中國機械工程學刊第四十一卷第五期第 623~626 頁(民國一百零九年)
Journal of the Chinese Society of Mechanical Engineers, Vol.41, No.5, pp 623~626 (2020)

Study on Labyrinth Seal Leakage Flow With Piston Eccentric Motion in a Labyrinth Compressor

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Keywords： labyrinth compressor, labyrinth seal, leakage flow, piston eccentric motion

ABSTRACT

This paper investigated eccentricity characteristics of the piston and its influence on leakage flowrate of the labyrinth seal. The eccentricity of the piston and the dynamic pressures in the cylinder and in the labyrinth cavities were tested on a labyrinth piston compressor. Then, a 2-dimension transient flow model was built for the fluid flow in labyrinth seal. The labyrinth leakage flow rate with and without piston eccentricity was obtained and compared.

INTRODUCTION

The labyrinth piston compressor is one of the key equipment in petrochemical industry. There are contactless seals between the piston and the cylinder wall with no lubricating medium. Therefore, the labyrinth piston compressor is well suited for compressing flammable, explosive, corrosive or clean gases. The principle of labyrinth seal is shown in the Fig. 1. The leakage gas flows from the high-pressure side to the low-pressure side through the labyrinth seal made up of a serial of teeth and cavities between the piston and the cylinder wall.

Paper Received June, 2019. Revised August, 2019, Accepted October, 2019, Author for Correspondence: Xiao-Ling Yu.

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When the leakage gas passes through a throttle tooth, it contracts and the velocity increases. After flowing into a cavity, the leakage gas velocity decreases rapidly due to the sudden expansion of the volume, and forms swirls in the cavity. The leakage gas flow in the labyrinth seal is obstructed by a serial of throttle teeth and cavities. The pressure energy is converted into the eddy energy and the heat energy. Therefore, under a certain pressure difference between the high pressure and the low pressure, the labyrinth leakage flow rate reduces because of a large flow resistance produced by the labyrinth seal structure.

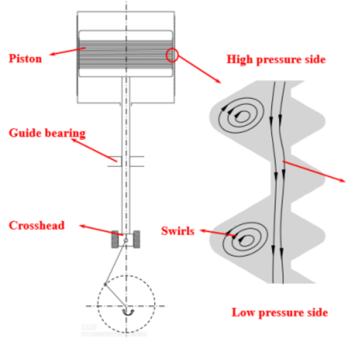


Fig. 1. Labyrinth seal flow.

A lot of research has been done on the labyrinth leakage flow. In early stage, the leakage flow in labyrinth seals was calculated by analytical formulas (Yucel et al. (2001)). In recent decades, experiments and numerical studies were carried out to investigate the labyrinth flow. Wang et al. (2007) studied the flow field in interlocking seals and stepped seals by numerical simulation. Pandey (2017) investigated the effects of operating pressure and oil temperature on the leakage flow characteristic of the two hydro-motors experimentally.

Many researches were mainly focused on structure parameters of the labyrinth seal. Sun et al. (2011) discussed the influence of the parameters such as tooth profile, tooth number, rotational speed and pressure ratio on the sealing performance. The shape of labyrinth tooth was optimized based on Latin hypercube sampling and Kriging method by Szymanski (2018).

The eccentric motion is unavoidable for the piston which will result in serious leakage of the compressor. Graunke et al. (1984) studied axis orbit of the piston with an initial eccentricity, and calculated the leakage flow rate through labyrinth seals using analytical formulas. Cheng et al. (2016) applied electromagnetic control system to ensure the concentric running of the piston and achieved good results with 80% eccentricity of piston reduced.

From above mentioned studies, we could see that few investigations studied eccentric movement characteristics of the piston and its effects on the labyrinth leakage flow rate. In this paper, eccentric movement of the piston in an air compressor under different working conditions was measured, and its influences on the labyrinth leakage flow rate were simulated using 2-dimension transient flow model.

EXPERIMENTS

The labyrinth piston air compressor test bench was built up as shown in Fig. 2. Air is inhaled and compressed by the compressor, and then is discharged and stored in a gas tank. The suction pressure is atmospheric pressure, while the discharge pressure can be adjusted by a valve on the discharge pipeline ranging from 0.2 to 0.5 MPa. Besides, the rotational speed of the compressor can be changed from 600 rpm, 700 rpm and 800 rpm respectively, by a frequency converter.

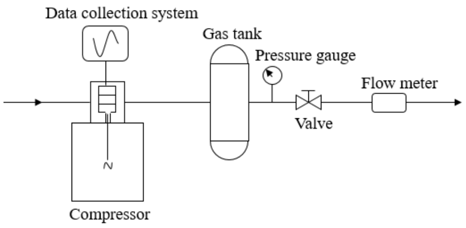


Fig. 2. Test system.

To measure the eccentric movement of the piston, an upper piston rod was designed and added to the top of the piston. The upper piston rod moved synchronously with the piston, and it can always stick out from the cylinder (as shown in Fig.3). An eddy current displacement sensor was mounted on a fixed bracket to measure the eccentric movement of the upper piston rod in Y direction as shown in Fig. 4.

The installation positions of transducers are shown in Fig. 3. Transducer 1 was fitted on the cylinder head to measure the dynamic pressure in the cylinder, while transducer 2 and transducer 3 were mounted on the piston to detect the dynamic pressures in the 26th and 40th cavities, respectively.

NI (National Instruments) data collection system was used to collect both pressure data and displacement data. The sampling frequency of the collection system is 2000 Hz, and the sampling time is 3 secs. The data processing was done in Mat Lab.

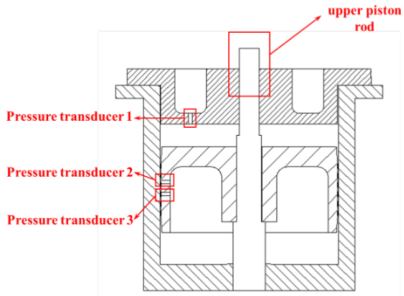


Fig. 3. Layout of the pressure transducers.

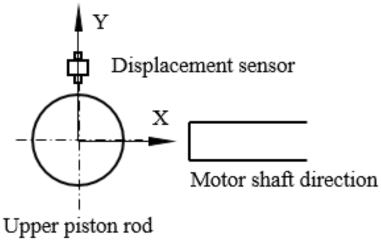


Fig. 4. Layout of the displacement sensor.

The experiments were conducted under 12 operating conditions with discharge pressure ranging in 0.2 MPa, 0.3 MPa, 0.4 MPa and 0.5 MPa, and rotational speed ranging in 600 rpm, 700rpm and 800rpm, respectively. For each condition, the eccentric movement of the piston, the dynamic pressures in the cylinder and in the two cavities were recorded.

SIMULATIONS

The sketch of structure of the labyrinth seal between piston and cylinder wall is shown in Fig. 5. The main sizes of the labyrinth seal are presented in Fig. 5. The numbers of labyrinth cavities on piston wall and cylinder wall are 51 and 141, respectively.

To study influences of eccentric movement of piston on the labyrinth leakage flow rate, a 2-dimension transient computational fluid dynamics (CFD) model of labyrinth seal flow was built. The computation zone was divided into four parts including the high pressure zone, the low pressure zone, and two labyrinth seal zones (shown in Fig. 6.). The compressed gas was considered as ideal gas, and the $k-\varepsilon$ turbulence model was also applied.

The boundary condition of the high pressure zone was dynamic pressure in the cylinder, which was measured in experiment. While the boundary condition of low pressure side was the atmospheric pressure.

The eccentricity of piston was fitted as a function with variable of time and then was written into the User Defined Function (UDF) file of the flow model. Moving mesh technology was also used in the simulation. And the grid independent solution was obtained. Using this CFD model, the pressure distributions in the computation zone and the mean leakage flow rate through the labyrinth seal in a revolution can be obtained.

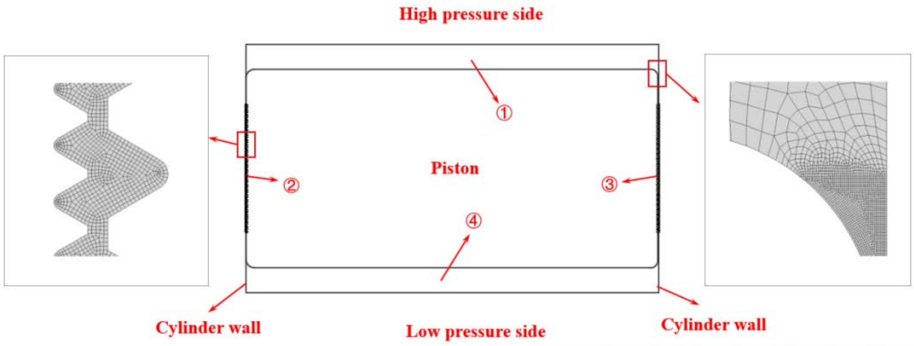


Fig. 6 The computation zone of the CFD model

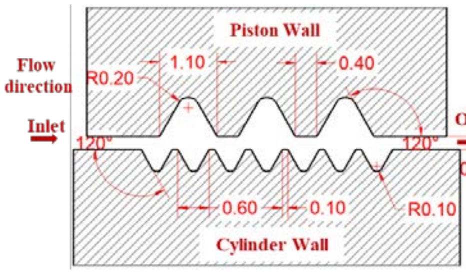


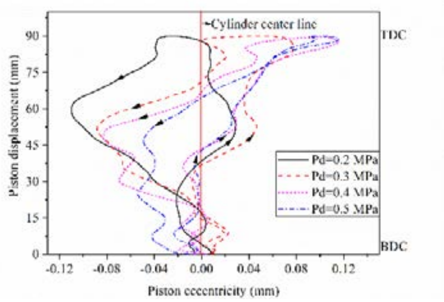
Fig. 5. Dimensions of the labyrinth seal (unit: mm).

RESULTS AND DISCUSSION

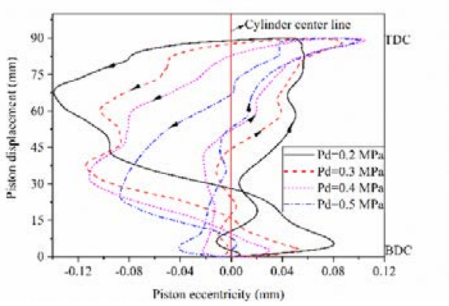
Fig. 7 shows the movement curves of the piston measured at different conditions. The piston moves from bottom dead center (BDC) to top dead center (TDC) and moves back. From Fig. 7, the eccentricity of the piston is the smallest at BDC, while the eccentricity is the largest at TDC. It was because at BDC the gas force is the smallest and the piston is near the guide bearing thus bending stiffness of the piston rod is high. The contrary is the case at TDC.

The comparisons of measured and simulated dynamic pressures in the labyrinth cavities during one revolution were shown in Fig. 8. As shown in these two figures, the simulated pressures matched well with the experiments with the relative errors lower than 13%. Hence it can prove that the transient CFD model of the labyrinth seal flow is reasonable.

The simulated labyrinth seal leakage flow rates at different discharge pressures and rotational speeds are illustrated in Fig. 9, from which we can see that, 1) the leakage flow rate almost increases linearly with the discharge pressure. This is because the pressure difference across the labyrinth seal increases with the discharge pressure increasing, and the pressure difference is the driving force of the leakage flow. 2) The leakage flow rate decreases with rotational speed increasing. For example the leakage flow rate at 800 rpm is about 75% of 600 rpm under 0.5 MPa. 3) The leakage flow rate increases obviously with eccentric movements of the piston. The leakage flow rate with piston eccentricity increases 21%, 30% and 20% respectively at 600 rpm, 700 rpm and 800 rpm under 0.5 MPa. The leakage flow rate grows exponentially with the clearance increasing. The clearance on one side of the piston increases obviously when eccentric motion occurs, so the leakage flow rate increases.

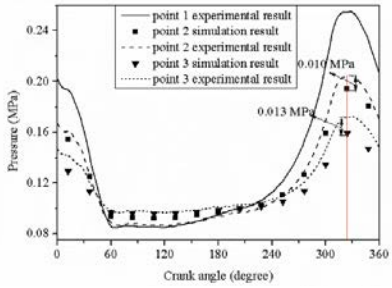


(a)Rotational speed:600 rpm

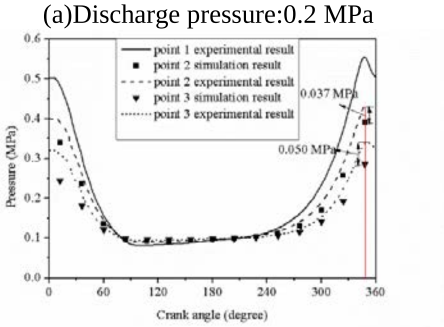


(b)Rotational speed:800 rpm

Fig. 7. Eccentric movement curves of the piston measured at different rotational speeds and different discharge pressures.



(a)Discharge pressure:0.2 MPa



(b)Discharge pressure:0.5 MPa

Fig. 8. Measured and computed dynamic pressures in the labyrinth cavities at 800 rpm.

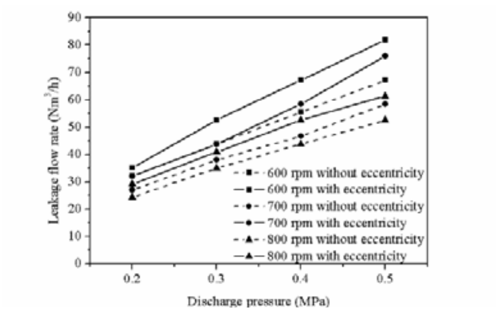


Fig. 9. Leakage flow rate under the cases with and without piston eccentricity.

CONCLUSIONS

In this paper, the eccentric movement of the piston and its influences on the labyrinth seal flow were studied. A labyrinth piston air compressor test bench was built to measure the piston eccentricity characteristics and dynamic pressures in the labyrinth cavities on the piston during one revolution. A 2-dimensional transient CFD model was built for the labyrinth seal flow field simulation. The following conclusions were drawn: 1) Under different operating conditions, the patterns of piston eccentric movement curves were similar. The eccentricity of the piston achieves the maximum and minimum at the TDC and BDC. 2) The measured and simulated dynamic pressures in the labyrinth cavities during one rotation at 800 rpm under different discharge pressures matched well with the maximum relative error of 13%. The accuracy of the simulated dynamic pressure results proves that the transient CFD model of the labyrinth seal flow is reasonable. 3) The leakage flow rate increases obviously with eccentric movements of the piston. The leakage flow rates with piston eccentricity rise by 21%, 30% and 20% at 600 rpm, 700 rpm and 800 rpm respectively under 0.5 MPa.

ACKNOWLEDGMENTS

The authors acknowledge the financial support of the National Science Foundation of China [No.51676150].

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NOMENCLATURE

R radius of the cavity.
k turbulence pulsation kinetic-energy.
ε dissipation rate of turbulence pulsation kinetic-energy.

迷宮壓縮機中活塞偏心運動對洩漏量影響的研究

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摘 要

本文研究了迷宮壓縮機活塞偏心運動規律及其對迷宮密封洩漏量的影響。首先，通過實驗測得了活塞的偏心運動軌跡和迷宮密封腔內的動態壓力分佈。然後，建立了迷宮流動的二維瞬態流動模型，通過模型研究了活塞有/無偏心運動兩種情況下的迷宮洩漏量，並將二者進行了對比。