

Numerical analysis on the cavitation and unsteady flow in a scroll hydraulic pump

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Abstract. This paper presents numerical analysis of unsteady flow in a scroll hydraulic pump to discover its flow mechanism. The dynamic mesh model has to be used to simulate the flow field unsteadily. The unsteady flow patterns and pressure distributions in the suction, squeezing and discharge chamber are analysed. The suction process continues until the crank angle reaches the 320 degree. Then the pressure in the chamber rises instantaneously, and the fluid begins to flow out from the chamber. Because of the high pressure difference at the clearance, the jet flow and the vortex appear, and the large flow losses generates with them. In addition, the velocity and static pressure distribution in the two symmetry crescent suction chamber is different remarkably. One reason is that the location of suction port cannot be set symmetrically for the simplification of the pump structure. Another reason for that is the fluid is impelled by different part of the orbiting scroll. The asymmetric pressure distribution will result in the extra force on the scroll. The cavitation generates at the negative pressure region. Therefore, the unsteady simulation shows some important phenomena. The structure of the scroll pump need to be optimized to reduce the maximum pressure, weaken the jet flow, vortex and the uneven pressure distribution to ensure the pump working safely and efficiently.

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 pump is different from the scroll compressor. Because the liquid is almost incompressible, the scroll pump has only a pair of working chamber, as shown in Figure 1. And the number of the scroll profile rotation 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 content 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 its high reliability.



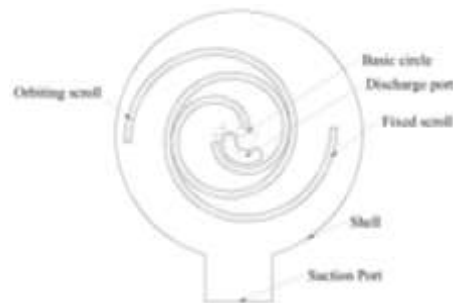


Figure 1. Working principle of scroll pump.

The scroll pump was studied by Zhu Jiang at first^[1]. In his research, a mathematic model of a scroll oil pump was developed. With the model, 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, which 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 researcher established the mathematic model which included the leakage model and described the working process of the pump^[4-7]. With the model, the pressure distribution in the working chamber and the performance of the pump were predicted. The pump was tested. 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. Yan and Qu studied the influence of the rotational speed on the pump^[8]. At the high speed, the pressure in suction chamber would be lower than the vaporizing pressure and the cavitations happened, which leads to high pressure fluctuation and vibration; at the low speed, the leakage increased and the pump efficiency decreased; so the optimal rotational speed existed. Although the researcher has obtained a lot of achievements, there are many problems unsolved about the scroll pump. One reason is that the present mathematic model was zero-dimension model which is based on the assumption that the pressure and temperature in the working chamber are uniformed. Actually, because of the flow loss and the structure of the working chamber, the fluid parameters in one chamber are inhomogeneous, and it is three-dimensional and unsteady flow in the chamber. So the zero-dimension model can not predicted the pump accurately.

Nowadays, the technology of computer fluid dynamics (CFD) has been applied in scroll compressor^[9,10], and can help the researchers to obtain more accurate pressure and temperature values in the working chamber. However, the CFD has merely been used in the scroll pump. In the present paper, numerical analysis of unsteady flow in a scroll hydraulic pump has been done to discover its flow mechanism. The flow field in the scroll pump is figured out, and some special phenomena about the pressure distribution in the chamber are revealed. The reason for the high pressure fluctuation has been analyzed, and the influence of meshing clearance on the pressure field and fluctuation will be studied. And some useful advices about the scroll pump are proposed to improve the performance of the scroll 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. But 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 Figure1, the fluid flows into the pump through the suction port, and is inhaled into the working chamber; then, it is squeezed and its pressure reaches at the discharge pressure and flows out by the discharge port.

The main scroll profiles geometric parameters are shown in table 1. The basic circle can be seen in the Figure1. The scroll pump has only one pair of working chamber, so the start involutes angle is π . The rotating radius can be changed to regulate the radial clearance.

Table 1. Scroll profiles geometric parameters and operating conditions

Geometric parameters		Operating conditions	
Items	values	Items	values
Radius of basic circle/mm	4.4563	Working fluid	Water
Pitch/mm	28	Rotating speed/mm	1440
Number of circle	1.75	Suction pressure/MPa	0.1
Start angle of involutes	π	Discharge pressure/MPa	0.4
Thickness of scroll vane/mm	4	Suction temperature/ $^{\circ}\text{C}$	25
Suction volume/ml	132		
Discharge port area/ mm^2	230		
Rotating radius/mm	10		
Height of scroll vane/mm	30		

Figure 2 shows the computational unstructured mesh which was generated in pre-processing software ICEM. The number of mesh is about 280000, which generally meets 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 is programmed with the user defined function (UDF) code in Fluent. The moving parameters of the scroll pump is shown in table 1.

The flow inside the pump is developed turbulence with curved walls. The $k-\epsilon$ turbulent model with renormalization group (RNG) is selected as the fluid model. Non-slip boundary condition is employed on the wall. Near wall regions are analyzed using the standard wall functions method. PISO algorithm of the pressure based segregated solver is applied. Pressure boundary conditions are adopted for inlet and outlet, which are given in table1. Because the pressure in the pump will become lower than the vaporized pressure of water at the local temperature, the cavitation model is added in the model to ensure its accuracy. The time step is 1.1574×10^{-4} s, when the orbiting scroll rotates 1 degree ($\pi/180$).



Figure 2. Grid model of the scroll pump.

3. Result and discussion

3.1 Pressure distribution

As to the scroll pump, the variation of pressure determines the torque, input power, the axial and radial force on the orbiting scroll and the vibration. Because the water are nearly incompressible, the radial clearance can not be set to 0, or else the pressure in the working chamber will almost reach the infinity. In this paper, the radial clearance is set to be 1mm.

Figure 3 shows the pressure distribution in the scroll pump at different crank angle. At the crank angle 0, it can be seen that a pair working chamber are closed. The suction process finishes and the next suction process will begin at once. The fluid in the working chamber will be discharged at the next discharge process. The pressure in the working chambers is almost uniform, except the two end of the crescent chambers. The pressure is about 0.54MPa, which is larger than the outlet pressure. It is because the volume of working chamber decreases at the crank angle 320°, the water in the working chamber is squeezed, and its pressure increases quickly. So at the two ends of the crescent chambers, the fluid flow through the clearance due to the high pressure difference. It is noticeable that the negative pressure exist at the external end of the crescent chamber. It is caused by the jet flow through the clearance under high pressure difference between chamber and the suction side.

At the crank angle of $\pi/2$, the pressure at the center of pump is about 0.4MPa, which is equal to the outlet pressure. In the external crescent chamber, there are two low pressure regions, the low pressure region at the end of the crescent is cause by the jet flow from the clearance. The velocity of fluid is very large, and the pressure decreases. The high speed fluid decelerates along the narrow passage and the pressure increase. After the low pressure region, a relative high pressure region exists. On the other side, at the entrance of the suction chamber, the fluid flows into the chamber with a high speed because of its volume increment. The high speed flow encounter the high pressure region, and generates the vortex. The energy of fluid is dissipated and a low pressure region forms.

At the crank angle of π , the suction entrance area reaches the maximum. The low pressure region caused by jet flow still exists, but its area decrease largely. As shown in Figure 3. (c), the pressure in the left suction chamber is remarkably different from the right suction chamber. It is caused by the position of the chamber entrance. The entrance of the left chamber faces directly at the suction port, so

the fluid flow into the chamber without any block. The velocity of fluid is very high, and the pressure in the chamber is low. The jet flow is stronger, so the area of negative pressure is larger. On the other side, the fluid flows into the suction chamber by a long way and its speed decreases a lot. And the pressure in the suction chamber is almost equal to the suction pressure. The pressure difference at the two sides of clearance is smaller and the negative pressure area is smaller.

At the crank angle of $3\pi/2$, the pressure difference between the left and the right chamber becomes larger. Besides the two low pressure regions in the working chamber, there is another low pressure region on the top of the shell. It is because the orbiting scroll moves up and squeezes fluid between the shell and the orbiting scroll. The fluid velocity increases and the pressure is reduced.

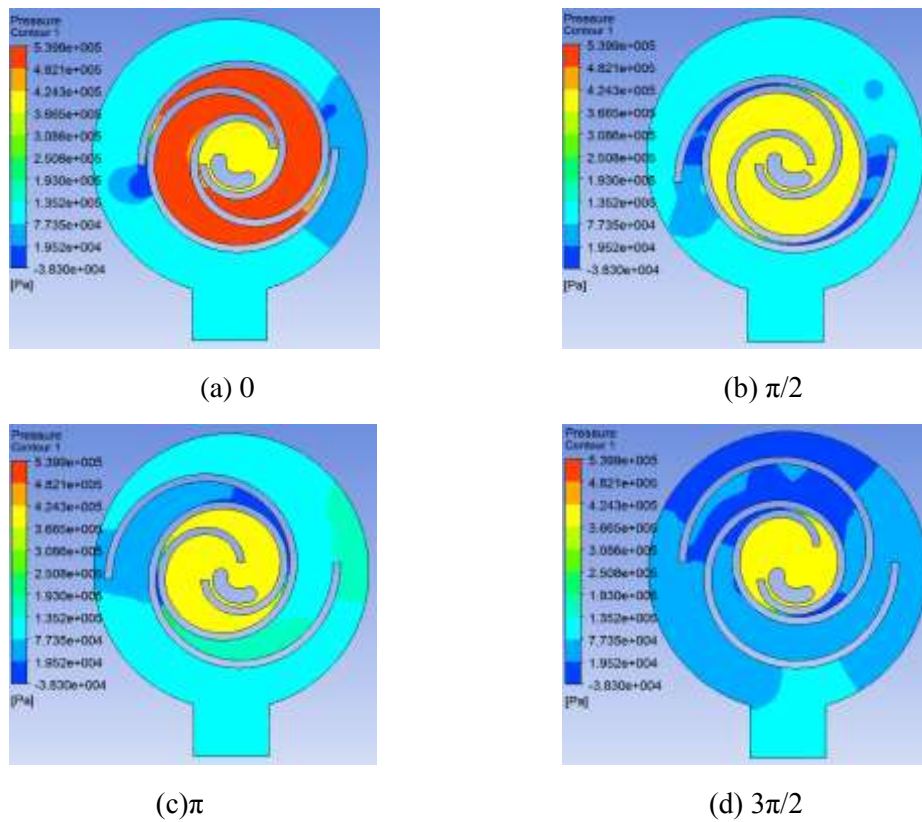


Figure 3. The pressure distribution in the scroll pump.

3.2 Streamlines and velocity vector

The Figure 4 shows the streamlines under different crank angle. From the streamline, the vortex can be seen clearly. In the suction chamber, the vortex exists all the time. And the vortex in the left chamber is larger than that in the right suction chamber, which results in the different pressure distribution in the two suction chamber. Between the scroll and the shell, there are many vortex, and the vortex positions change with the crank angle. It can be seen that there are big vortex at the entrance of suction chamber when the crank angle changes between 0 to π . Because the area of entrance is quite small, the high speed fluid is blocked by the small entrance, and the vortex generates. At the top of the shell, the moving orbiting scroll drives the fluid flow with it. So the vortex changes with the position of the orbiting scroll in the four figures.

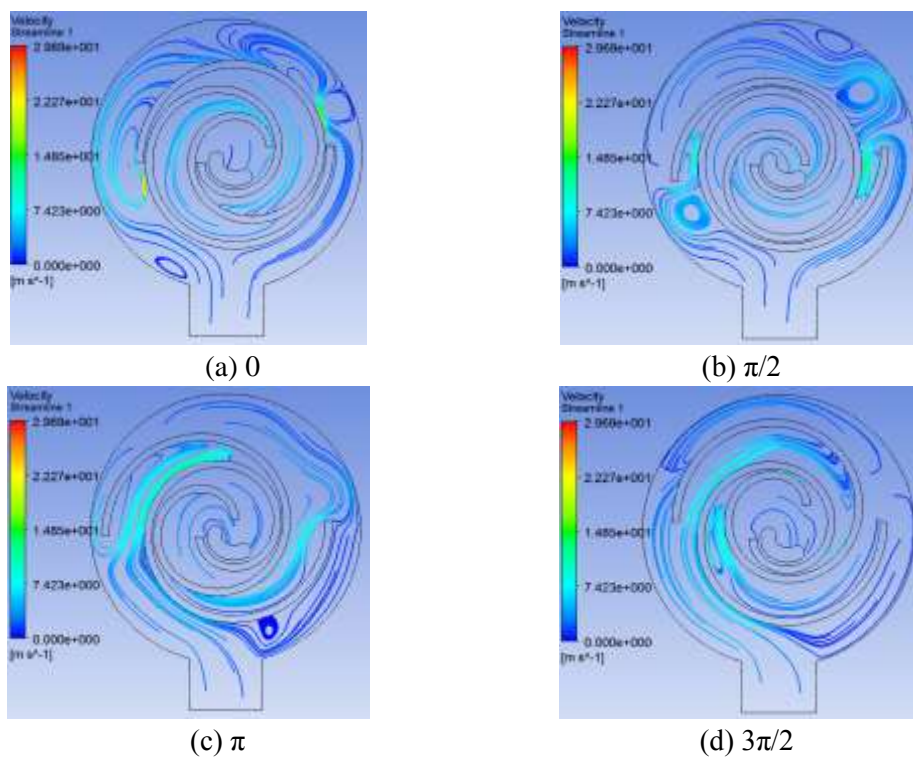


Figure 4. The streamline in the scroll pump.

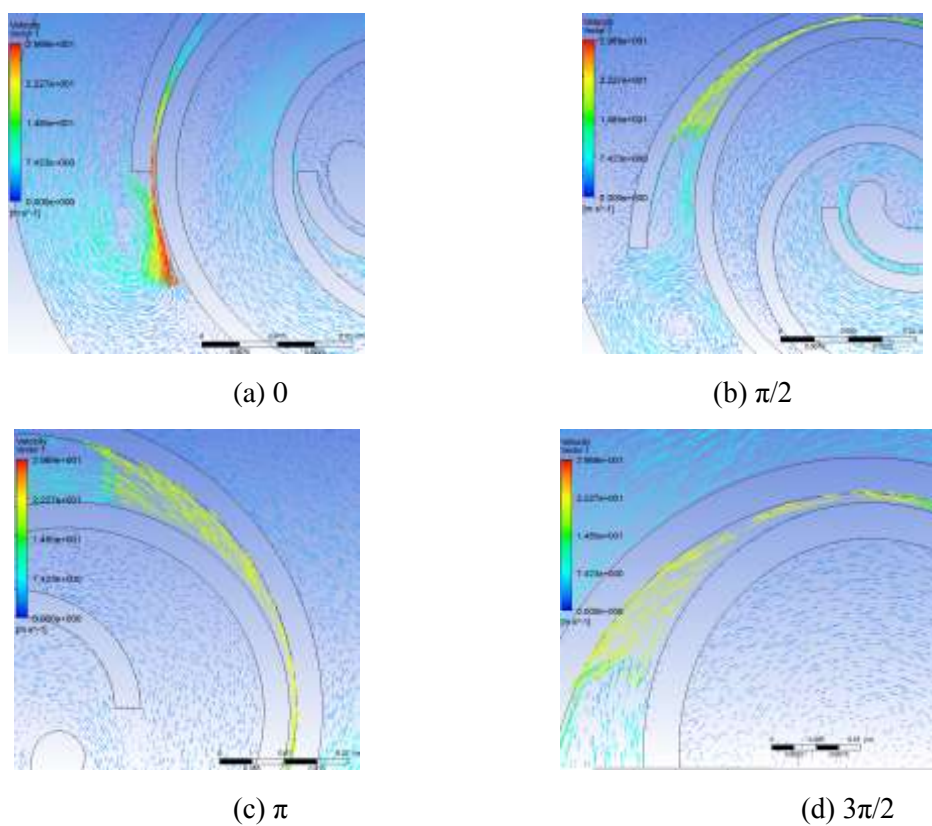


Figure 5. The velocity vector at the radial clearance.

Figure 5 displays the velocity vectors at the radial clearances at different crank angles. The clearances is just like a nozzle. The fluid is accelerated through the clearance by the pressure difference. The high speed flow gives rise to the vortex and negative pressure region. When the crank angle is 0, it can be seen that the jet flow from the clearance encounters with the suction flow and generate a big vortex at the entrance of suction chamber. The vortex dissipates the kinetic and pressure energy and the negative pressure region generates, which can be seen in Figure 3. The other three picture shows the vortices in the suction chamber. It can be seen that the high speed fluid mixes with the suction fluid and change their momentum. The velocity of fluid decreases and the pressure increases. A part of fluid goes back because they get the enough anti-direction momentum.

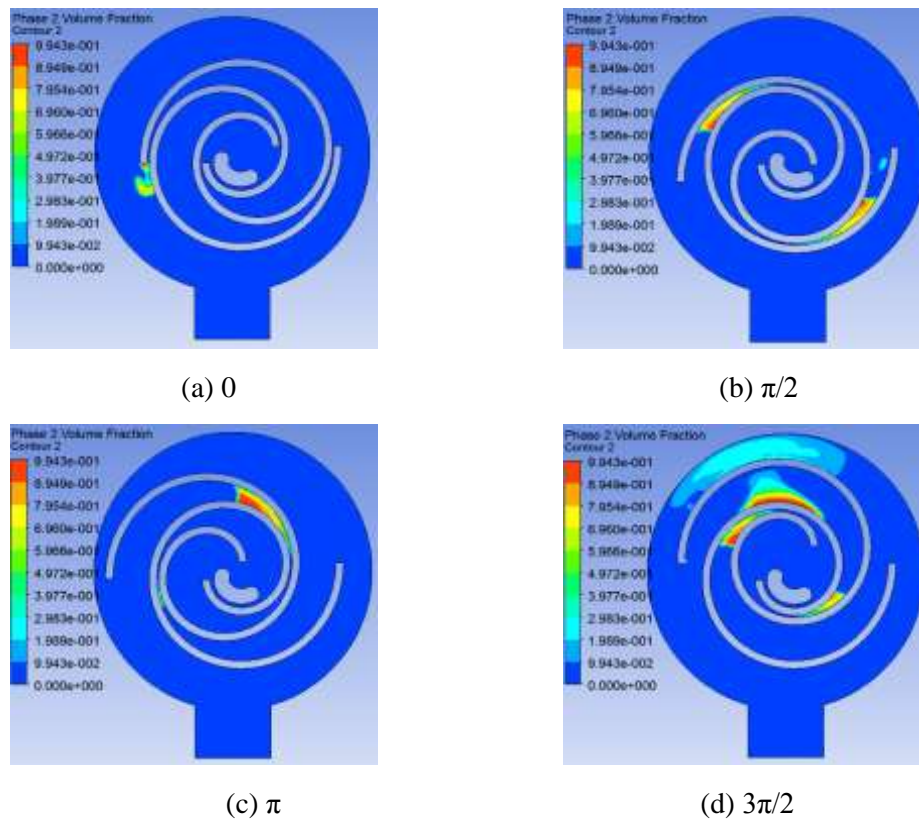


Figure 6. The gas phase volume cloud.

3.3 The gas phase volume cloud

At the radius clearance position, the pressure decreases with the increment of the fluid velocity. When the pressure becomes lower than the vaporized pressure of water at the local temperature, the water vaporized. This phenomena is called by cavitation, which is a key problem in the centrifugal pump. If the cavitation model is not applied in the mathematic model, the negative pressure could reaches the -0.6Mpa, which is impossible practically. So the cavitation model is added into the model, and the gas phase volume cloud are shown in Figure 6. It can be seen that the cavitation mainly happens at the low pressure side of the radial clearance. Another places where the cavitation happens are at the vortex, especially in Figure 6(a) and Figure 6(d). Once the cavitation happens, the gas generates and will take the space of liquid. As to the centrifugal pump, the pump efficiency will fall down. However, in the

scroll pump, the gas will be compressed again and transported with the liquid. So the cavitation influence the characteristic of pump faintly. But the cavitation will lead to the vibration and cavitation erosion, which reduce the reliability of the scroll pump. Therefore, the structure of scroll pump needs to be optimized to prevent the cavitation from generating.

4. Conclusion

In this paper, a two dimensional transient numerical model of a scroll pump is established. The dynamic mesh technology is applied to solve the problem of moving wall of the fluid domain. The pressure distribution, streamline, velocity vector and gas phase volume cloud at different crank angle are figured out by the model. And, some useful conclusion can be drawn as follows.

- (1) The fluid in the working chamber is squeezed after the suction volume reaches maximum, and its pressure rises quickly and becomes larger than the outlet pressure.
- (2) At the radial clearance, the jet flow caused by large pressure difference generates and leads to the negative pressure distribution at the downstream of the clearance.
- (3) The asymmetric structure of suction entrance leads to the pressure distribution difference between the two suction chambers, which will lead to the unbalanced force on the orbiting scroll.
- (4) At the downstream of the radial clearance, the high speed jet flow encounters with the suction flow and exchange their momentum, the vortex generates and the static pressure decreases.
- (5) In the space between the orbiting scroll and the shell, the moving orbiting scroll drives the fluid and the vortex changes with the crank angle, which is also the reason of the imbalance of the pressure between the two suction chambers.
- (6) The cavitation generates at the negative pressure region and the vapor volume fraction reaches 0.9; the cavitation will not influence the characteristic of the pump, but the cavitation erosion and the vibration will reduce the reliability of the pump.

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