1998

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INFLUENCE OF VANE SLOT BACK-PRESSURE ON THE CHARACTERISTIC OF VANE MOTION IN ROTARY VANE COMPRESSOR

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ABSTRACT

The rotary vane compressor for automobile conditioning system is analyzed in this paper. Numerical model is used to calculate forces exerting on vanes and rotor. The discussion is focused on the influence of vane slot back-pressure on vane characteristic and compressor efficiency. It is concluded that appropriate constant vane slot back-pressure is effective to guarantee the contact of vane tip with cylinder inner wall and the minimum friction losses in the same time. The research work in this paper is the basis of optimum design.

INTRODUCTION

A new type of rotary vane compressor was developed in 1970's (see Fig. 1). It has been widely developing since then because it has compact structure, balanced internal force, and high efficiency.

Rotor and cylinder are mounted in concentric in this type of compressor so that it can be used to compress gas in both sides of its sealed arc, or, one side is used as compressor and another side is used as expander.

We designed a new outline of inner cylinder wall and developed dynamic computation program in general use. The results of analysis show that vane slot back-pressure is one of the most important design parameter. It has great influence on characteristic of vane motion and compressor efficiency. The structure characteristic of this type vane compressor is being analyzed and dynamic model is proposed in this paper. Further, the properties of compressor in several different forms of vane slot back-pressure cavity are compared.
DYNAMIC MODEL OF VANE

There are several vane slots in rotor of vane compressor. Vanes are put into vane slot. When shaft rotates, vane keeps in touch with cylinder wall as the function of centrifugal force and gas back-pressure, thus volume between rotor and cylinder is divided into several parts. Since the variation of each element volume with shaft angle is same, we could use one of them as analytic object. According to Darlambe theory forces acting on vane are list as follows:

1) Inertial force: including relative inertial force $F_{me}$, centrifugal force $F_{mr}$, and cologorial inertial forces $F_{mk}$.

2) Initiative forces: including gas force $F_{p}$ caused by pressure difference in either side of vane, vane slot back-pressure force $F_{bk}$, vane tip force $F_{tp}$ acting by cylinder wall.

3) Binding forces and friction forces: including binding forces acting between vane and cylinder $F_{nc}$, bottom of vane and vane slot $F_{nb}$, vane and top of slot $F_{nm}$. Friction forces corresponding to these binding forces are $F_{fc}, F_{fb}, F_{fm}$ respectively. Forces mentioned above are all of the function of shaft angle.

The dynamic model is based on following hypotheses:

1) Not considering discharge pressure losses.
2) Weight of vane is neglected.
3) Friction coefficient between vane and vane slot, vane and cylinder wall keep constant.
4) Not considering heat transformation between elementary volumes, elementary volume and cylinder wall. Compression process is adiabatic.

The force balance function group of vane is shown as follows:

$$
\begin{align*}
\begin{bmatrix}
\mu \cdot \cos \theta_{ff} & \mu \cdot \cos \theta_{fm} & \cos \theta_{fc} + \mu \cdot \cos \theta_{fc} \\
\text{sign}(F_{ab}) & \text{sign}(F_{ab}) & \sin \theta_{fc} + \mu \cdot \sin \theta_{fc} \\
\text{sign}(F_{ab}) \cdot h & \text{sign}(F_{ab}) \cdot l & 0
\end{bmatrix}
& \begin{bmatrix}
F_{ab}/\text{sign}(F_{ab}) \\
F_{nm}/\text{sign}(F_{nm}) \\
F_{nc}
\end{bmatrix}
= \begin{bmatrix}
b_1 \\
b_2 \\
b_3
\end{bmatrix}
\end{align*}
$$

Fig. 1 Structure of new rotary vane compressor

Fig. 2 Forces acting on vane
where, constant file vector is expressed: 
\[ b_1 = -(F_{m_1} \cos \theta_{F_{1_1}} + F_{m_2} + F_{i_1}), \]
\[ b_2 = -(F_{m_2} \sin \theta_{F_{2_1}} + F_{m_3} + F_{i_2}), \]
\[ b_3 = 0.5(F_{m_3} \sin \theta_{F_{3_1}} \cdot h + F_{m_4} \cdot h + F_{i_3_1}), \]
\[ \text{sign}(F) \]
is sign of forces, it getting +1 as the force is positive and getting -1 as the force is negative.

We can acquire the relationship between each supporting force (or friction force) and shaft angle. Then the force acting on rotor by vanes is:
\[ \vec{F}_{vane}(\theta) = \sum_{i=1}^{n} [\vec{F}_{sa}(\theta_i) + \vec{F}_{sa}(\theta_i) + \vec{F}_{fs}(\theta_i) + \vec{F}_{fs}(\theta) + \vec{F}_{fs}(\theta)] \]
where, \( \theta \) is the phase angle \( \theta_i = \theta + (i-1)\beta \), \( i \) refers to number \( i \) vane, \( \beta \) is angle between two vanes.

Force acting on rotor by gas pressure is:
\[ \vec{F}_{gas}(\theta) = \sum_{i=1}^{n} (\int_{q_1}^{q_2} P_i(\theta) d\theta)L \]
where, \( q_1 \) and \( q_2 \) are start angle and finish angle of number \( i \) elementary volume respectively, \( P_i(\theta) \) is pressure in number \( i \) elementary volume in angle \( \theta \), \( L \) is axial length of cylinder.

Further, considering of friction force acting between front and back bearing and cylinder, rotor and cylinder, or, \( F_{fric}(\theta) \), then total force acting on shaft is:
\[ \vec{F}_{tot}(\theta) = \vec{F}_{vane}(\theta) + \vec{F}_{gas}(\theta) + \vec{F}_{fric}(\theta) \]

Dynamic computation program of this new type rotary vane compressor with friendly interface. Elementary volume, force acting on vane or rotor at arbitrary angle can be easily got as long as you input necessary parameters. A vane compressor of 96ml discharge volume is taken as a calculating example in this paper. The cylinder wall outline is complex and its shape is similar to ellipse. Some fundamental parameters can be seen in table 1.

### TABLE 1 BASIC PARAMETERS OF COMPRESSOR

<table>
<thead>
<tr>
<th>Vane number</th>
<th>Rotation speed (rpm)</th>
<th>Suction pressure (Mpa)</th>
<th>Discharge pressure (Mpa)</th>
<th>Refrigerant</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1800</td>
<td>0.3</td>
<td>1.45</td>
<td>R134a</td>
</tr>
</tbody>
</table>

### INFLUENCE OF VANE SLOT BACK-PRESSURE ON VANE MOTION

Vane slot back-pressure cavity refers to volume between bottom of vane and slot. Usually a certain pressure is kept in the cavity to insure the contact of vane tip with cylinder wall and the sealing of compression chamber. The design of back-pres-
sure cavity is of significant importance to the reliability and efficiency of compressor, which influence the state of vane motion, wear and tear of vane, leakage volume of refrigerant, friction losses, and etc.

Supporting forces between vane and cylinder wall could be used to indicate if there is separation between them. During actual process, supporting force is impossible below zero, otherwise vane and cylinder is out of contact. Moreover, Fnc has great influence upon friction losses. Factors follows may have effect on Fnc:

1) Rotation speed:

As rotation speed increase, eccentric force exerting on vane will increase so that vanes contact with cylinder wall more tightly. Computation result shows that increase of rotation speed has little influence on supporting force and friction force which exerting between vane slot and vane. On the other side, however, indicated power and friction power will increase too. There exist an optimal rotation speed value at which vane keeps in touch with cylinder wall and mechanical efficiency gets higher. The choose of speed should also considering about vane life, vibration and noise of machine.

2) Vane number:

Pressure difference between either side of vane will decrease while vane number increase thus influence supporting force between vane tip and cylinder wall indirectly. Increase of vane numbers are of assistance to pushing vane out of vane slot. According to criterion of mechanical efficiency, vane number also has an optimal value.

3) Vane slot back-pressure

To increase vane slot back-pressure is one of the most efficient way to keep vane in touch with cylinder wall. Usually rotation speed and vane number may vary only within a small scope. However, Back-pressure could be chosen in a relatively wide range and has prominent influence on supporting force Fnc.

Since the variation of back-pressure only slightly influence Fnm and Fnb before discharge process it has little effect on friction power caused by relatively movement of vane and vane slot, but significant influence on Fnc during suction, compress, and discharge phase, thus increase friction power between vane tip and cylinder. From this point, back-pressure has an optimal value which keeps friction power lowest and continuous contact of vane tip and cylinder wall. Back-pressure also influence vane
states in vane slot and there are four basic forms of states: (1) Forward tilt, (2) Backward tilt, (3) Hard forward and (4) Hard backward, see fig. 3.

Fig. 3 Motion states of vane

Vane motion state changed during the rotation of shaft. The relationship between vane motion state and shaft angle varies with the variation of back-pressure. Three typical structures of vane slot are used as examples in this paper to analyze influence of back-pressure to this new type of rotary vane compressor.

1) variation pressure in back-pressure cavity:

Variation pressure refers here that back-pressure force acting on vane bottom equals to pressure force acting on vane tip at all the time. Vane is throw out of vane slot depending on eccentric force only.

Using parameters given in table 1 the relationship between vane motion state and shaft angle is shown as solid line in Fig. 4. Vane clings to slot's back side at first and soon changed to Forward tilt. When rotation angle is near to 85 degree, vane state changed to Back forward tilt owing to large pressure difference. Then with decrease of pressure differential, vane state changed to Hard forward and soon restores to Hard backward.

It can be checked if vane keeps in contact with cylinder wall from the sign of Fnc. Fig 5 shows that vane separates from cylinder wall in a small scope (approximately 85 deg to 87 deg) during compression process. This will induce leakage of refrigerant which is not allowed during practice running of compressor.

In actual, variation pressure in vane slot back-pressure cavity is impossible to exist. Pressure variation in the cavity couldn't keep pace with rotation speed. Back-pressure act as average value form. As an ideal situation variation pressure cavity is researching basis of other cavity form.
2) Close cavity:

when back-pressure cavity is closed, gas in it will be compressed or expanded due to in or out of vane in vane slot. Calculation result show that close structure form is very unreasonable. This case is caused by that vane extend length near to maximum value when it is most liable to separate with cylinder wall so that back-pressure is not high enough to push vane tip contacting with cylinder wall. To assure the contact, back-pressure must be very high and friction losses is too large to acceptable. Conclusion could be made that close form of back-pressure is not suitable.

3) Constant back-pressure cavity:

We may see back-pressure as constant value if it only fluctuate in small range. Back-pressure is fixed on discharge pressure Pd in this article.

Relationship between supporting force Fnc and shaft angle see the solid line in Fig. 5. It may be seen from the figure that Fnc increase greatly owing to high constant back-pressure especially in suction and initial compress process. The negative effect is that friction losses increase and machinery efficiency decrease. However, power losses in constant back-pressure cavity is much less than that in close ones. The superiority is obvious.

Under constant pressure vane motion state is different from that of variation pressure. It can be seen from dotted line in fig. 4 that vane state changes between Forward tilt and Backward tilt in the main and there are only a little transition period of Hard forward and Hard backward. Compared to variation pressure, vane Forward tilt period is longer than Backward tilt period.

As stated above, there is an optimal value of back-pressure. The relationship between supporting force Fnc and shaft angle under back-pressure at 0.5, 0.8, 1.0, 1.2 times discharge pressure respectively is shown in Fig. 6.

Back-pressure greatly impact vane motion and system's friction losses. While back-pressure is relatively low, such as 0.6 times discharge pressure in this example, vane will separate from cylinder wall during compression and discharge period and will induce leakage seriously.
If back-pressure is overly high, friction losses will greatly increase though vane keep in touch with cylinder wall. Calculating results show that when back-pressure is 1.2 time discharge pressure Pd compared with that of 0.8Pd, friction losses increase 8.55%.

CONCLUSION

Through the analysis and calculation of influence of vane slot back-pressure to motion characteristics of vane and compressor efficiency, it is concluded that close form of back-pressure cavity should be avoided. Compressor efficiency is relatively high under variation back-pressure, but vane may separated from cylinder wall under some certain strike and thermodynamic parameters. Meanwhile variation pressure is not exist in actual situation. Analyse show that constant back-pressure cavity is a kind of reasonable structure, but it's friction losses increase evidently compared to that under variation back-pressure. Since rotation speed and vane number could also be used to adjust vane state, choosing them properly and decreasing slot back-pressure at reasonable range are benefit to increase mechanical efficiency. In addition, designing more reasonable back-pressure cavity in which pressure is lower in suction phase and higher in vulnerable sector is the further objective for engineering and technical personnel.

REFERENCES