Research on dynamic leakage flow in the labyrinth seal of a labyrinth piston compressor

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Abstract. To study the labyrinth leakage flow characteristics of a labyrinth piston compressor, firstly, a transient flow model was built to simulate the fluid flow through labyrinth seals. The dynamic pressures in the labyrinth chambers and the leakage flow rate were obtained by solving the transient flow model. Then, an experimental rig based on a labyrinth piston air compressor with rotational speed of 400 to 900 rpm, and discharge pressure of 0.2 to 0.5 MPa was built to validate the simulation results. In the experiments, dynamic pressures in the cylinder and in the labyrinth chambers were measured at different discharge pressures and different rotational speeds. The simulation results of pressures showed a good agreement with the experimental ones with the maximum relative error of 20%. Later, the transient flow model was used to study the dynamic pressure distribution and leakage flow rate through the labyrinth chambers. The results show that the pressure drop across each labyrinth chamber increases along the leakage flow path from the compression chamber side to the environment side. The pressure drop of the last third chambers accounts for 50% of the total pressure drop of all the chambers. The leakage flow rate increases quickly with the increase of the discharge pressure at low rotational speed. At the speed of 500 rpm, the leakage mass flow doubles when discharge pressure increases from 0.2 MPa to 0.5 MPa. However the growth rate slows down at a high speed of 800 rpm. The leakage characteristics indicate that the labyrinth piston compressor should work at a high rotational speed and a low discharge pressure.

Keywords: labyrinth piston compressor, leakage flow, transient flow model

1. Introduction
The labyrinth piston compressor is a special kind of piston compressor without piston rings. It has advantages of oil-free lubrication and high reliability because the clearance between the
piston and cylinder wall is sealed by the labyrinth seals. Therefore, the labyrinth piston compressor is well suited for compressing flammable, explosive, corrosive or clean gases. However, severe gas leakage has always been a technical problem for the labyrinth piston compressor. The leakage should be responsible for low efficiency of the compressor. So the accurate simulation of gas leakage through labyrinth seals is crucial for the labyrinth piston compressor design. The aim of this work is to investigate the dynamic flow process in the labyrinth seals via transient flow simulation, and to obtain the accurate leakage flow rate of a given labyrinth piston compressor.

Yucel[1] applied analytical equations to predicted the leakage flow in labyrinth seals. But these means cannot further deepen the understanding of the flow inside the labyrinth seals. In recent decades, experiments and numerical studies were carried out to investigate the labyrinth flow. Wang[2] et al. investigated the flow field of two kinds of seal structures and found that stepped labyrinth seals were more efficient than interlocking seals. Tang[3] et al. compared the results of CFD method with that of formula calculations and found the sealing performance was the best when the tooth angle was 60° and the cavity depth was 3.5 to 4 mm. Sun[4] et al. mainly discussed the parameters like tooth structure, tooth number, rotational speed and pressure ratio which had effect on the sealing performance, based on the three-dimensional steady numerical steady simulation. Zhou[5] et al. applied CFD simulations to investigate the labyrinth seal performance in a linear piston compressor under different conditions of clearance and observed that the linear seal was better than the labyrinth seal in some particular situation. Zhao[6] et al. studied the straight-through labyrinth seal in a turbo machine and investigated the effect of the cavity factors like depth and width in the labyrinth by CFD simulations. Szymanski[7] et al. used a kind of optimization method based on Latin hypercube sampling and Kriging method to lower the labyrinth leakage rate, and the results of leakage rate decreased by over 20% which were validated by CFD simulations and experiments. LIU[8] et al. established a model of straight labyrinth seal and studied the effects of Reynolds numbers and T/C on flow field, pressure loss, and heat transfer. Feng[9] et al. applied CFD method and experimental method to study the effects of different parameters of the cavities on the leakage rate. Schaller[10] et al. studied the application of the labyrinth seal in a reciprocating compressor by simulation and experimental method. They found rectangle-shaped seals with optimized factors had the best performance and the leakage rate could drop by 38%.

From above mentioned studies, we can see that a lot of studies investigated the fluid flow in the labyrinth seal using steady simulation method and most of the work concentrated on turbo machine. The dynamic flow process through labyrinth seals in piston compressor is not clear, therefore the leakage rate through labyrinth seals cannot be determined accurately. A transient flow model was built to simulate the fluid flow through the labyrinth seal in this paper. The pressure distribution in the labyrinth chamber and the leakage rate in one revolution were obtained by the model. The simulation results were validated by experiments on a labyrinth piston air compressor.

2. Transient model of leakage flow through labyrinth seals

The structure of labyrinth seals is shown in figure 1. There are small labyrinth cavities on the inner wall of the cylinder and bigger labyrinth cavities on the piston. The diameter of the piston is 250
mm and the clearance $\delta$ between the piston and the cylinder wall is 0.25 mm. There are 51 labyrinth chambers on the piston surface.

**Figure 1.** Structure of the labyrinth seals.

In this study, the commercial software FLUENT was used to simulate the fluid flow through the labyrinth seal. To fully understand the flow field, the piston, the entire labyrinth seals and the compression chamber were combined as a simulation zone in the model. The boundary conditions and key parameter setup in the model are illustrated in table 1.

**Table 1.** Model setup.

| Setup                |                  |
|----------------------|------------------|
| Turbulent model      | Standard $k-\varepsilon$ turbulence model |
| Fluid                | Ideal air        |
| Inlet                | Transient pressure-inlet(experimental date) |
| Outlet               | Pressure-outlet(100 kPa, 300 K) |
| Dynamic zone         | Piston           |

3. **Experimental rig**

To validate the simulation results, an experimental rig was built up based on a labyrinth piston air compressor with rotational speed of 400 to 900 rpm, and discharge pressure of 0.2 to 0.5 MPa. The compressor test system is shown in figure 2. The data collection system was used to collect pressure data and the valve was used to control the discharge pressure of the compressor.

**Figure 2.** Experiment system.

In the experiments, the dynamic pressures in the cylinder and in the labyrinth chambers were
needed to be measured in one revolution of the working process. The pressure transducers are required to be capable of measuring dynamic pressure in the labyrinth chambers with adequate accuracy, and to be small enough to have no influence on the flow in the labyrinth seals. In view of these demands, the dynamic pressure transducer with small volume and high response frequency was used. The transducer setup is shown in figure 3. Transducer 1 was fitted on the top of the cylinder head to measure the dynamic pressure in the cylinder, while transducer 2 and transducer 3 were set on the piston to detect the dynamic pressures in the 26th and the 40th chamber respectively counting from the inside of the compression chamber to the outside.

![Image of pressure transducer setup](image)

**Figure 3.** Locations of the pressure transducers.

4. Results and discussions

4.1 Model validation

The measured and simulated dynamic pressures in the labyrinth chambers in one revolution under different rotational speeds and discharge pressures are compared in figure 4 (a) to (d). Here the cylinder pressure measured by the pressure transducer 1 was performed as the transient inlet boundary condition of the transient flow model, and pressures of the two labyrinth chambers measured respectively by the pressure transducer 2 and 3 were used to validate the simulation results. As shown in these figures, the simulation results matched well with the experimental ones with the maximum relative error of 20% under different rotational speeds and discharge pressures. The possible reason for the discrepancy between the experimental and the simulation results could be the vibration of the piston which means the clearance varies in the circumferential direction of the piston.

![Graphs showing simulation and experimental results](image)

(a) Rotational speed: 500 rpm, discharge pressure: 200 kPa.  
(b) Rotational speed: 500 rpm, discharge pressure: 500 kPa.
Figure 4. Dynamic pressures of the labyrinth chambers in one revolution.

4.2 Leakage characteristics of labyrinth seals
The validated transient flow model was used to study leakage characteristics of labyrinth seals of the piston compressor in the experimental rig. The pressure distribution in the labyrinth chambers was obtained when the discharge pressure was 0.5 MPa, and the rotational speed is 500 rpm. The labyrinth chambers in the piston were divided into three sections evenly along the piston axis. The pressure contour results of each section are shown in figure 5, and the pressure in each chamber is plotted in figure 6 at the moment of the pressure in the cylinder being 0.5 MPa. It reveals that the pressure drop across each labyrinth chamber increases gradually along the leakage flow path from from the compression chamber side to the environment side. The pressure drop $\Delta P_1$, $\Delta P_2$ and $\Delta P_3$ of chambers in the three sections account for 21.5%, 28.4% and 50.1% of the total pressure drop respectively. The pressure drop of the last third chambers accounts for half of the total pressure drop of all the chambers.

Figure 5. Pressure contours in the labyrinth seals

(c) Rotational speed: 800 rpm, discharge pressure: 200 kPa.
(d) Rotational speed: 800 rpm, discharge pressure: 500 kPa.
The leakage mass flow rate through the labyrinth chambers in one revolution can be derived from simulation results of the transient flow model. The leakage mass flow rate at different discharge pressures and different rotational speeds is plotted in figure 7. The result shows that the leakage mass flow rate increases with increase of the discharge pressure at a certain rotational speed, and the growth rate is almost linear at a low rotational speed. At the rotational speed of 500 rpm, the leakage mass flow doubles when discharge pressure increases from 0.2 MPa to 0.5 MPa. However the growth rate slows down at a high rotational speed of 800 rpm. Therefore, according to the leakage characteristics of the labyrinth seal, the labyrinth piston compressor should work at a high rotational speed and a low discharge pressure.

5. Conclusions

In this paper, a transient flow model was built for the flow in the labyrinth seal of a labyrinth piston compressor. To validate the simulation results of the model, the dynamic pressures in the cylinder and in the labyrinth chambers were measured in experiments on a labyrinth piston air compressor under different rotational speeds and different discharge pressure. Then, the transient flow model was used to study the leakage flow characteristics in the labyrinth seal. The following conclusions were drawn.
(1) The pressure drop across each labyrinth chamber increases gradually along the leakage flow path from the compression chamber side to the environment side. The pressure drop of the last third chambers accounts for half of the total pressure drop of all the chambers.

(2) The leakage mass flow rate increases with the increase of the discharge pressure at a certain rotational speed, and the growth rate is almost linear at a low rotational speed. When the rotational speed is 500 rpm, the leakage mass flow doubles as discharge pressure increases from 0.2 MPa to 0.5 MPa. However the growth rate slows down at a high rotational speed of 800 rpm.

(3) Therefore, according to the results, the labyrinth piston compressor should work at a high rotational speed and a low discharge pressure.

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