inveter FM 50, 2.5kW, 415V/50Hz - 240V/50Hz
Electric Motor	**Simex**,Induction Motor, 2 pole,415V/50Hz, 3 phase Power : 2.2kW/
Pressure Gauge	**OMEGA** PGI Pressure Gauge 63 mm - 20bar (LPG) & 40 bar (HPG), Accuracy: 0.1%
Flow meter	**Solatron Mobrey**, Rotameter type, liquid:R134a, range:2g/s ~ 20 g/s,density:1.155.2g/cc,viscosity:0.17cP
Tachometer	**Sanpometer,** DT 2236B
Power meter	**PowerTek ISW 8350-** Three Phase Power Meter / Watt Meter

3.2 Experimental result of Single vane of varies of speed

The experimental result shows that the volumetric efficiency slightly increases from 88% to 91% as shown in Figure 7. The single vane prototype shows a quite high volumetric efficiency if compared to established scroll or rolling piston compressor. The calculated results for the volumetric efficiency of rolling piston is about 90% to 95 % [4] at operating condition of suction pressure,p_s 0.62 MPa, the discharge pressure, p_d 2.17 MPa and the suction temperature, T_s 18 °C. It can be stated that all the clearance at internal leakage area and suction heating effect was designed in good condition.

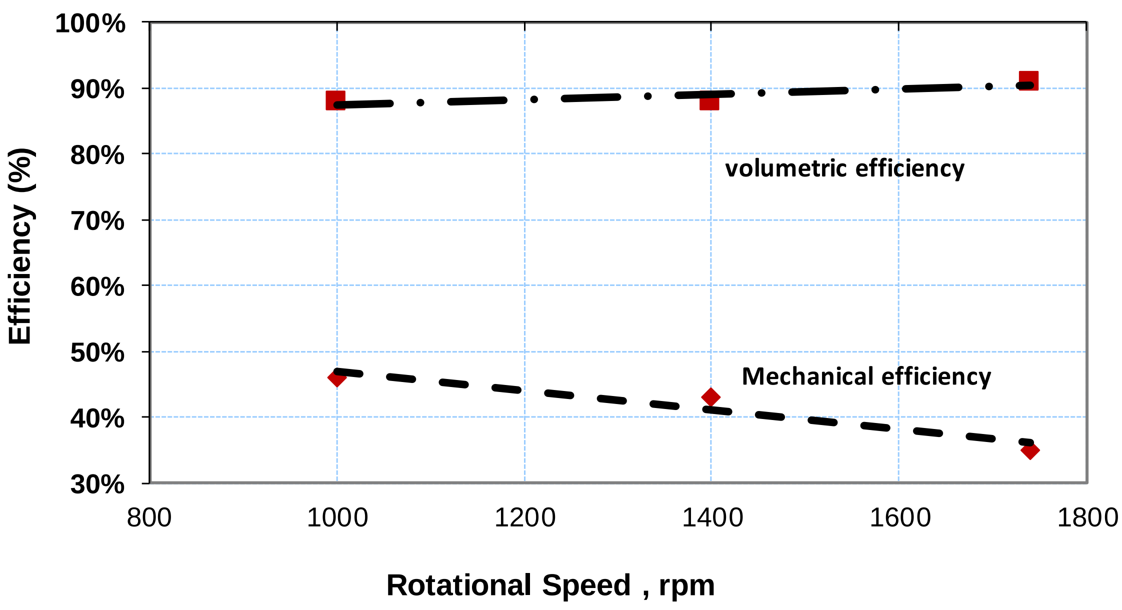


Figure 7. Performance result of RSSVR compressor

The mechanical efficiency of the RSSVR compressor is calculated from the ratio of polytropic power to shaft power. At low speed of rotation, the result shows that mechanical efficiency was lower than 50%. However, it decreased to about 43 % at speed 1400 rpm and then lower to 35% at 1700 rpm. At low speed suspected the lubrication system not functioning well compare to high speed. Also, it is expected that coefficient of friction is higher than 0.6 at speed 1700 rpm due to severe wear occurring (scratch mark) in end face sleeve and end plate as shown in Figure 8. The wear on the rotating part due to material condition, where on this component was no coating or treatment element had been applied to rotating component. In addition, the flatness tolerance at end faces of sleeve and end plate was of incorrect tolerance. However, the value was below than expected as discussed by Teh and Ooi [5], where mechanical efficiency of rotary compressor theoretically performed at average 90%. The wear and tear of the material very severe after while due to uncoated material that used for vane and sleeve.

Figure 8. Scratch mark on end face sleeve

3.3 Experimental result of single, three and five-vane at constant speed

The results experimental of three and five vane compressors shown in Figure 9. The speed of rotation of the compressor was selected at speed of 1400 rpm. The performance of the volumetric efficiency is dramatically decreased from about 88 % to 45%. It clearly shows that the single vane has a great volumetric efficiency, while three-vane and five-vane were about 65 % and 45%, respectively. From this graph, the five vane indicates very lower volumetric efficiency. By adding another or more vane in the RSSVR compressor, the volumetric efficiency drops. It happens due to the suction area which becomes smaller and contributed suction heating and suction pressure loss at suction process. Also, uneven tolerance gaps at end faces of secondary vane and between upper surfaces of sleeve and upper plate have caused severe instantaneous internal leakage. The tolerance at eccentric and end faces of vane are assumed to be at 30 µm. The target volumetric efficiency of the five compressor is about 70%. This value was referred to study carried out in MVR (oval -shape) compressor for car air conditioning by Sarip [6]. Therefore, the design for five-vane compressor needs more intensive and extensive improvement on how to prevent internal leakage.

Furthermore, the mechanical efficiency of the tested compressor displays at average of 45%. The result shows an average mechanical efficiency for all numbers of vane. By adding more vane, the frictional losses related to vane also increases and slightly reduces the mechanical efficiency of compressor. As expected by adding more secondary vane, the friction occurred at side and end surface but at the tip is estimated to be small due to the sleeve simultaneously rotate and create small rubbing angle between vane tip and inner sleeve surface. The low value below 50% was suspected from the wear and tear of rotating component of the compressors due to uncoated surface of vane and other was suspected arise from machining quality at each of vane slots and the problem was same as discussed in RSSVR compressor.

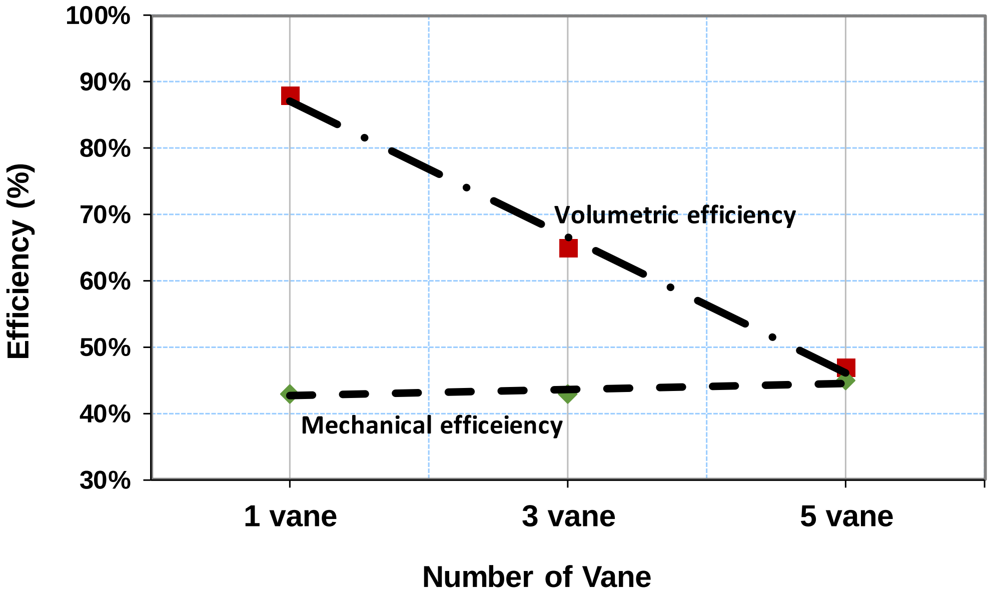


Figure 9. Performance result of RSMVR compressor at 1400 rpm

4. Conclusion

The prototype of RSSVR and RSMVR compressors have been successfully developed, tested and commissioned. The experimental work of single, three and five-vane RSVR compressors have been successful carried out at speeds of 1000, 1400 and 1700 rpm at the pressure ratio values of below 3.0. The actual volumetric efficiency of each compressor prototype was measured and the average values obtained are between 45% to 90%. It was the prototype of the single vane compressor that performed fairly accurately and the performance is comparable to that of similar existing compressor models, such as those of scroll or rolling piston types, respectively. The mechanical efficiencies of the compressor were measured giving average values of 45% which is below the expected value if compare to that existing vane compressor. From the experiment it can be concluded that RSSVR compressor has shown to give a fairly accurate performance data which is comparable to that of RSMVR compressor. Then from the design perspective, the five-vane compressor is more compact in term of swept volume if compared to that of single and three-vane compressors. Nevertheless, the compressor prototype still needs much improvement due to its very low volumetric efficiency

Acknowledgments

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