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A Study on Novel High Efficiency Vane Compressor

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ABSTRACT

This paper proposed a novel high efficiency structure of vane compressor. This kind of compressor can translate the sliding friction between the vane and cylinder into rolling friction, which can significantly reduce the loss of mechanical friction. Compared with conventional vane compressor, this compressor has been proved high efficiency and reliability. Then the structure and operation principle was introduced, differences of mechanical friction loss between the two compressors were compared and analyzed in this paper.

1. INTRODUCTION

With the advantages of simple structure, easy processing, self-balance of rotor, low noise, less vibration, tittle torque ripple, low cost of manufacturing and so on, vane compressor is widely used in the fields of air compressor, vacuum pump, small refrigeration and air conditioning equipment, and automotive air conditioning compressors.

The main disadvantage of the traditional vane compressor is that mechanical friction between vane tip and cylinder is more serious. The power consumption of mechanical friction accounts for 29.1% of the total power. And the friction power of vane tip and cylinder accounts for 81.2% of the mechanical friction power (Ma G Y& Li H Q. 2001). Therefore, friction power loss and reliability between vane tip and cylinder are the biggest bottlenecks in the wider application of vane compressor, many researches has been done to this caused by the accumulator(Wu J H, Zhang L, et al. 2004, A.R. Sarip, M.N. Musa. 2012 , Raito Kawamura, Shin Sekiya, et al.2016).

This paper proposed a novel high efficiency structure of vane compressor, which reduces the friction power of vane tip and extends its application range.

2. BASIC STRUCTURE

Figure 1 shows the basic structure of a novel high efficiency vane compressor (HEVC). Compared with the conventional vane compressor, 2 rolling bearings are added on and beneath the cylinder. HEVC mainly consists of a shell, a motor and a compression mechanism. The compression mechanism is accommodated in the bottom of shell, and it is composed of a main bearing, cylinder, sub bearing, shaft, two rolling bearings and three vanes (Figure 2). The suction port and discharge port are set in the cylinder radial. Low-pressure refrigerant is sucked into the compression mechanism. Then it is pressurized to high pressure in compression mechanism and discharged into the interior of shell. Finally, the refrigerant is discharged to the outside of compressor through the gap of the motor and discharge pipe.

Figure 2 shows the basic structure of the compression mechanism. There are 3 vane grooves in the shaft, vanes are assembled in each vane groove.

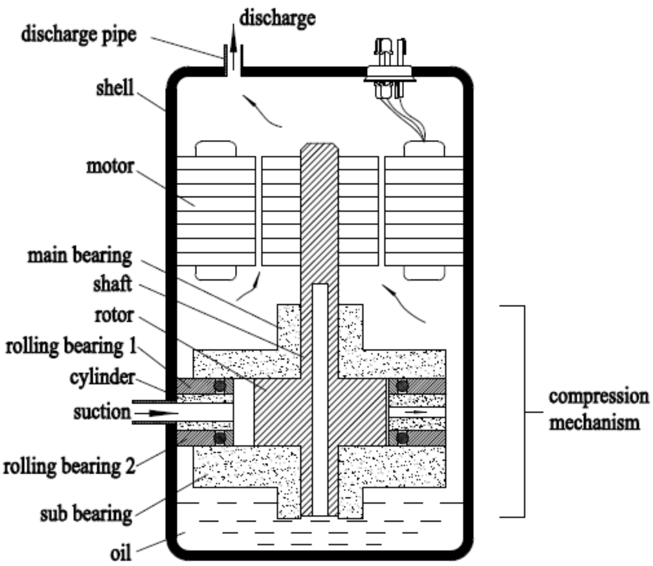


Figure 1: Basic structure of HEVC

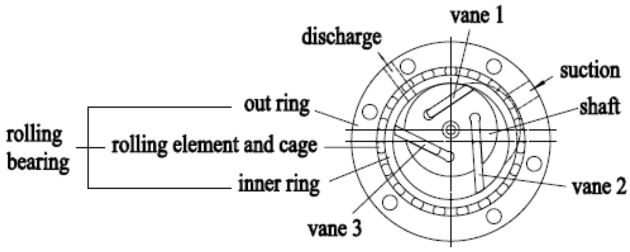


Figure 2: Basic structure of compression mechanism

Figure 3 shows the assembly of vane tip with cylinder and rolling bearing. The cylinder and rolling bearing are assembled coaxially. And the diameter of cylinder is smaller than that of the inner rings. So the vane tip contacts the inner ring of bearing, then forms a clearance δ_c with the inner wall of cylinder. If δ_c is too small, it may lead vane to contact with the cylinder when the former parts are subjected to deformation, which cannot reduce the friction. If δ_c is too large, it will cause leakage. Therefore, δ_c has an optimal range.

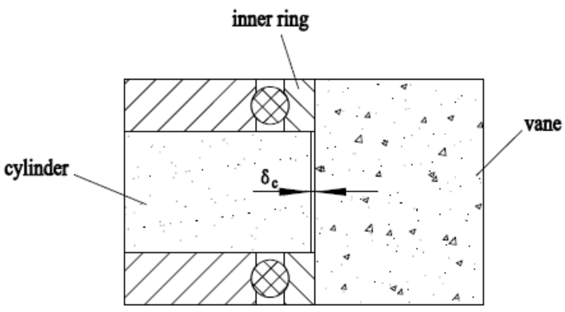


Figure 3: Assembly of the vane tip with cylinder and rolling bearing

3. OPERATING PRINCIPLE

Figure 4 shows the compression process of HEVC. During the operation of compressor, the friction force of vane tip between inner ring drives rolling bearing to rotate. Vane tip doesn't contact with cylinder, and there is no friction between them. As a result, friction loss and wear of vane tip can be reduced effectively which will improve HEVC's reliability at the same time.

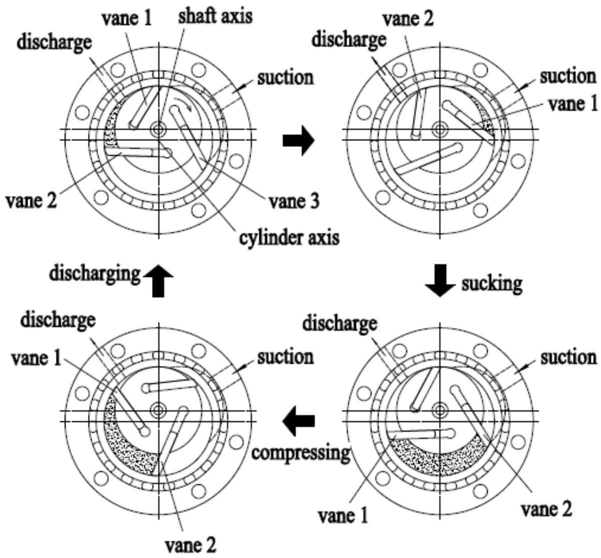


Figure 4: Compression process of HEVC

4. THE ANALYSIS OF MECHANICAL LOSS

Compared with conventional vane compressor, HEVC converts part of the sliding friction between vane tip and cylinder into rolling friction by introducing rolling bearings, which reduces frictional power loss significantly. But, the inner ring end and the rolling bearing itself bring extra power loss. Therefore, it is necessary to analyze the overall mechanical loss (Kong X Z. Yang H L &Sun T S.2005).

The compressor has 3 kinds of lubrication: boundary, mixed, fluid friction. Because of the complexity of frictional process, a part of the load is supported by solid contact (boundary friction) and remainder by a fluid film. So it is very difficult to determine the coefficient of friction in mixed frictional process. Therefore, the friction at each location is assumed to ideal state: boundary or fluid friction. When friction meets the following conditions: convergence space, lubricating oil and speed difference, the fluid dynamic pressure lubrication can be used to calculate the conditions. The rest is calculated according to the boundary friction.

Including friction loss due to viscous drag between the kinematic pair and lubricating oil in a shell chamber, 9 locations where frictions occur are assumed as shown in Table 1, Figures 5 and 6.

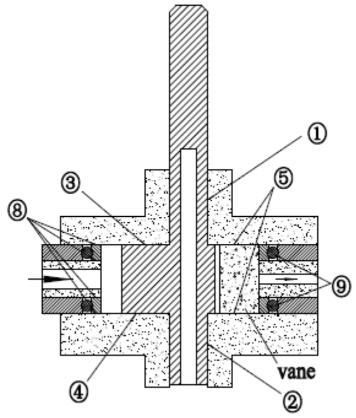
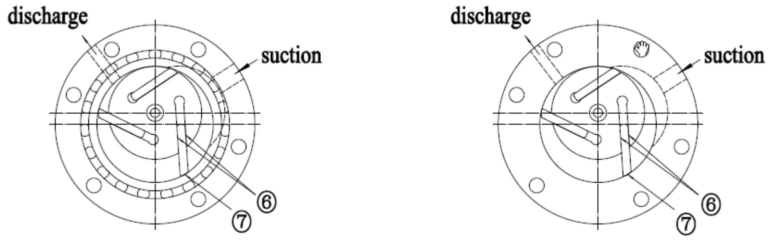


Figure 5: Locations of some friction



(a) HEVC (b) Conventional

Figure 6: Friction locations of vane and van tip

Table 1: Friction Models Assumed

No.	Locations Of Friction	Model
1	Shaft and Main Bearing	Fluid
2	Shaft and Sub Bearing	Fluid
3	Rotor end and Main Bearing End (Upper Thrust Bearing)	Fluid
4	Rotor end and Sub Bearing End (Lower Thrust Bearing)	Boundary
5	Vane end and Bearing End	Boundary
6	Vane and Vane Groove	Boundary
7	Vane Tip and Inner Ring(Cylinder) Wall	Fluid
8	Inner Ring End	Fluid
9	Rolling Bearing	Other

4.1 Shaft and Main Bearing

The main bearing is a typical journal bearing to be used for the compressor. And satisfies the above hypotheses of fluid motive power lubrication, Petroff's equation for fluid frictional loss is introduced.

$$W_1 = \frac{2\pi\eta\omega_s^2 R_s^3 h_{mb}}{\delta_{sm}} \quad (1)$$

4.2 Shaft and Sub Bearing

Similarly as the main bearing, Petroff's equation is also applied for the sub bearing.

$$W_2 = \frac{2\pi\eta\omega_s^2 R_s^3 h_{sb}}{\delta_{ss}} \quad (2)$$

4.3 Rotor end and Main Bearing End (Upper Thrust Bearing)

Since the gap and speed difference between rotor end and main bearing end, and the load is light. It is assumed that a better oil film can be formed here. So the fluid friction is introduced.

$$W_3 = \frac{\pi\eta\omega_s^2 \left(R_r^2 + R_s^2\right)\left(R_r^2 - R_s^2\right)}{2\delta_{rm}} \quad (3)$$

4.4 Rotor end and Sub Bearing End (Lower Thrust Bearing)

Due to the action of motor and shaft, lower thrust face forms a metal-to-metal contact with the cylinder. The formation of oil film is more difficult. So the boundary friction is introduced.

$$W_4 = \frac{2\mu_{tb}\omega_s F(R_r^3 - R_s^3)}{3\left(R_r^2 - R_s^2\right)} \quad (4)$$

4.5 Vane end and Bearing End

Similarly as 4.3, the load between vane end and bearing end is slight, so fluid friction should be considered.

$$W_5 = 3\frac{2\eta bLv_v^2}{\delta_{vm}} \quad (5)$$

4.6 Vane and Vane Grooves

In course of motion, vanes form the line-contact with vane grooves due to gas force acting on both sides of the vane. It is difficult to form an oil film. So the calculation here is based on boundary friction.

$$W_6 = 3(\mu_{vs} f_1 v_{vi} + \mu_{vs} f_2 v_{vi}) \quad (6)$$

4.7 Vane Tip and Inner Ring (Cylinder) Wall

Due to centrifugal force and oil pressure which come from vane tail, vane tip will cling and relative slide along the inner ring wall. Thus, a line contact is formed between vane and inner ring (cylinder) wall. Similarly as 4.6, the boundary friction is introduced. And v_t is the relative speed.

$$W_7 = 3\mu_{vi} f_{vt} v_{vi} \quad (7)$$

4.8 Inner Ring End

The compression mechanism has 2 rolling bearings, each inner ring has 2 friction pairs. The calculation model of each friction pair are the same. And the inner ring has gap with cylinder or bearing, with lubricating oil and speed difference. It is assumed that a better oil film can be formed here, so the calculation is based on fluid friction. Formula for a single friction pair is shown as W′. The total friction loss is W_8.

$$W' = \frac{\pi\eta(R_o^4 - R_i^4)\omega_{ir}^2}{\delta_{im}} \quad (8)$$

$$W_8 = 4\frac{\pi\eta(R_o^{\ 4} - R_i^4)\omega_{ir}^2}{\delta_{im}} \tag{9}$$

4.9 Rolling Bearing

Because of the complex motion state of rolling bearings, their frictional torque calculations are currently based on empirical formulas. This paper refers to the calculation model of SKF (Sweden) (Guo H J.1994). The friction loss is made up of rolling friction torque, sliding friction torque, seal element friction torque and the frictional torque caused by drag loss, vortex, splash, etc.

$$M = M_{rf} + M_{sf} + M_{sef} + M_{drag} \tag{10}$$

$$W_9 = \frac{Mn}{9550} \tag{11}$$

Table 2 shows the working conditions and related parameters.

Table 2: Working Conditions and Related Parameters

Refrigerant	R410A
Condensation Temperature(°C)	54.4
Evaporation Temperature(°C)	7.2
Displacement (cc)	42.8
Cylinder Diameter(mm)	60
Rotation Speed(r/min)	1800

According to the above formulae and parameters, the mechanical loss between HVEC and conventional vane compressor is calculated, as shown in Table 3.

Table 3: Comparison of the mechanical loss

Friction Pairs Category	HVEC	Conventional
W1/(W)	24.28	
W2/(W)	14.78	
W3/(W)	8.36	
W4/(W)	1.73	
W5/(W)	2.34	
W6/(W)	122.55	
W7/(W)	40.39	272.11
W8/(W)	40.90	/
W9/(W)	20.65	/
W/(W)	275.99	446.16

On the basis of other conditions remain the same, the total power consumption of the compressor can be reduced by 170.17W, and COP (coefficient of performance) can be increased by 12%.

5. FEATURES AND PROBLEMS ON STRUCTURE

Due to the use of rolling bearings, HEVC can translate the sliding friction between vane tip and cylinder inner wall into rolling friction, so it can significantly reduce mechanical power consumption. At the same time it retains the advantages of conventional vane compressor. In the field of refrigeration and air conditioning, there are several advantages compared with rotary compressor.

5.1 Volumetric Efficiency

HEVC has a multi-volume cavity structure and its compression process is equivalent to two or more stages. Therefore the pressure difference between the adjacent two vanes is low (Ma G Y& Li H Q. 2001). As shown in Figure 7, leakage to the suction is slight which has little influence on the suction.

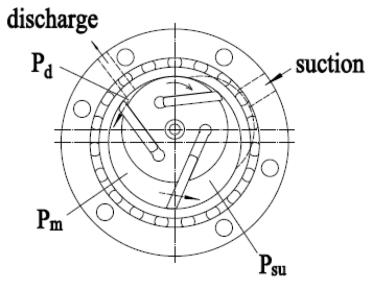


Figure 7: The model of leakage to suction

5.2 Size

As shown in Figure 8, under the same structure size, the displacement of the rotary compressor is V_{c1}, the displacement of the vane compressor with three vanes is $3{\cdot}V_{c2}$. Therefore the volume utilization ratio of cylinder is higher than rotary compressor.

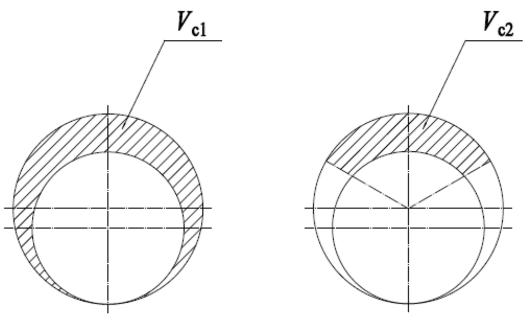


Figure 8: Volume comparison of two compressors (horizontal cross-sectional view)

So compared to a rotary compressor, HEVC's size can be designed to be smaller at the same displacement. It is beneficial to installation in the air conditioning system, HEVC can reduce the size of whole air conditioner and the cost of material. At the same size, HEVC is easily design to larger displacement, so it can run at a lower frequency in the same air conditioning system, which is helpful to improve the reliability of compressor.

5.3 Torque

HEVC's multi-cavity compression process is working simultaneously. Stage-by-stage compression, flow uniformity and small gas pulsation. As shown in Figure 9 and Table 4 (calculated and compared with the rotary compressor), the torque peak is low and torque ripple is little, under the same displacement design. Compared with rotary compressor with same shaft diameter, HEVC has low shaft load and high reliability during the operation.

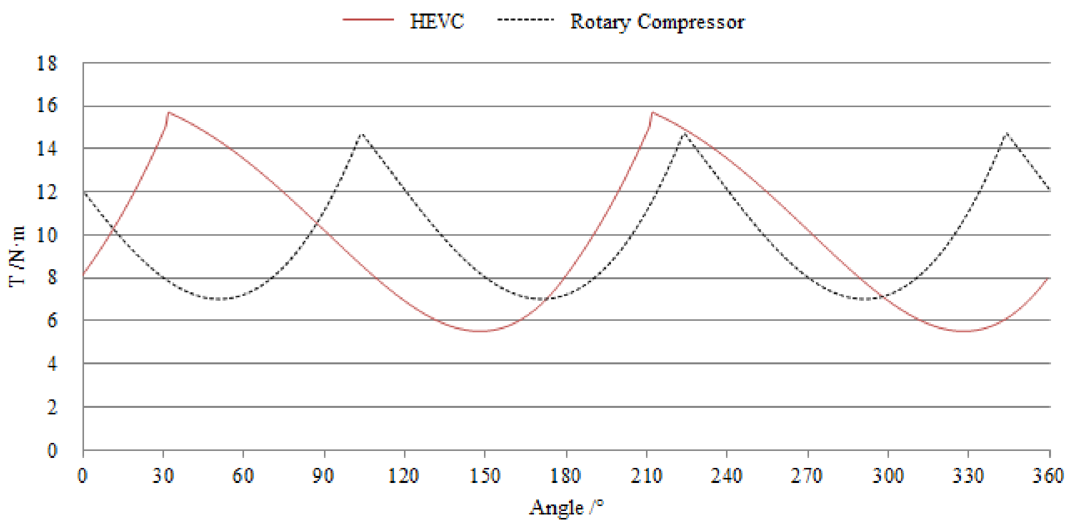


Figure 9: Torque comparison of two compressors

Table 4: Torque of two compressors

	HEVC	Rotary Compressor
T_{max}/N·m	14.7099	15.6898
T_{min}/N·m	7.0194	5.5167
T_{max}-T_{min}/N·m	7.6905	10.1731

Due to the use of rolling bearings, the clearance δ_c and reliability of rolling bearing is the focus of HEVC's design.

6. CONCLUSION

This paper introduced a novel high efficiency vane compressor, and its characteristics have been analyzed. Mainly as follows:

- Vane compressor has the advantages of high volumetric efficiency, small size and little torque ripple. Because of high sliding friction between vane and cylinder, mechanical friction loss of the conventional vane compressor is large, so COP of compressor is low, which limits the scope of its application.
- The striking feature of HEVC is the use of rolling bearings, which can translate sliding friction between vane tip and cylinder inner wall into rolling friction. The inner ring end and the rolling bearing itself bring extra power loss. But compared with conventional vane compressor, the total power consumption of HEVC can be reduced by 170.17W, and COP can be increased by 12%.
- Due to the effect on performance, the clearance δ_c and assembly process are the key research directions in the future.
- In order to ensure the reliability of rolling bearings, it is necessary to design the lubricating oil circuit for rolling bearings.

NOMENCLATURE

η	oil viscosity	MPa·s
ω	angular speed	Rad·s^{-1}
n	rotation speed	r·.min^{-1}
δ	clearance	Rad·s^{-1}
R	radius	mm

h	height	mm
μ	friction coefficient	/
F	weight of motor and shaft	N
b	width of vane	mm
L	length of vane	mm
v	velocity	$m \cdot s^{-1}$
f	support reaction	N
V	volume	mm^3
M	torque	N·m
P	pressure	MPa
T	torque	N·m

Subscript

s	shaft
ir	inner ring
vc	vane tip and cylinder
sm	shaft and main bearing
ss	shaft and sub bearing
rm	rotor end and main bearing end
vm	vane end and main bearing end
im	inner ring end and main bearing end
o	outer
i	inner
r	rotor
mb	main bearing
sb	sub bearing
tb	lower thrust bearing
vs	vane and vane groove
vn	vane tip and inner ring wall
v	vane
vi	vane tip and inner ring
1	right side
2	left side
vt	vane tip
rf	rolling friction
sf	sliding friction
sef	seal element friction
drag	drag loss
c1	compressor 1
c2	compressor 2
su	suction
d	discharge
m	middle
max	maximum
min	minimum

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