Design Improvements of Vane Bearing Compressor

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Abstract. A variant of vane bearing compressor with double rolling bearing had been introduced two years ago (Hu and Xu, 2019). In order to solve the problems of complex assembly process and abnormal wear in the vane bearing compressor with double rolling bearing, this paper presents a type of improved vane bearing compressor with single rolling bearing. The improved vane bearing compressor integrates the rolling bearings and the cylinder into a rolling bearing cylinder unit. The suction and discharge ports are placed on the end face of the main bearing. With these improvements, the number of the end face friction pairs of rolling bearing inner ring is reduced by half, the number of parts is reduced accordingly, and the assembly process is thus made simpler than that with double rolling bearing. This paper introduces the operational characteristics and makes a series of structure optimization to improve the performance of the improved vane bearing compressor with single rolling bearing. The energy efficiency of the improved vane bearing compressor with single rolling bearing is found to be 5% higher than that with the double rolling bearing.

1. Introduction
With the advantages of simple structure, easy processing, self-balance of rotor, low noise and vibration, lower torque fluctuation, low cost of manufacturing and so on, vane compressor is widely used in the fields of air compression, vacuuming, low capacity refrigeration, air conditioning equipment and automotive air conditioning.

The severe mechanical friction between the vane tip and the inner wall of the cylinder is the main disadvantage of the conventional vane compressor. In order to mitigate this problem, the optimal back pressure of the vane had been discussed and a segmented throttling back pressure chamber had been introduced [1]. Ma et al. pointed out that the frictional loss of vane tip accounts for 87.1% of the total mechanical loss of the compressor [2]. A large number of research results indicate that with the action of the appropriate back pressure which is acting on the back of the vane, the contact force between the vane tip and the inner wall of cylinder could be minimized, the friction loss can thus be reduced effectively and the performance of compressor can be improved [3-5]. Guo et al. set three back pressure states, and showed that constant back pressure is more conducive to improve the motion characteristics and the performance of compressor [6]. The above studies have focused on how to reduce the power loss at the vane tip. Therefore, the frictional loss and the reliability at the rubbing region between vane tip and cylinder are the bottlenecks limiting the wider application of the compressor.

A variant of the vane bearing compressor with double rolling bearing (VBC-D) had been introduced
in 2019 (Hu and Xu, 2019) [7]. With the action of the double rolling bearing, the sliding friction between vane tip and cylinder inner wall has been translated into rolling friction. The inner ring of bearing rotates together with vane under the action of friction, which reduces the relative speed of the vane tip and the inner wall of cylinder. Therefore, the frictional power loss at the vane tip reduced. However, this brings other complications such as (i) a complex assembly process, and (ii) an unreasonably small clearance control, which is prone to abnormal wear.

In order to solve the above two issues (i) and (ii), this paper presents a new variant of vane bearing compressor with single rolling bearing (VBC-S). The VBC-S adopts a single rolling bearing structure and the suction as well as the discharge ports are placed on the end face of the main bearing. With these design changes, the rubbing regions at the end face is reduced by half, the number of parts is also reduced, and the assembly process has also been made simpler.

2. Basic structure

Figure 1 shows the pump structure for VBC-D [7]. It is composed of a main bearing, a cylinder, a sub bearing, a shaft, two rolling bearings and three vanes. The vane tip is in contact with the inner surface of the inner rings for the two rolling bearing and leaves a gap with the inner wall of the cylinder. During the operation of the compressor, the frictional force of the vane tip at the inner ring of the rolling bearing drives and rotates the rolling bearing. Therefore, the vane tip does not in contact with the cylinder and hence no friction loss between them.

Figure 1. The pump body structure of the VBC-D

Figure 2 shows the pump structure for VBC-S. It is composed of a main bearing, a bearing cylinder, a sub bearing, a shaft, and three vanes. The rolling bearings and the cylinder are integrated into a rolling bearing cylinder unit whose inner ring rotate freely. The friction between the vane tip and the inner ring of the rolling bearing cylinder rotates the rolling bearing.

Due to the cylinder subassembly is replaced by a bearing cylinder unit, the suction and discharge ports will have to be repositioned.

As shown in Figure 2, a suction port begins with a circular channel located radially at the main bearing radially and it connects to the crescent shaped suction port which is located at the end face of the main bearing.

The discharge port is located at the end face of the main bearing. The sliding vane sweeps over the
discharge port during the discharge process. If the width of the discharge port is too large, the sliding vane is not wide enough to cover the discharge port completely. When this situation occurs, the front chamber of the slide vane will be communicated with the rear chamber, resulting in an undesirable internal leakage. If however, the discharge port is too small, it will cause a serious over compression and results in significant discharge loss. Therefore, the shape of the exhaust port is designed to be the shape like rhombus to ensure the area of discharge, and the side width is less than the thickness of the sliding vane to avoid internal leakage.

In the end of the discharge process, the gap of the working chamber gets narrower. The end face cross-sectional area of this gap is too narrow for the discharge port. Therefore, this paper presents an annular discharge “channel” for the end stage of the discharge. The annular discharge “channel” is composed of a U-shaped groove located on the side of the vane slot and an annular groove is located at the main bearing. With the compressor rotating, the U-shaped groove on the rotor will connect to the annular groove of the main bearing only the end of discharge process. Thus, the high-pressure gas is discharged from the pump through the U-groove of the rotor and the annular groove of the main bearing.

Figure 2. The pump structure of the VBC-S

3. Contrastive analysis between the VBC-D and the VBC-S

3.1 Quantity of component
The VBC-S which is proposed in this paper combines the cylinder, upper rolling bearing and lower rolling bearing into one bearing cylinder, which has two fewer parts than the VBC-D. Compare with the VBC-D, there is no need to assemble the upper rolling bearing and the lower rolling bearing with the cylinder first in the single rolling bearing scheme and four assembly screws can be reduced. Therefore, the number of pump parts in VBC-S is reduced by six, and the actual assembly efficiency is increased by more than 30%.

3.2 Structure analysis
The suction port of the VBC-D is set in the radial direction of the cylinder. In order to meet the requirements of the suction port size, the cylinder must ensure a certain thickness. At the same time, only the inner rings of the upper rolling bearing and the lower rolling bearing are in contact with the sliding vane tip during the operation, but a certain contact area is needed to ensure the bearing capacity.
So the bearing also needs to ensure a certain height, which eventually leads to a higher overall height of the cylinder assembly.

For the VBC-S, there is no suction port and exhaust port in the radial direction of the bearing cylinder. The inner ring of the bearing cylinder is in contact with the sliding vane tip in the whole height direction to ensure the bearing capacity. Therefore, the height of the bearing cylinder can be appropriately reduced.

3.3 Mechanical loss analysis in theoretical
Based on the structural characteristics of VBC-D and VBC-S, this paper aims to compare the difference of friction loss caused by inner ring. According to the double rolling bearing scheme of VBC-D [7], there are four friction pairs between two inner rings and upper rolling bearing, lower rolling bearing, cylinder. But for the case of the single rolling bearing scheme of VBC-S, there is only one inner ring, hence the number of friction pairs is reduced to two.

Assuming viscous friction, the loss calculation of one friction pair [8] is given in Equation (1).

\[
W' = \frac{\pi \eta (R_o^2 - R_i^2) \omega_{ir}^2}{\delta_{im}}
\]  

(1)

where \(\eta\) is the dynamic viscosity of lubricating oil, \(R_o\) is the outer radius of inner ring, \(R_i\) is the inner radius of inner ring, \(\omega_{ir}\) is the angular velocity of inner ring, \(\delta_{im}\) is the oil film thickness within the inner ring and the main bearing.

Under specific working conditions, this paper compares theoretical mechanical loss for VBC-D and VBC-S with the same design parameters which are shown in Table 1.

The operational conditions and related parameters are given in Table 2. Table 3 shows that the frictional loss of the VBC-S is 81.8W lower than that of the VBC-D.

4. Performance optimization of VBC-S

4.1 Pressure loss
This measured variation of the working chamber pressure of VBC-S is shown in Figure 3.
As shown in Figure 3, there appears to have some suction loss during the suction process. At the end of the suction process, the working chamber breaks away from the suction port and the compression process begins. The chamber pressure increases as the working chamber volume reduces. When the chamber pressure reaches that of the set discharge pressure, the discharge valve opens and the discharge process begins. Figure 3 shows that there is discharge loss indicated by over compression during the discharge process.

There is no relevant data from 320°~360° angular position due to the cavity space thus this range is too small to accommodate the pressure sensor.

4.2 Two suction structures
In view of the suction loss of the VBC-S in high operating speed, a suction structure is re-designed to locate at the main and sub bearing to increase the suction port area as shown in Figure 4.
The test rig schematic of compressor performance is shown in Figure 5, the main components are compressor, condenser, electronic expansion valve, evaporator, and mass-flow meter. There are some temperature and pressure sensors on pipe lines, their measuring positions are also shown in Figure 5.

![Figure 5. The test rig schematic of compressor performance](image)

According to the measured results shown in Figure 6, as compared with that with only one suction port, the refrigerating capacity of the compressor with two suction ports is increased by 3.57%, the power consumption is increased by 2.28%, and the COP is increased by 1.26%. With the suction area increases, the amount of compressed refrigerant also increases, so the power consumption increases.

![Figure 6. Comparison of the performances in different suction structure](image)
4.3 Two rhombus-shaped discharge ports
As shown in Figure 7, to reduce the over-compression at the initial stage of discharge process, two rhombus-shaped discharge ports are located in the axial direction of the main bearing to increase the discharge port area.

![Diagram of a compressor with two discharge ports](image)

**Figure 7.** The pump structure of the VBC-S with two discharge ports

**Figure 8** shows the comparison of instantaneous discharge velocity at the initial stage of discharge, the results show that the discharge velocity can be reduced by 47% after increasing the discharge area.

![Graph comparing discharge velocity](image)

**Figure 8.** The instantaneous discharge velocity at the initial stage of discharge

According to the results of the performance test which is shown in Figure 9, as compared with the single discharge port, the refrigerating capacity of the compressor with double port is increased by 0.35%, the power consumption is decreased by 1.26%, and the COP is increased by 1.63%. With the reduction in over compression, the pressure difference between the front and rear cavities reduces. At the same time, the internal leakage of the pump decreases and the cooling capacity increases.
4.4 Other structural optimization

In order to further improve the performance of the VBC-S, the bearing cylinder height, inner diameter, rotor eccentricity and other parameters are optimized on the basis of double suction and double exhaust ports.

According to the measured results shown in Figure 10, as compared with the VBC-D, the refrigerating capacity of the VBC-S increased by 2.99%, the power consumption reduces by 2.68%, and the COP increased by 5.86%.

Figure 9. Comparison of the performances in different discharge port number

**Figure 10.** Comparison of the performances between the VBC-S and the VBC-D
5. Reliability

After the performance test of the VBC-D [7], the pump parts were separated. As shown in Figure 11, the inner wall near the suction port of the cylinder had serious wear. The reason may be that the radial load exerted on the inner ring of the bearing by the back pressure of the sliding vane caused the clearance of the bearing at this angle to be basically zero or negative, and causes the vane tip to rub with the inner wall of the cylinder, resulting in large friction and abnormal wear.

![Figure 11. The serious wear of the VBC-D cylinder](image)

In the reliability test, VBC-S operated continuously for 300 hours under high load conditions (the evaporation pressure is 8.8 bar, the condensation pressure is 38.7 bar, and the suction temperature is 30°C). Figure 12 shows the wear of the pump parts after the reliability test of the VBC-S. The results show that there is no obvious wear and scratch, and the reliability is greater than that of the VBC-D.

![Figure 12. The wear of the VBC-S pump parts](image)
6. Conclusion
This paper introduces an improved high efficiency variant of vane compressor (VBC-S) with a single rolling bearing. When compared to the vane compressor (VBC-D) with double rolling bearings, the following are observed:

(1) The structure of the VBC-S is simpler, the number of parts is reduced, and the height of the bearing cylinder can be adjusted more freely. And the assembly efficiency can be improved by more than 30%.

(2) Through the design of suction and discharge ports, the suction and discharge losses are reduced. After the design optimization, the energy efficiency of VBC-S is 5% higher than that of VBC-D.

(3) The results of reliability test show that under high load condition, VBC-S runs continuously for 300 hours without abnormal wear.

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