Investigation on the influence of leakage clearance on the flow field and performance of scroll hydraulic pump

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Abstract: In the present paper, the computer fluid dynamics (CFD) with dynamic mesh model had been applied in scroll hydraulic pump to obtain its flow field at different leakage clearance. The fluid force on the orbiting scroll, the mass flow rate and the hydraulic efficiency at different leakage clearance were calculated based on the flow field data. The results indicated that when the leakage clearance increased from 0.5mm to 1.5mm, the average pressure, maximum of pressure fluctuation, leakage jet flow velocity, shaft power, cavitation degree decreased and the leakage flow rate increased. If the leakage clearance was 2.0mm, the high pressure discharge fluid flowed through the clearance and led to the increase of the average pressure and fluid force. When the leakage clearance is 1.0mm, the average pressure is far lower than that at the 0.5mm clearance, and the hydraulic efficiency is the highest.

1. Introduction
Scroll pump was derived from the scroll compressor which has been used for air-conditioner. The working fluid in scroll pump is liquid while the fluid in scroll compressor is gas, so the structure of scroll hydraulic pump is different from that of the scroll compressor. Because the liquid is almost incompressible, the scroll pump has only one pair of working chamber, as shown in Figure 1. And the number of the scroll profile laps is 1.5 theoretically. The scroll pump is a kind of positive displacement pump. It is suitable to transport the high viscous fluids, and allows the high gas volume fraction in the fluid. The flow rate of the pump is usually small and its lift changes little with the volume flow rate. Compared to other positive pump, the scroll pump operates smoothly, and its noise and vibration are low. Also, the structure of scroll pump is simple, which results in high reliability.

The scroll pump was studied by Zhu Jiang at first[1]. In his research, a mathematic model of a scroll oil pump was developed, and the influence of the discharge port on the scroll pump was analyzed. Then the prototype was manufactured and tested, the results indicated that the high pressure fluctuation existed in the working chamber. The amplitude of pressure fluctuation was related to the position angle of discharge groove, the oil viscosity and the leakage clearance[2]. Then, the researcher Jiang Bo and Wang Disheng developed the scroll oil pump SCP-1.08/0.6 which adopted the straight line involute and double acting structure[3]. Based on the pump, the researchers[4-6] established the mathematic model which described the working process and the leakage of the pump. With the model, the pressure distribution in the working chamber and the performance of the pump were predicted. The tested results showed the variation of the pressure with the crank angle in the working chamber, and indicated that the maximum pressure happened at the end of the suction process or the beginning of the discharge process. Moreover, the researcher supported that the maximum pressure can be reduced by enlarging the axial clearance of the pump. Obviously, the leakage clearances have significant effect on the pressure pulse and performance of the pump. However, the previous model adopted the ideal
nozzle model to simulate the inhomogeneous and transient leakage flow. The model cannot predict the influence of leakage flow on the flow field in the pump accurately.

Figure 1. Working principle of scroll pump.

Currently, the computer fluid dynamics (CFD) has been applied in scroll compressor \cite{7-10} and scroll pump \cite{11}. The CFD can help the researchers to obtain more accurate pressure and temperature data in the working chamber. In the present paper, numerical analysis of unsteady flow in a scroll hydraulic pump with several leakage clearances had been done to discover the effect of leakage clearance on the flow field and performance of the scroll pump. The flow fields of different leakage clearances were figured out. The pressure in the working chamber were monitored and displayed. Also, the force and performance were analyzed. Some useful advices about the scroll pump were proposed to improve the performance of the scroll hydraulic pump.

2. Mathematic model

The scroll pump consists of many parts, such as the fixed scroll, the orbiting scroll, the main shaft, the motor and the shell. In this paper, the mathematic model is only relevant to the fluid domain in the scroll chamber, so the main research parts are the fixed scroll and orbiting scroll. As shown in Figure 1, the fluid flows into the pump through the inlet, and is inhaled into the suction chamber through the suction port; then, it is squeezed and its pressure reaches at the discharge pressure and flows out through the outlet. The main scroll profiles geometric parameters are shown in Table 1. The basic circle can be seen in the Figure 1. The scroll pump has only one pair of working chamber, so the start involutes angle is $\pi$. The rotating radius can be changed to regulate the radial clearance. The leakage clearance was set in the geometric model, according to the Table 1.

![Figure 1. Working principle of scroll pump.](image)

Figure 2 shows the computational unstructured mesh which was generated in pre-processing software. The number of mesh elements was about 280000, which generally met the simulation accuracy requirement. Because the orbiting scroll moves with the crank angle, the dynamic mesh technology needs to be used. The triangular mesh was updated by the functions of smoothing and remeshing at appropriate time step to control the mesh skewness. The movement of orbiting scroll was controlled by a file, which was programmed with the user defined function (UDF) code. The moving parameters of the scroll pump is shown in Table 1.

The flow field inside the pump is full of turbulence because of the curved wall. The k-\(\varepsilon\) turbulent model with renormalization group (RNG) was selected as the fluid model. Non-slip boundary condition was employed on the wall. Near wall regions were analyzed using the standard wall functions method. PISO algorithm of the pressure based segregated solver was applied. Pressure boundary conditions which were given in Table 1 were adopted for inlet and outlet. When the local pressure becomes lower than the vaporized pressure of water at the local temperature, the water vaporized. This phenomena is called by cavitation. In the scroll hydraulic pump, at the clearance of the working chamber, the local pressure will be lower than the vaporized pressure of water. Hence, the cavitation model was added into the CFD model to ensure its accuracy. The cavitation model is the Schnerr-Sauer model. This model coupled the density of bubbles with the gas volume fraction to
obtain the evaporated and condensed mass rate\textsuperscript{[12]}. The time step is $1.1574 \times 10^{-4}$ s, when the orbiting scroll rotates 1 degree ($\pi/180$).

### Table 1. Scroll profiles geometric parameters and operating conditions

| Geometric parameters     | values  | Operating conditions       | values |
|--------------------------|---------|----------------------------|--------|
| Radius of basic circle/mm| 4.4563  | Working fluid              | Water  |
| Number of circle         | 1.75    | Rotating speed/mm          | 1440   |
| Start angle of involutes | $\pi$   | Suction pressure(A)/MPa    | 0.1    |
| Thickness of scroll vane/mm | 4       | Discharge pressure(A)/MPa | 0.4    |
| Suction volume/ml        | 132     | Suction temperature/$^\circ$C | 25    |
| Rotating radius/mm       | 8,8.5,9.9.5 | Leakage Clearance/mm    | 2,1.5,1,0.5 |
| Height of scroll vane/mm | 30      |                            |        |

![Figure 2. Grid model of the scroll pump](image)  

3. Result and discussion

3.1. Influence of leakage clearance on the flow field  
The radial leakage clearance were set to be 0.5mm, 1mm, 1.5mm, 2mm. The Grid models of different leakage clearances were created respectively. And the flow fields were calculated when the crank angle varied from 0 to 360° transiently. Hence, the flow field data at every crank angle could be calculated. However, it is not necessary to show too many flow field figures. According to the working principle of scroll hydraulic pump, the flow field at 0 crank angle is the most important, because at that time the suction chamber closes completely and the suction and discharge process will begin at next crank angle. Therefore, the flow field figures at 0 crank angle would be shown.

In Figure 3, the pressure fields at different leakage clearance are displayed. It can be seen that the maximum pressure decreases from 1.4MPa to 0.45MPa when the clearance rises from 0.5mm to 2mm. When the suction chamber closes, the volume of the chamber decreases and the working fluid in the chamber is compressed. Because water is almost incompressible, the pressure in the chamber will rise quickly. The working fluid in the suction chamber will leak out through the clearance to reduce the pressure in the chamber. The smaller the clearance is, the higher the pressure is.

In addition, the pressure difference between the right and left suction chamber decreases with the leakage clearance. The maximum pressure difference is about 0.2MPa at 0.5mm leakage clearance. And the minimum pressure difference is about 0.05MPa at 2mm leakage clearance. When the leakage
clearance are 0.5mm and 1.5mm, the left chamber pressure is larger than the right one generally. Conversely, the right chamber pressure is larger the right one at 1mm and 2mm clearances.

**Figure 3.** Pressure fields at different leakage clearance

The pressure distribution in shell chamber is noticeable. The low pressure area at both suction port goes down when the leakage clearance increases from 0.5mm to 1.5mm. The reason is that the jet flow velocity decreases with the reduction of pressure difference And the influence area of the jet flow shrinks with jet flow velocity.

The Figure 4 shows the streamline at different leakage clearances. It can be seen that the jet flow exists at the clearance and the maximum velocity happens at the external clearance except at the 1.5mm leakage clearance. The maximum velocity decreases with the clearance first and then rises at 2mm leakage clearance. The velocity magnitude determines the value of negative pressure and the dimension of vortex. Therefore, the value of negative pressure and dimension of vortex at 0.5mm leakage external clearance are the largest.

The velocity in the suction chamber is influenced by the velocity of moving wall and the leakage flow. The moving wall propels the working fluid moving forward and the leakage flow enlarges or weaken the velocity. When the clearance is large, the leakage flow rate is large, which results in the large area of vortex in the suction chamber, such as the chamber at the clearance 2mm.

The vortex in the shell chamber also changes with the clearance leakage. At the left shell chamber, the jet flow from the working chamber crashes the inlet flow and forms two vortexes. One is at the entrance of the left shell chamber, the other is around the suction port. The area of the vortex is proportional to the jet flow velocity. At the right shell chamber, the jet flow from the working chamber...
combines with the inlet flow and moves forward. Nevertheless, the orbiting scroll moves clockwise, which drives the fluid near the wall moving downward and also offsets the momentum of flow moving forward. Therefore, two vortexes form. One is at the top of the shell chamber, the other is at the entrance of the suction port. The vortex area and position are related to the jet flow velocity.

When the leakage clearance is 2mm, the number of vortex in the shell and suction chamber is larger, which was caused by the larger leakage flow rate and leads to larger flow loss.

![Streamline at different leakage clearances](image)

**Figure 4.** The streamline at different leakage clearance

The gas volume fraction represents the water vapor volume ratio locally caused by cavitation phenomenon. Its cloud contours are shown in Figure 5. When the local absolute pressure is lower than the water saturated pressure (3540Pa), the cavitation happens. The lower pressure in the flow field is mainly caused by the leakage jet flow. Consequently, the cavitation mainly happens at small leakage clearance. And its strength and area at 0.5mm leakage clearance are larger than that at 1mm leakage clearance.

3.2. The discharge volume flow rate

As shown in Figure 6, the discharge volume flow rate at different leakage clearance is given when the crank angle varies from 0 to 720°. The discharge volume flow rate lines fluctuate with the crank angle periodically, which indicates that the number of calculation step of mathematical is enough. The diagram also displays that the flow characteristic of scroll pump is periodical. Because the discharge
pressure (or lift) is fixed, the discharge volume flow rate represent the transport ability of the pump. The discharge flow rate at the 0.5mm leakage clearance is the largest since its leakage flow rate is the smallest. With the increase of leakage clearance, the discharge flow rate decreases. At the 2mm leakage clearance, the discharge flow rate becomes negative between the 180 and 330 crank angle, which means that the working fluid flows back from the outlet to the inlet. Obviously, because of the large leakage clearance, the leakage flow rate is larger than that driven by the pump.

![Figure 5. The gas volume fraction cloud contour at different leakage clearance](image1)

![Figure 6. Discharge volume flow rate at different leakage clearance](image2)
3.3. The pressure diagram at monitor point

Figure 7 and Figure 8 show the pressure diagrams of point 2 and point 7 at different leakage clearance. As shown in Figure 1, the point 2 and point 7 are set near the fixed scroll wall at the different working chamber, so the pressure diagrams of them can reflect the pressure variation of the left and right working chamber.

Figure 7. Pressure diagram of point 2 at different leakage clearance

The crank angles of point 2 and point 7 are about 125°. In the pressure diagram, the pressure before the crank angle 125° represents the pressure of discharge chamber. The pressure is higher than the discharge pressure to propel the working fluid out of the outlet. After that, it is the pressure of suction chamber, so the pressure is very low due to the enlargement of local volume and high flow velocity, in order to inhale the working fluid from the inlet. At this time, the pressure lines coincide. It is because the cavitation happens and the pressure is the saturated pressure of water. From the two figures, there are many pressure fluctuations which are caused by the variation of local volume and flow velocity. The pressure diagram of 1.0mm leakage clearance has the fewest pressure peaks, and also its maximum pressure is the lowest. It indicates that the 1.0mm leakage clearance may be the optimum one. The position of maximum peak is related to the leakage clearance. The crank angle of maximum peak decreases with the leakage clearance. One reason for this is that the large leakage flow prevents the increase of pressure of suction chamber.

Figure 8. Pressure diagram of point 7 at different leakage clearance

3.4. The performance of the scroll pump

With the pressure data of working chamber, the fluid force \( F_o \) on the orbiting scroll can be calculated out. So the shaft power can be figured out by the following equation:

\[
W_s = \frac{2\pi F_o r_o n}{60}
\]
With the transient discharge flow rate of the outlet $\dot{V}_t$ shown in Figure 6, the average transport mass flow rate can be integrated by the equation as follow:

$$\dot{m} = \frac{1}{2n} \rho \int_0^{2\pi} \dot{V}_t \, d\theta$$  \hspace{1cm} (2)

And the hydraulic efficiency of the pump can be calculated by the following equation:

$$\eta = \frac{\dot{m} (p_{out} - p_{in})}{W_s}$$  \hspace{1cm} (3)

Figure 9 shows the hydraulic efficiency and shaft power at different leakage clearance. The shaft power decreases with the leakage clearance firstly. Then the shaft power increases. The reason of power decrease is that the pressure of the working chamber decreases with the leakage clearance, so the fluid force on the orbiting scroll goes down. The minimum shaft power is 938W at 1.5mm leakage clearance. At the clearance of 2.0mm, the shaft power is larger. The reason for that is that large quantity of discharge liquid flow back through the leakage clearance, which can be seen in Figure 6. Because the pressure of back flow is discharge pressure, it will result in the increment of average pressure in working chamber. The maximum hydraulic efficiency happens at the clearance 1.0mm. When the clearance is smaller, the pressure in the working chamber is so high that the shaft power are larger. And, when the clearance is larger, the leakage flow rate will reduce the transport flow rate of the pump and enlarge the fluid loss of the pump. Hence, among the four clearances, the 1.0mm is the best one.

![Figure 9. Hydraulic efficiency and shaft power at different leakage clearance](image)

### 4. Conclusion

The transient flow fields of scroll hydraulic pump at different leakage clearance were calculated with the numerical model based on the dynamic mesh technology and fluid dynamics. The flow field and performance of the scroll hydraulic pump were analysed and the conclusions are summarized as follow.

When the leakage clearance is smaller, the average pressure of working chamber, the maximum pressure of pressure fluctuation and the jet flow velocity are higher. The area of vortex caused by the jet flow is larger. The cavitation happens at the vortex. And the orbiting force and shaft power is higher. With the increase of the leakage clearance, all the parameters are weakened. However, if the leakage clearance is too large, the discharge fluid flows back through the clearance, the flow field is full of vortex. The average pressure is improved by the high pressure back flow. The flow loss, fluid force and shaft power are also very high. Hence, there is an optimal leakage clearance. At the 1mm leakage clearance, the hydraulic efficiency are the highest. Among the four clearance, the 1.0mm leakage clearance is the best one.

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