DEVELOPMENT AND ANALYSIS A NEW INTEGRATED MOTOR ROTARY VANE COMPRESSOR

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ABSTRACT

The aim of this thesis was to develop and analyse a new rotating sleeve vane rotary compressor and to demonstrate the possibility of integrating the compressor with DC hollow rotor torque motor. The integration of the compressor with DC hollow rotor torque motor completely differs from the existing conventional driven method which is typically driven by a sequence of electrical motor or pulley to rotate the mechanical shaft of a compressor. The novelty of this study is to develop a more compact refrigerant compressor for a modular transport refrigeration and air-conditioning systems, which will make the systems to be more competitive in terms of sizing and operating stability. The main objective of the study was to design, develop, test, and evaluate the performance of a novel rotating sleeve of single and multi-vane compressor prototype. The novel rotary-vane design was applied to a new integrated concept of DC hollow rotor torque motor rotary compressor. Theoretical and experimental studies were carried out on the prototype of a single and multi-vane (three- and five-vane) rotating sleeve vane rotary compressor prototypes, each of which was installed on a refrigeration system as experimental test-bed. Each test was carried out to obtain the mechanical and volumetric efficiencies, as the refrigeration plant operated in a complete thermodynamic cycle. During these tests, the prototype was run by an external motor connected to the compressor via a shaft. The results show that the single vane compressor prototype has a similar volumetric efficiency of about 80% with that of rolling piston compressor of equivalent capacity. A double increment in capacity to about 50 cc was observed in the multi-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. The DC hollow rotor torque motor integration concept was found to be successful and the idea is technically feasible.

ABSTRAK

Kajian utama bagi tesis ini adalah untuk membangun dan menganalisa sebuah pemampat bilah berputar baharu iaitu sarung berputar (*rotating sleeve*) dan seterusnya untuk mengesahkan bahawa pemampat ini boleh diintegrasikan dengan *DC hollow rotor torque motor*. Pemampat yang diintegrasikan ini adalah berbeza sama sekali jika dibandingkan dengan kaedah pemacuan biasa bagi sesebuah pemampat, kebiasaannya sebuah pemampat akan dipacu oleh motor elektrik atau takal bagi memutarkan aci mekanikal pemampat. Rekabentuk integrasi pemampat yang baru ini dijangka akan memberikan impak dalam pembangunan aplikasi yang lebih kompak bagi unit pendingin hawa yang seterusnya berdaya saing untuk memberikan kelebihan dari segi saiz dan juga kestabilan operasi. Objektif utama kajian ini adalah untuk mereka bentuk, membangun, menguji, dan menilai prestasi pemampat yang dibahagikan kepada prototaip bilah tunggal dan berbilang bilah. Seterusnya prototaip pemampat ini akan diintegrasikan dengan *DC hollow rotor torque motor*. Kajian secara teoretikal dan eksperimental telah dijalankan ke atas prototaip pemampat bilah tunggal dan berbilang bilah (tiga dan lima bilah) dan setiap satunya telah diuji di pelantar ujikaji sistem penyejukan. Ujikaji yang dijalankan adalah untuk menilai kecekapan mekanikal dan isipadu prototaip pemampat semasa kitar lengkap termodinamik system tersebut. Prototaip pemampat yang diuji ini dipacu dengan kaedah motor elektrik dan mekanikal aci pemampat. Berdasarkan keputusan analisis, prototaip pemampat bilah tunggal mempunyai kecekapan isipadu yang sama iaitu sekitar 80% jika dibandingkan dengan pemampat *rolling piston* yang berkapasiti sama. Peningkatan kapasiti sebanyak dua kali ganda kepada sekitar 50 cc telah diperhatikan bagi prototaip pemampat berbilang bilah yang mempunyai dimensi keseluruhan dan konfigurasi rekabentuk yang sama seperti pemampat bilah tunggal. Kecekapan isipadunya adalah setanding dengan pemampat bilah berputar sedia ada iaitu sekitar 70%. Keputusan bagi konsep pemampat yang diintegrasikan dengan *DC hollow rotor torque motor* secara teknikalnya telah berjaya dan idea ini terbukti secara teknikal sesuai untuk dilaksanakan.

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A_v	-	Area of pressure force on vane
f_L	-	Friction factor
$f_{pv,1}$	-	Side primary vane friction force 1
$f_{pv,2}$	-	Side primary vane friction force 2
$f_{sv,1}$	-	Side secondary vane friction force 1
$f_{sv,2}$	-	Side secondary vane friction force 2
$F_{N,r}$	-	Normal force on rotor surface
$F_{N,s}$	-	Normal force on sleeve surface
F_b	-	Back pressure force
F_{cen}	-	Centrifugal force
F_{co}	-	Coriolis force
F_{ma_L}	-	Linear vane inertia force
F_{ma_r}	-	Radial vane inertia force
F_p	-	Side pressure force
g	-	Gravity = 9.81 $\mathrm{m/s^2}$
h	-	Enthalpy
h_{dis}	-	Enthalpy of refrigerant at discharge process
h_{liq}	-	Enthalpy of refrigerant after condenser
h_{suc}	-	Enthalpy of refrigerant at suction process
H_v	-	Height of vane
HPG	-	High pressure gauge
I_r	-	Mass ineartia of rotor
I_s	-	Mass ineartia of sleeve
L_L	-	Length leakage path
L_c	-	Length of cell
LPG	-	Low pressure gauge

$\dot{m}_{ref}$	-	Mass flow rate of refrigerant
$\dot{m}$	-	Mass flow rate
m_L	-	Cell mass leakage
m_c	-	Cell mass
m_v	-	Mass of vane
M	-	Hydraulic mean diameter
M_o	-	Moment
N_v	-	Number of vane
p_{LC}	-	Cell pressure of leading cell
p_{TC}	-	Cell pressure of trailing cell
p_{TXV}	-	Pressure of refrigerant after TXV
$p_{ambient}$	-	Ambient pressure
p_c	-	Cell pressure
p_{cond}	-	Pressure of refrigerant in condenser
p_{dis}	-	Discharge pressure
p_{dis}	-	Suction pressure
p_{evap}	-	Pressure of refrigerant in evaporator
P	-	Power
P_{f_e}	-	Friction power at end surface of rotor and sleeve
$P_{f_{ec}}$	-	Friction power at eccentric rotor and sleeve
$P_{I,r}$	-	Inertia power of rotor
$P_{I,s}$	-	Inertia power of sleeve
$P_{f\ ave}$	-	Average friction power
P_f	-	Friction power
P_{ideal}	-	Adiabatic power
$P_{indicated}$	-	Indicated power
P_{motor}	-	Electrical motor power
P_{shaft}	-	Shaft power
$\dot{Q}_{ref}$	-	Cooling capacity
Q_c	-	Heat transfer occurred in cell
r_p	-	Pressure ratio
rpm	-	Rotational speed

$\ddot{R}_\theta, a_v$	-	Vane linear acceleration
$\dot{R}_\theta, v_v$	-	Vane linear velocity
R_{cg}	-	Centre gravity radius of vane
R_e	-	Reynold number
R_g	-	Gas constant
$R_{pv,1}$	-	Side primary vane reaction force 1
$R_{pv,2}$	-	Side primary vane reaction force 2
$R_{pv,N}$	-	Normal primary vane reaction force
$R_{pv,r}$	-	End primary vane reaction radial force
$R_{pv,t}$	-	End primary vane reaction tangential force
R_r	-	Rotor radius
R_s	-	Sleeve radius
R_{st}	-	Outer sleeve radius
$R_{sv,1}$	-	Side secondary vane reaction force 1
$R_{sv,2}$	-	Side secondary vane reaction force 2
$R_{sv,N}$	-	Tip secondary vane reaction force
$R_{sv,r}$	-	Tip secondary vane reaction radial force
$R_{sv,t}$	-	Tip secondary vane reaction tangential force
R_v	-	Vane tip radius
R_θ	-	Vane radius
t	-	time
t_v	-	Thickness of vane
T	-	Temperature
$T_{ambient}$	-	Ambient temperature
T_c	-	Cell temperature
T_{dis}	-	Discharge temperature
T_{liq}	-	Temperature before enter TXV
T_{suc}	-	Suction temperature
$\mathrm{T}_{b,r/s}$	-	Torque friction at bearing of rotor or sleeve
$\mathrm{T}_{e,r/s}$	-	Torque friction at end surface of rotor or sleeve
T_{ec}	-	Torque friction at eccentric of rotor-sleeve surface
T_r	-	Torque of rotor

T_s	-	Torque of sleeve
TXV	-	Thermostatic expansion valve
v_L	-	Mean leakage velocity
V	-	Volume
$V_{c\,max}$	-	Cell volume maximum
V_c	-	Cell volume
$V_{crescent}$	-	Crescent volume
V_{slot}	-	Vane slot volume
V_{swept}	-	Swept volume
V_{tv}	-	Vane thickness volume
VAC	-	Voltage alternating current
VDC	-	Voltage direct current
w_L	-	Width leakage path
β_1	-	Start of suction angle
β_2	-	End of suction angle
β_3	-	Start of discharge angle
β_4	-	End of discharge angle
η_{comp}	-	Compression efficiency
η_{mech}	-	Mechanical efficiency
η_{motor}	-	Electrical motor efficiency
η_{total}	-	Total efficiency
η_v	-	Volumetric efficiency
$\theta_{\beta 2}$	-	Leading vane angle at end of suction
μ_f	-	Coeficient of friction
μ_g	-	Dynamic viscocity of refrigerant
μ_{oil}	-	Dynamic viscocity of lubricant
ν_1	-	Specific volume at point 1 (suction port)
ν_g	-	Kinematic viscocity of refrigerant
ρ_c	-	Cell refrigerant density
ρ_{suc}	-	Suction refrigerant density
ϕ	-	Swivel angle
σ	-	ratio of $\frac{2\pi}{N_v}$

θ	-	Leading vane angle
ζ	-	ratio of $\frac{\varepsilon}{R_s}$
ε	-	Eccentric of rotor -sleeve
δ,c	-	Clearence
γ	-	Index Isentropic
β	-	Sleeve angle
Ω	-	ratio of $\frac{R_r}{R_s}$
Γ	-	ratio of $\frac{L_c}{R_s}$
Δ	-	Losses
$\dot{\phi}$	-	Swivel angular velocity of primary vane
$\omega_s, \dot{\beta}$	-	Sleeve angular velocity
ω_{rel}	-	Relative angular velocity of sleeve and rotor
$\omega_r, \dot{\theta}$	-	Rotor angular velocity

Subscript

a	-	axial
b	-	bearing
cg	-	centre of gravity
$comp$	-	compression
dis	-	discharge
ec	-	eccentric
f	-	friction
i	-	in
L	-	leakage, linear
LV	-	leading vane
o	-	out
pv	-	primary vane
r	-	radial, rotor
suc	-	suction
sv	-	secondary vane
TV	-	trailing vane
x, y	-	Cartesian coordinate

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CHAPTER 1

INTRODUCTION

1.1 Introductory

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 as shown in Figure 1.1.

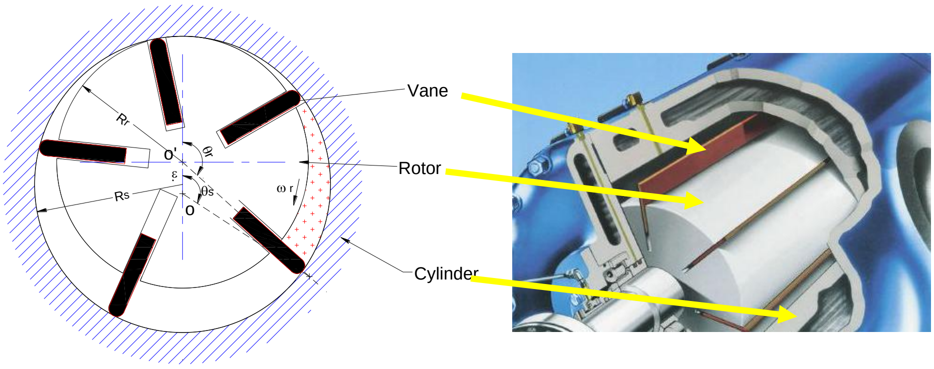
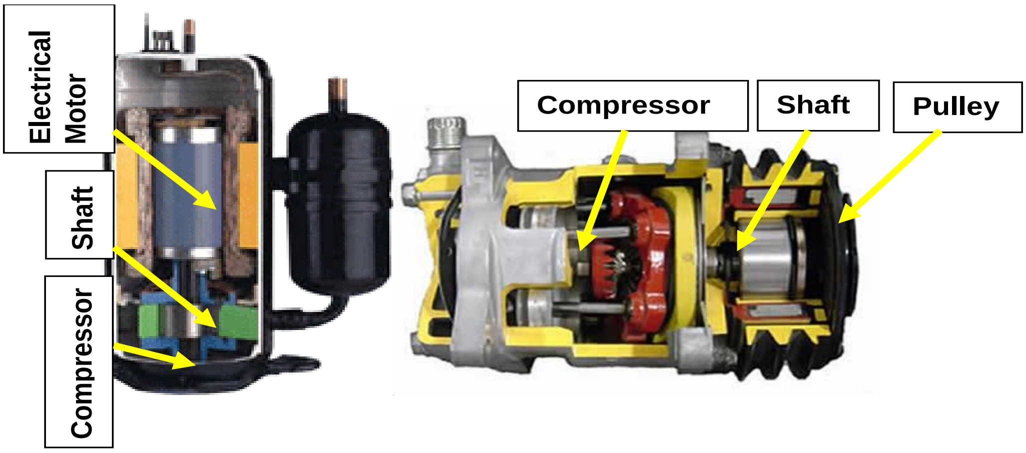


Figure 1.1 Sectional view of MVR compressor

The compressor is typically driven by a sequence of electrical motor/pulley – shaft – compressor, as shown in Figure 1.2. 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 concept have been identified based on number of vanes. The compressor is known as Rotating Sleeve Single Vane Rotary (RSSVR) compressor and Rotating Sleeve Multi Vane Rotary (RSMVR) compressor, respectively. On further analysis it was found that this idea is theoretically and technically feasible. However due to financial and time constraint the new idea is developed only up to a preliminary prototype stage to demonstrate the potential possibility and opportunity of succesfull integration of a hollow rotor torque motor rotary compressor model.



(a) (b)

Figure 1.2 Typical of drive train of rotary compressor a) Hermetic compressor, (b) Semi-hermetic compressor

To date, no other rotary compressor concepts can make this integration possible. With no shaft, hence less number of bearings, the mechanical efficiency is expected to improve. The hermetic tank that houses the motor-compressor assembly will now be smaller and shorter. It is interesting to find out the mutual beneficial process of superheating the refrigerant vapour and the cooling of the motor which is now located very close to the suction port. The current motor compressor and motor assembly is shown in Figure 1.3, where brushless motor is connected to the compressor via an external shaft to drive the compressor. Motor and compressor are enclosed in a fully hermetic tank and becomes an integrated system.

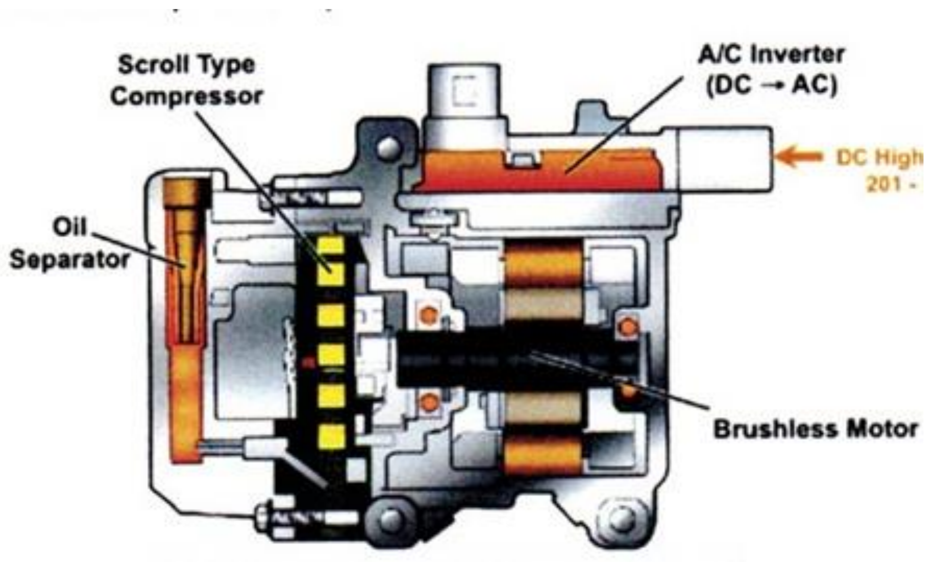


Figure 1.3 Current technology of integrated DC motor rotary compressor (Mavrigian,2013)

The design of a concentrically RSMVR compressor can be a breakthrough in rotary vane compressor technology. Furthermore, integrated DC RSMVR compressor is totally different from current technology. It can be explained in Figure 1.4 that the compressor does not need external connecting shaft anymore as it is located inside a hollow rotor motor, resulting in the size of the hermetic compressor assembly to be significantly more compact.

The aim of present study is two-fold. First is to conduct analytical and experimental study on RSSVR and RSMVR compressor concepts. Second is to demonstrate the possibility of integrating the new compressor model with a hollow rotor torque motor.

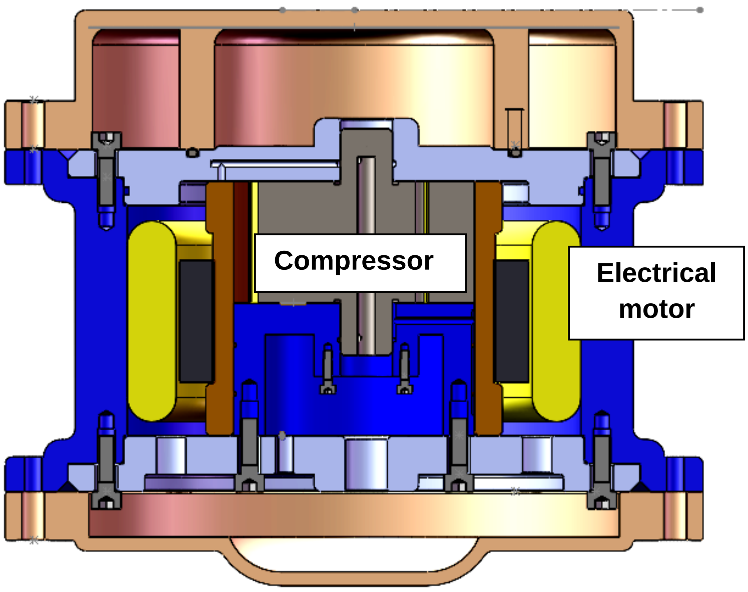


Figure 1.4 Conceptual design of integrated of DC motor RSVR compressor

1.2 Problem Statement

The current vane rotary compressors, such as that of MVR 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, as shown in Figure 1.5. 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.

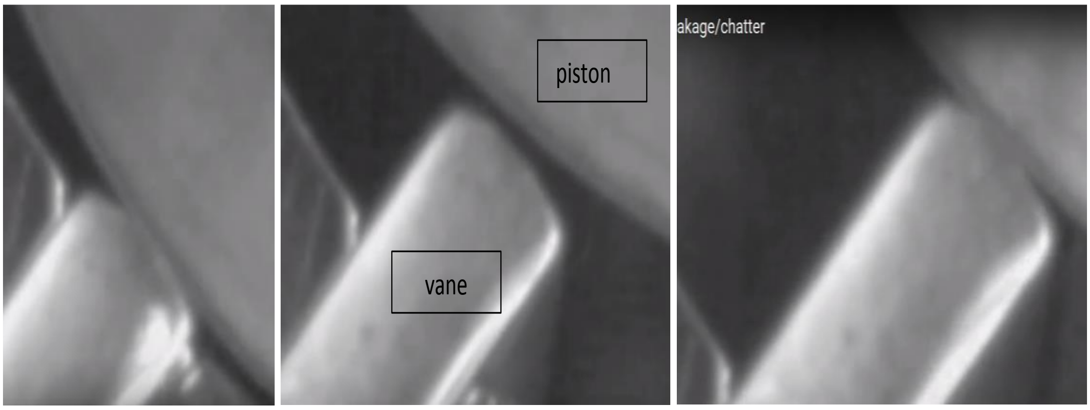


Figure 1.5 Motion of vane and piston of rolling piston compressor at 6000 fps, (Tesla500, 2009, 1:50)

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 four of secondary vanes, thus creating the multi suction/compression chambers, respectively. 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 as shown in Figure 1.6 which also shows that at certain low speeds all secondary vanes do not participate in the compression process. In addition, at the same low speeds there is no leakage around the tip of the secondary vane and this will give a higher volumetric efficiency.

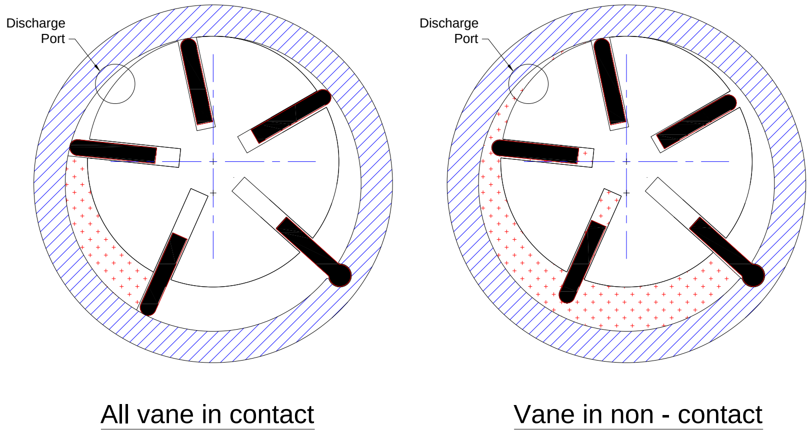


Figure 1.6 Comparison of two positions of RSMVR on each secondary vane tip at high speed and low speed

Furthermore, the eccentricity between the rotor and the rotating sleeve creates an interesting movement of each secondary vane in relation to the sleeve. When centers of rotor, any secondary vane and sleeve are all three in line, as shown in Figure 1.7 the rubbing action of the sliding vane with the inner surface of the sleeve is in the direction of rotation and occurs within a certain small angle. However, when the same three centers are in line for the second time within the same revolution, the rubbing action is in the opposite direction. The friction on the tip of each secondary vane is estimated to be small and the rubbing angle of the portion on the sleeve that each secondary vane rubs is about 15º. However, in a conventional MVR compressor, the vane tip is rubbing against the cylinder wall throughout the rotation (or 360º). Therefore, at high speed the friction between secondary vane tip and the inner surface of sleeve is less than that MVR compressor due to no more rubbing against the stationary wall but now with relative velocity of the vane tip and the sleeve. In general, the RSVR compressor is supposed to perform better compared to the existing MVR and rolling piston compressor, in term of mechanical and volumetric efficiencies

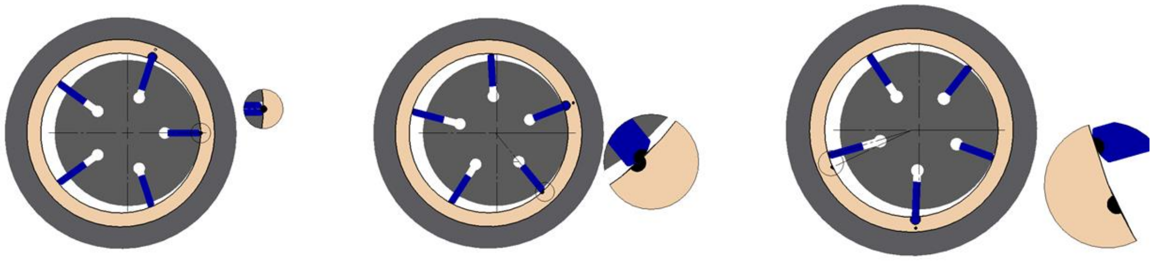


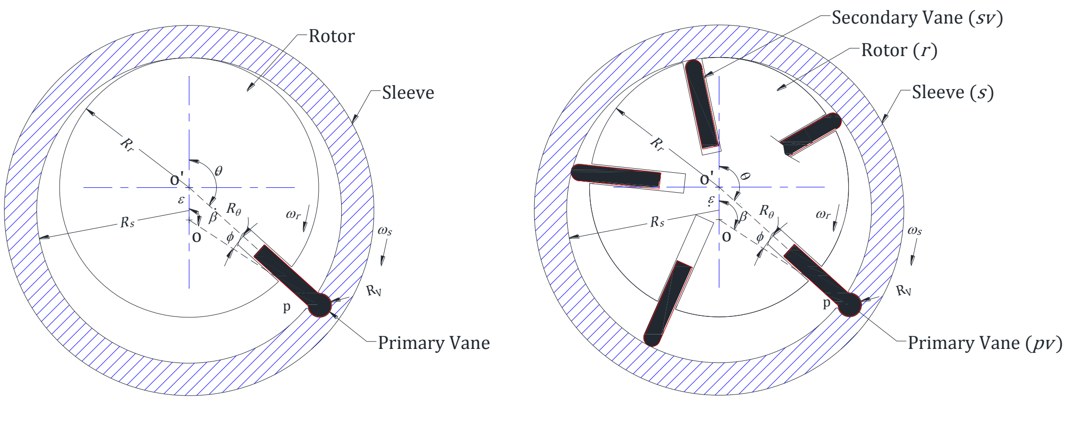
Figure 1.7 Rubbing surfaces of secondary vane and of sleeve at different leading vane angle

1.3 Rotating Sleeve Vane Rotary Compressor

In the year 2001, Musa (2007) developed a new concept of single vane compressor namely, rotating sleeve single vane rotary (RSSVR) compressor. As shown in Figure 1.8(a), one end of the vane is embedded into the sleeve and during rotation the other part of the vane is pushed in and pulls out of a slot in the rotor. The primary function of the vane is to drive the sleeve to rotate along and together with the rotor; all components perform the compression process. A patent was filed in the same year and granted in year 2007. There are also other similar concepts, some are modifications to this model, being developed and studied by other researchers. Examples of such concepts are the synchronal vane by Zong Chang *et al.* (2004), the revolving vane by Teh and Ooi (2009a). Figure 1.8(a) shows the typical diagram of RSSVR compressor. Evolved from this single primary vane of embedded end model, a multi-vane concept which has a single primary vane and multiple secondary vane is introduced. Unlike the primary vane the function of these secondary vanes is to perform compression only. The invention is called a rotating sleeve multi vane rotary (RSMVR) compressor and the concept is as shown in Figure 1.8(b). The thermodynamic process in this RSMVR compressor concept is similar to that in a conventional MVR compressor.

MVR compressor has an advantage over other models in terms of compact size, simple mechanism, low level of noise of 59 dB and below (Chang, 1983) and very high speed of rotation of up to 4000 rpm (Ucer and Aksel, 1980). However, the compressor is not suitable for large capacity operations if the discharge pressure is more than 14 bar. It will cause bending of the vane due to high bending stresses and may cause the vane to get stuck in the slot. In addition, non-lubricated compressor operation is not suitable for this vane type. Moreover, in a frictional analysis, the 84% of total compressor power is to overcome vane friction and about 85% of vane friction is produced at the vane tips each of which rubs against the stationary inner cylinder surface (Kaiser, 2004). In fact, if the coefficient of friction is more than 0.2, friction from vane tips requires up to 50% of the theoretical compressor power.

Back to RSMVR compressor, other advantage is that the swept volume is virtually increased to about twice that of the RSSVR. For example, if the RSSVR compressor has radius of rotor 30 mm, inner radius of sleeve 34.5 mm and length 32.6 mm, then the swept volume is 32.46 cc. On addition of four secondary vanes becomes an RSMVR compressor, the virtual swept volume is 66.63 cc. Thus, if a swept volume is specified as 32.46 cc, adopting an RSMVR concept makes the compressor smaller, compact and lighter.



(a) (b)

Figure 1.8 Sectional view of a) RSSVR compressor b) RSMVR compressor

The working principle of the RSMVR compressor is basically the same as that of MVR compressor. Both have four thermodynamic processes namely expansion, suction, compression and discharge and total mass delivered is a multiple of the number of vanes with the leading cell as a rotating reference angle.

1.4 Design Specification

Table 1.1 shows the main dimensions for RSSVR and RSMVR compressor. The details of the configuration and working condition can be referred in Chapter 4. The arrangement locations of each component are based on established conceptual design by Yusof (2005) and Teh and Ooi (2009c).

Table 1.1 : Main dimension of RSSVR and RSMVR compressor

Parameter	**Value**	**Unit**
Rotor radius, R_r	31.0	mm
Inner Sleeve radius, R_s	34.5	mm
Chamber length, L_c	35.0	mm
Vane width, T_v	4.0	mm
Vane heigth, H_v	15.0	mm
Suction open, β_1	5^o	degree
Suction close, β_2	144^o	degree
Discharge open, β_3	318^o	degree
Discharge close, β_4	338^o	degree

1.5 Objectives

The objectives of the research are as follows:

i. To show that the number of vanes has some effects on the performance of RSVR compressors.

ii. To predict well the performance of an RSVR compressor by a new mathematical model which is to be developed and validated.

1.6 Scopes of Research

Scopes of research are outlined as follows:

i. Undertake literature review for rotary vane compressor (leakage, lubrication, design, mathematical model and experimental work)
ii. Develop a mathematical model for RSVR compressor with one, three and five number of vanes, respectively.
iii. Design and fabricate the new RSSVR and RSMVR compressor based on established conceptual design.
iv. Design and build (all in accordance to British Standard) a test rig for compressor performance testing on and of a refrigeration plant
v. Undertake performance testing, also according to British Standard.
vi. Validate the theoretical and experimental results.
vii. Arrange a demonstration for the operation of a hollow rotor torque DC motor

1.7 Research Methodology

The methodology of the research is shown by a flow chart shown in Figure 1.9 and the detail of some task is described in Figure 1.10.

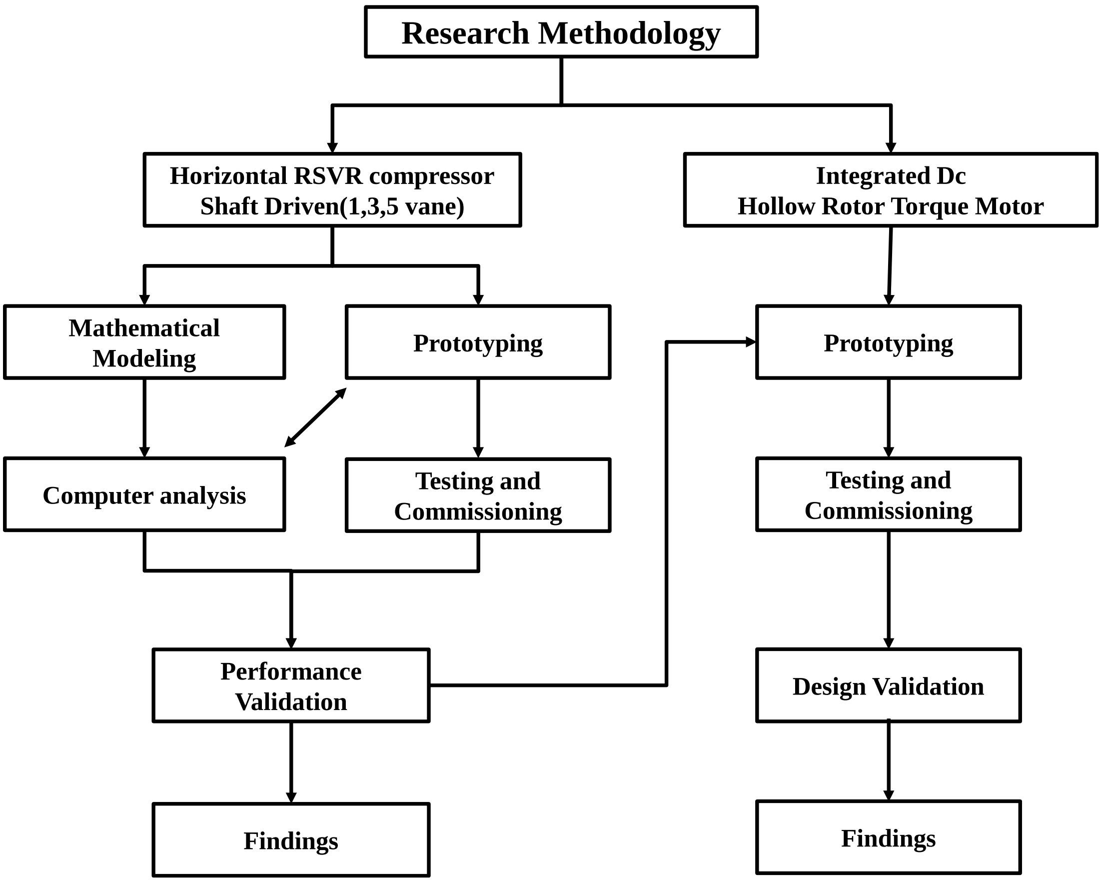


Figure 1.9 Research methodology flow

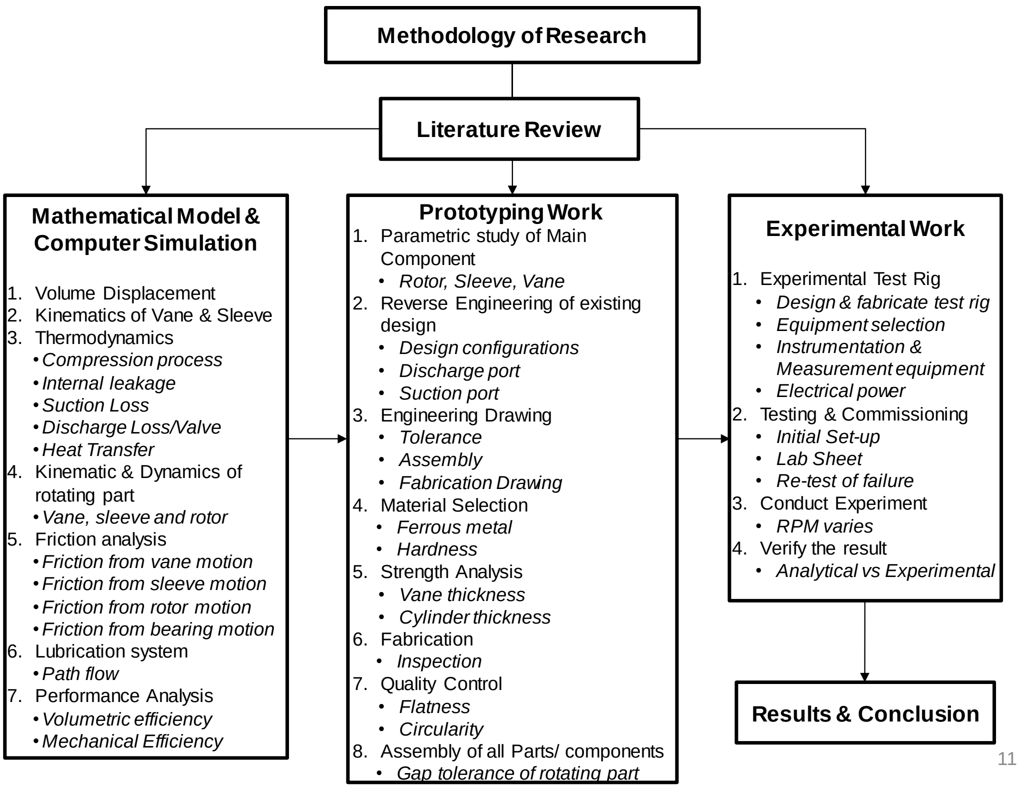


Figure 1.10 Detail research methodology

1.8 Significance of Research

The main focus of the research is on the attempt to design, develop, and test the mechanism of RSSVR and RSMVR compressor and to demonstrate the operation of the hollow rotor torque motor. The expected output of the research will be a new idea of knowledge to design and fabricate a new RSSVR and RSMVR compressor model which is relatively small, lighter, more compact and efficient than that of the existing models of equivalent capacity. Examples of immediate and future applications of the new compressor technology are for air-conditioning of cabins of parked trucks and motor homes, electric car, hybrid car and conventional vehicles, refrigerated trucks, luxury boats and yachts, etc.

1.9 Thesis Overviews

The report of the research work is presented in the proceeding chapters. Chapter 2 presents the review of research papers/report on rotary vane compressors, that have been published since 1972 to 2014. It covers eight topics such as internal leakage, dynamics of vane, lubrication, heat transfer, mathematical model, experimental work, design and optimization. Chapter 3 presents the methodology on how to predict the performance of each of the newly developed compressors by using own respectively developed mathematical models. The development of each model involves geometrical, thermodynamics, kinematics and dynamics, and performance analysis. Chapter 4 presents the prototyping work, development of test rig, testing and commissioning and collecting data to evaluate the performance of the new compressors. In Chapter 5, result of theoretical analysis and validation of the compressor models are presented against that obtained from experiment. Chapter 6 presents conclusion of the entire work and as well as recommendations for future initiatives.

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