

The mechanism performance of improved oil pump with micro-structured vanes

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Abstract: The wear of oil pump vanes easily leads to the noise and vibration, even results the decrease of volume efficiency and total efficiency. In order to reduce the friction and improve the lubrication between the vane and the pump inner wall, the micro-machining of micro-structure on the oil pump vanes is proposed. First, the micro-V-grooves with the depth ranging from 500 μm to 50 μm were micro-grinding on the top of the vanes by a diamond grinding wheel. Secondly, the experiments were conducted to test the actual flow rate, the output power and the overall efficiency of the oil pump with and without the micro-groove vanes. Then, the computational fluid dynamics (CFD) method was adopted to simulate the pump internal flow field. Finally, the micro-flow field between the internal wall of the oil pump and the top of micro-grooved vanes was analyzed. The results shows that the pump overall efficiency increased as the decrease of micro-groove depth from 500 μm to 50 μm and not be affected by the rotate speed and working frequency of the pump rotator. Especially the micro-groove with depth of 50 μm , the actual flow rate, the output power and the overall efficiency reached to the maximum. From CFD simulation, the velocity of the micro-flow between the surfaces of the vane and inner wall was larger than the pump linear velocity when the microstructure depth is larger than 50 μm , leading to an internal leakage. When the micro-groove depth is between 10-50 μm , the velocity of the micro-flow was less than the pump linear velocity and no internal leakage was found, but the oil film thickness is too small to be beneficial to lubrication according to the fluid dynamic characteristics. Thus, for the oil pump equipping with micro- grooved vane with the depth of 50 μm , the internal leakage not only is avoided but the lubrication efficiency is improved and the oil pump efficiency is also enhanced.

1. Introduction

Vane pump is a kind of volumetric pumps which widely used in machine tools and in hydraulic systems, such as transport gasoline, diesel oil, lubricating oil and other low viscosity of light fuel oil, because of the simple compact structure and the strong self-priming capacity. Vane pump consists mainly of a stator and an eccentric rotor, vanes, end covers and other parts. When the pump rotates, the sliding vanes move in the rotor slots and ride against the inner wall of the stator by centrifugal force [1], these vanes, in conjunction with the inner wall of the stator, provide sealed chambers. The fluid enters into the pumping chambers from the suction port and is expelled from the discharge port effectively. However, in some high pressure variable displacement vane pumps[2], evidence of wear



tracks was found on the inner surface of the stator, as a consequence of the sliding contact between the stator and vanes, and the pump internal leakage frequently occurs because of the pressure difference among the pumping chambers. In order to overcome the above problems, a lot of works focused on the overall performance of the pump by numerical simulation. Yong Lu, s research [3] demonstrated that the improvement of volumetric efficiency of the pump was the key to increase the prototype pump performance. Shao Fei used the computational fluid dynamics(CFD) numerical calculation method to analyze the flow characteristic in single—acting vane pump [4]. Wang Xing-kun also used the CFD studied the instantaneous flow and monitoring pressure of the double-acting vane pump [5]. Xue liang optimize the pump structure in view of the flow loss by finite element simulation method [6].

Many studies have demonstrated that the structure characteristics of vane pump and the contact between the stator and vanes are very essential to the pump whole performance, especially the micro-structure on the vane have a great influence on the pump working performance. In order to reduce wear, it is meaningful to use the surface engineering technology to process microstructure on top of the vanes and then to increase the volumetric efficiency and decrease maintenance costs of the pump. Now surface microstructure manufacture mainly depends on the UV (ultraviolet) embossed [7], laser [8], ion beams light [9], chemical etching processing technology [10] and micro mechanical processing technology [11]. Diamond micro-grinding method is an effective micro mechanical processing method for hard brittle materials [12]. The use of diamond grinding wheel V-tip has successfully applied to micro-manufacture micro-groove array on single crystal silicon, quartz glass, hard alloy steel [13-14].

In this paper, various depths of micro V-groove array were micro-ground on the top of the graphite vane to study the fluid dynamic characteristics and mechanism performance of improved oil pump. First, the micro-grooves with the depth ranging from 500 μm to 50 μm were micro-grinding on the top of the vanes by a diamond grinding wheel. Secondly, the experiments were conducted to test the actual flow rate, the output power and the overall efficiency of the oil pump with and without the micro-groove vanes. Then, the CFD numerical calculation method was applied to study the internal flow field of the micro-structured pump. Finally, the influence of the different dimensions of micro-groove arrays on the lubrication and the mechanical efficiency during pump working process were analyzed.

2. Fabrication of micro-V-grooved vanes

Before micro-ground the micro V-groove array on top of the graphite vane, the micro-V-tip of diamond grinding wheel should be finishing. Figure 1 shows the finishing process of diamond grinding wheel micro-V-tip, the fabrication of V-tip diamond grinding wheel can refer to our precious study reference [14]. Where, a is the diamond tool feed depth, v_f is the feed speed, n is the grinding wheel revolve speed. In this paper, a is of 1~20 μm , v_f of 500 mm/min, n of 2000~3000r/min. The average abrasive particle size of the employed resin-bond diamond grinding wheel is 36~40 μm , the grinding wheel width is of 5 mm, 125mm in diameter. The finished diamond grinding wheel is showed in Figure 1(b).

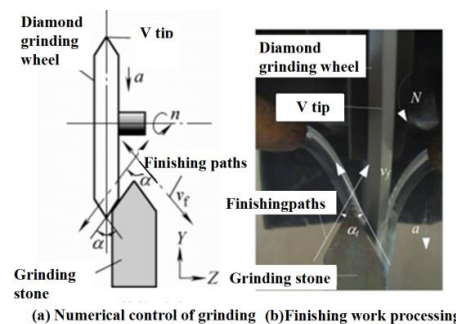


Figure 1. Finishing of diamond grinding wheel micro-V-tip

Figure 2 demonstrates the diamond grinding wheel V tips process on the vane tip surface, walking along the equal interval paths in an alternative positive and negative direction. With several micrometers feed depth each time, the micro-V-groove array can be formed gradually. Five groups of vane samples were prepared with different micro-V-groove depth of 500 μm , 200 μm , 100 μm , 50 μm and 0 μm (no micro-structure). And each group of sample consists of six vanes with the same micro-V-groove structure. The processed graphite vanes samples with micro-V-groove array can be seen in figure 3. The grinding processing conditions are shown in table 1.

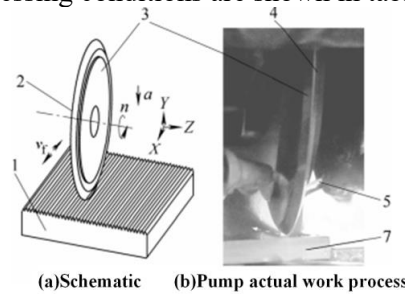


Figure 2. Micro-grinding of micro-V-groove arrays on vane surface

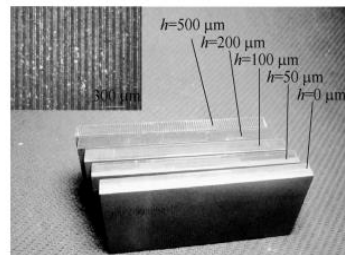


Figure 3. The graphite vanes with micro-V-groove arrays

Table 1. Grinding processing conditions

CNC grinding machine	SMART B818
Diamond grinding wheel	The average abrasive particle size 36 ~ 40 μm , resin-bond, revolving speed $n=2000\sim3000\text{r/min}$
Rough machining	The feed depth $a=5\mu\text{m}$, the feed speed $v_f=500\text{mm/min}$ the total feed depth $\sum a=80\sim140\mu\text{m}$
Finish machining	The feed depth $a=1\mu\text{m}$, the feed speed $v_f=100\text{mm/min}$ the total feed depth $\sum a=10\sim20\mu\text{m}$
Cooling liquid	water

3. Experiments

Figure 4 shows the configuration and schematic diagram of the vane pump used in experiments. It can be seen that the pump is mainly consisted of a shaft, a rotor and six pieces of vanes. The locating ring provides radial force to the vanes to ensure that the vane tip is well in contact with the inner wall of the stator. Thus, each hydraulic chamber is sealed by two adjacent vanes, two end covers between the rotor and the stator. As the rotor rotates in clockwise direction, the chamber volume starts increasing slowly from the inlet and decreasing gradually after passing by the outlet. Thus, a pressure difference is produced and therefore induces oil enter into the pump from the inlet and flow out through the outlet effectively.

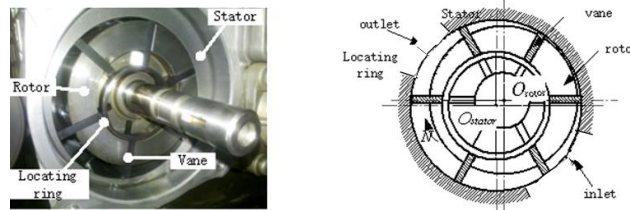


Figure 4. Configuration and schematic diagram of the vane pump

The performance test experiments of the oil pump were carried out after the preparation of micro-V-grooved vanes. In each test, six vanes were installed in the one pump at one time. The actual flow Q_o (L/min), the output power P_o (Watt, W) and the total efficiency ρ at different rotor speed were measured. The actual flow Q_o means that the output flow of the working pump at unit time, the output power P_o is the product of the actual flow and the output pressure, the overall efficiency ρ can be calculated by equation (1) as follows:

$$\rho = \frac{P_o}{P_i} = \frac{\Delta p Q_o}{P_i} \quad (1)$$

Here, Δp is the difference of import and export pressure.

Figure 5 exhibits the actual flow and output power of oil pump changing with the rotor speed and the micro-V-groove depth. It shows that the actual flow increases with the increasing rotor speed. The actual flow for the vanes with larger micro-V-groove depth (200 μm to 500 μm) is lower than that for the traditional vanes (no micro-V-groove array). This may be because the micro-V-groove with larger depth seduces the oil flow through these grooves. So the micro-V-groove turns out to be a tunnel leading to an inner leakage, which causes smaller volume efficiency. However, when the rotor speed is greater than 360 r/min, the actual flow for smaller micro-V-groove depth vane pump (50 μm and 100 μm) are larger than the traditional pump. This may indicate that when the micro-V-grooves decrease to a certain extent, it can both reduce the inner leakage and increase the oil flow. The change of the output power is similar to the change of pump actual flow (see figure 5b). It shows that the vanes with smaller micro-groove depth (50 μm and 100 μm) alternately have higher output power than the traditional vanes as the rotor speed exceeds 360 r/min.

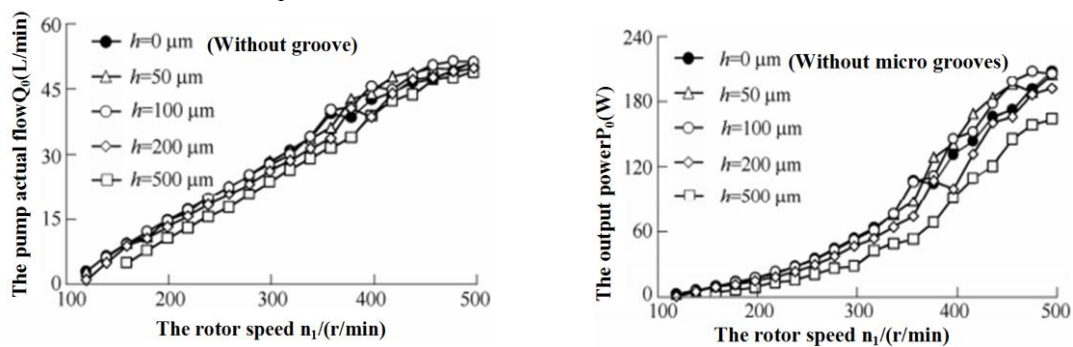


Figure 5. The pump actual flow rate and output power as a function of micro grooves structure depth

Figure 6 shows the change law of the overall efficiency which is the reflection the pump power ratio. The case of micro-V-groove depth 500 μm vanes has the lowest overall efficiency. But as the micro-V-groove depth is above 200 μm , the overall efficiency is higher than the traditional vanes. Apparently, the vanes with the micro-V-groove of 100 μm in depth have the highest overall efficiency. The reason can be explained by its highest actual flow and output power.

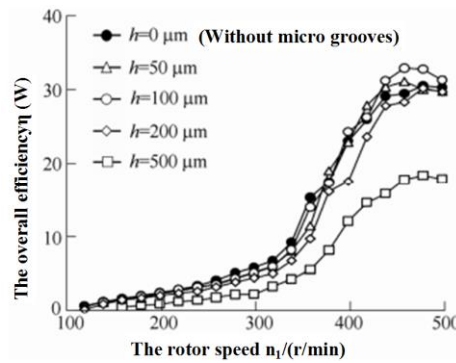


Figure 6. The overall efficiency as a function of micro grooves structure depth

4. Performance simulation of the vane pump

Pumplinx is CFD software that provides unique capabilities for the analysis and design of fluid pumps, motors, compressors, valves and other fluid flow devices and systems with rotating/sliding components. The software offers numerous modules include flow, heat, turbulence, Lagrangian particle tracking, and moving/sliding grid. It is credible to use the software to simulate the flow field and pressure distribution of the pump. And the Fluent CFD software is utilized for numerical simulation of vane pump to analyze the micro-flow field between the inner wall of the stator and the vane tip. The applied software follows the fundamental laws of conservation of mass, heat, and momentum. Therefore, the governing equations [15] include the following equations.

The continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad (2)$$

The energy equation:

$$\frac{\partial}{\partial t} (\rho E_f + \nabla \cdot (\vec{v}(\rho E_f + P_f))) = \nabla \cdot (k_{eff} \nabla T_f) \quad (3)$$

Where, ρ is the fluid density and $\vec{v}$ the velocity field in the whole domain. E_f is the enthalpy of the fluid, T_f the temperature field, and k_{eff} the conductivity coefficient of the fluid.

The momentum equation:

$$\frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla P_f + \nabla \cdot [\mu (\nabla \vec{v} + \nabla \vec{v}^T)] + \rho \vec{g} + \vec{F}_s \quad (4)$$

Where, P_f is the pressure domain, g is the gravity force. F_s is the surface tension force with formula, κ is the curvature and the normal vector to the interface.

4.1 Calculation model

Figure 7 shows the pump interior model of the Pumplinx flow simulation. The computing size is consistent with the real fluid domain size. The stator inner diameter is 98.506mm and the rotor outer wall diameter is 88.938 mm, the eccentric distance is of 4.76 mm. Therefore, the nearest distance between the rotor and the stator, is only 0.024mm, which can be deemed as a fixed calculation size between the vane tip and the stator, as the micro-V-groove depth is various. The simulation rotating speed is set as 45 rad/s in clockwise direction, because the pump actual flow and output power are different at different speed. And the suction port is located at the lower left where the detected pressure is about 0.2MPa. The pressure of discharge port is 0.02MPa. Figure 7(b) is the enlarged diagram of the interface between the vane tip and the stator. The micro-V-groove depth changes from the 0 to 500 μm . Figure 7(c) is the model for FLUENT simulation. Boundary conditions are defined as follows: The upper surface(stator) is considered as stationary wall, the lower jagged vane surface is regarded as moving wall, rotational speed is 45 rad/s, the pressure value are set according to the Pumplinx simulation result.

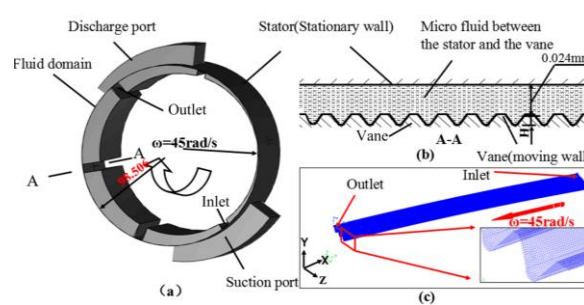


Figure 7. Pump interior model of the Pumplinx flow simulation

4.2 Pumplinx Simulation

The pressure distribution of vane pump versus time is shown in Figure 8. The pump is symmetrical along the axis B-B, the exhibition of pressure distribution can be displayed for half circle. The pump chamber was partitioned into 10 chamber units, in order to iterative computation. The pump operation period is settled as 0.139535s per a circle, which means ten times in calculation per a circle. Each chamber pressure periodically changes with the pump rotation period. The suction port pressure is always lower than the discharge port, as the fluid flow from the suction port to discharge port. Each chamber volume increase firstly then decrease. The pressure of the micro fluid between the vane tip and the inner wall of stator can be roughly divided into the following three cases: Case I, the inlet pressure of the micro fluid is about 0.2 MPa greater than the outlet; Case II, the inlet pressure is about 0.2MPa less than the outlet, as the outlet chamber fluid is incorporated into the discharge port. Case III, the inlet equal to the outlet, it includes that they all are approximately equal to the discharge port 0.24 MPa, or equal to the suction port pressure 0.024MPa, there are four vanes basically belong to this situation in pump operation .

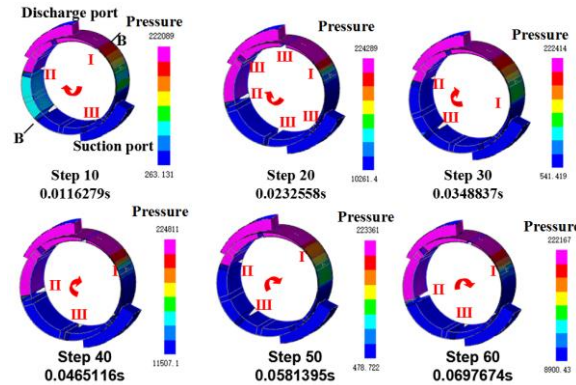


Figure 8. Pressure distribution of vane pump versus time

Table 2. The simulation initial parameters

Medium	Rotate speed	Density	Dynamic viscosity	Suction pressure	Discharge pressure
Gas oil	45rad/s	725kg/m ³	0.0007kg•(m•s) ⁻¹	0.24MPa	0.024MPa

Figure 9 shows the pressure change of six specific monitoring points, the points showed in Figure 9(a). Point 1 monitors the pressure of discharge port while Point 4 monitors the pressure of the suction port. The simulation result in accord with the experiment detected data. It can be known that the initial pressure of the point 2 is about 0.2MPa here, point 6 is approximate to 0MPa. But after rotated half a cycle, the pressure situation was exchanged. This is because that the chambers are connected to the discharge port between the two places marked by point 3 and point 5, the pressure is affected heavily by the discharge port, but once exceed the position, the pressure is then closely to the suction port (see figure 9(a)). What's more, the pressure for the two micro fluid regions marked by point 3 and point 5 also changed as one falls another rises (see figure 9(c)). The period for micro fluid under low pressure

is longer than the period under high pressure. Thus, when one region pressure is reduced, another region pressure will not be improved rapidly.

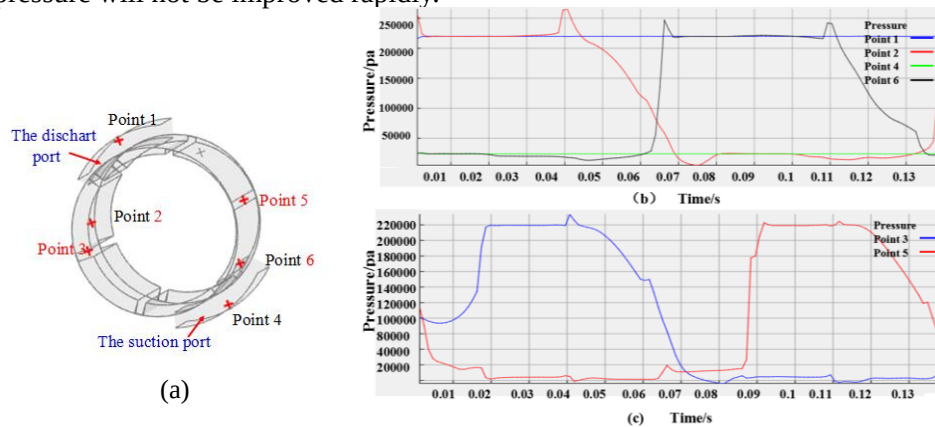


Figure 9. The monitoring points pressure change

4.3 FLUENT simulation

According to the Pumplinx simulation results, the pressure of the micro-fluid between the vane tip and the stator can be divided into three cases according to the difference pressure of the inlet and the outlet. This part used FLUENT software to simulate and discuss the fluid dynamic characteristics for No.I, No.II, No. III micro-fluid.

4.3.1 Case I: Inlet pressure 0.2MPa and outlet pressure 0 MPa. The micro fluid average velocity, the volumetric flow rate, and the total leak amount for 0-500 μm depth of the micro-V-grooved vanes are showed in figure 10. The average speed of inlet and outlet are equal in any case due to the fluid momentum conservation, the average speed is of 1.206 m/s for the traditional vanes, but only 0.803m/s for micro-V-groove depth of 10 μm . Increase the micro-V-groove depth, the average velocity also increases, the average speed are 1.60 m/s, 2.96 m/s for 50 μm and 100 μm , respectively. Increase the depth further up to 500 μm , the average velocity reaches to 10.641 m/s. Because the average speed determines the volumetric flow rate, the volumetric flow rate accordingly changes with the average speed, which can be demonstrated by figure 10 (b).

The rotor linear velocity is of 2 m/s based on the rotor speed 45 rad/s and the rotor radius, it is a standard velocity to estimate the liquid leakage of pump. The total leak amounts for various micro-V-groove depth also displayed in figure10 (b), the leakage value above zero means no leakage. This situation is only for micro-V-groove less than 50 μm . When the depth is more than 50 μm , the leakage increases promptly.

The fluid speed has a great influence on the flow resistance value, the average speed of micro-V-grooved vanes with 10 μm depth less than that for traditional vanes. This may be because this size of micro-structures on vanes increases the interface friction. Increasing the micro-V-groove depth to 50 μm not only can reduce the resistance but also can avoid leakage, which can be seen from figure10 (b). As the depth greater than 50 μm , the leakage is serious, especially the depth is 500 μm that the volumetric flow rate and the pump total leakage reduced to the minimum. Thus, the micro-V-groove depth of 50 μm is the optimal size on such condition.

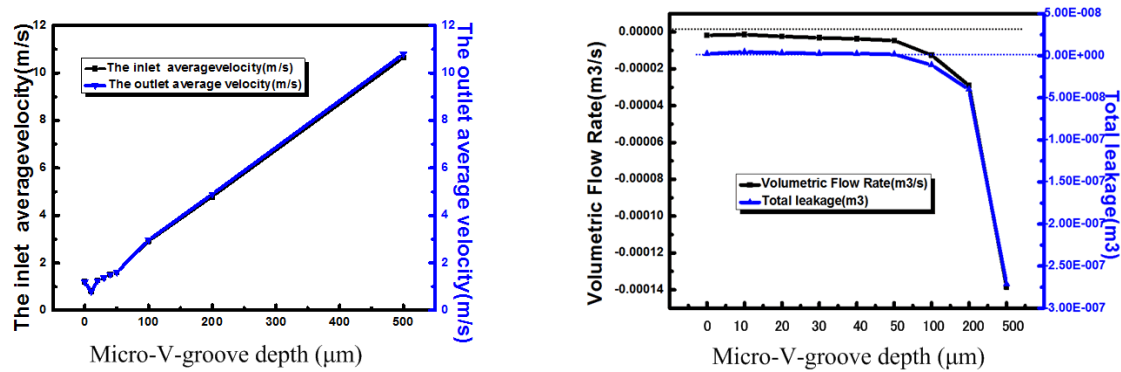


Figure 10. The average velocity, the volumetric flow rate and total leakage versus micro-V-groove depth

Figure 11 shows the micro-flow velocity field distribution. Obviously, the micro-fluid flow is in laminar flow state (see figure 11(a)), the largest velocity of micro-flow is near the vane tip, and the liquid velocity decrease linearly from the vane tip to the stator inner wall. Similarly, for the vane tip with micro-V-grooves, the velocity of the liquid filling in the grooves higher than the vane linear velocity, the fluid against the stator inner wall is the minimum. Figure 11(b) is the micro-flow velocity distribution of depth of 50 μm, the vane tip overall velocity is larger than the traditional one. The micro-fluid velocity decreases gradually from micro-grooves to inner wall of stator. According to the theology of lubrication and Reynolds equation [16], the pressure difference between the interface of vane tip and inner wall caused by the oil film thickness is helpful to bear the part of centrifugal force. So the lubrication effect applied by the oil in micro-V-groove is conducive to friction reduction. Nevertheless, the turbulent flow hanged around in the grooves as for the case of the vane with 500 μm micro-V-groove (see Figure 11(b)) and the velocity in micro-V-groove center is larger than linear velocity of vane.

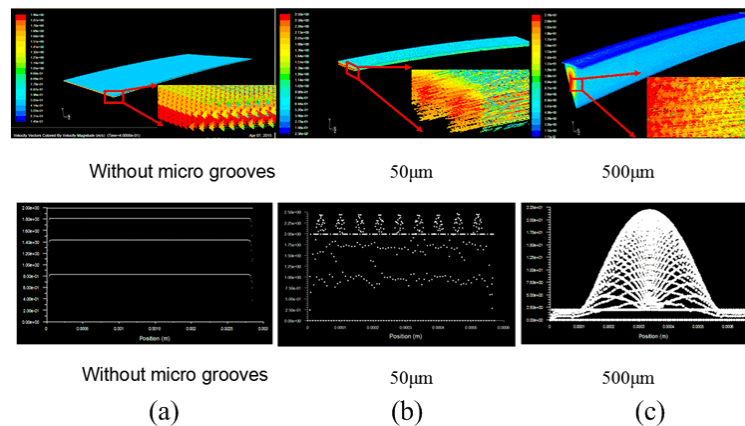


Figure 11. The flow field distribution and the outlet velocity probability distribution

4.3.2 Case II: Inlet pressure 0MPa and outlet pressure 0.2MPa. From figure 12, the average velocity, volume flow rate and mass flow rate are similar to No.1 micro fluid, the average velocity of micro-V-groove depth of 10 μm is still the minimum, the difference is that the average velocity are smaller for all kinds of cases. For instance, the average velocity is only 1.189 m/s for depth of 100 μm, smaller than the No.1 micro-fluid velocity 2.902 m/s, as mentioned above. It can be observed that the flow rate of traditional vanes and for the depth less than 50 μm are negative, which means no inner leakage happened. For the depth greater than 100 μm, the flow rate becomes positive, so the leakage occurred. This result is agreed with the experiment results (see figure 5).

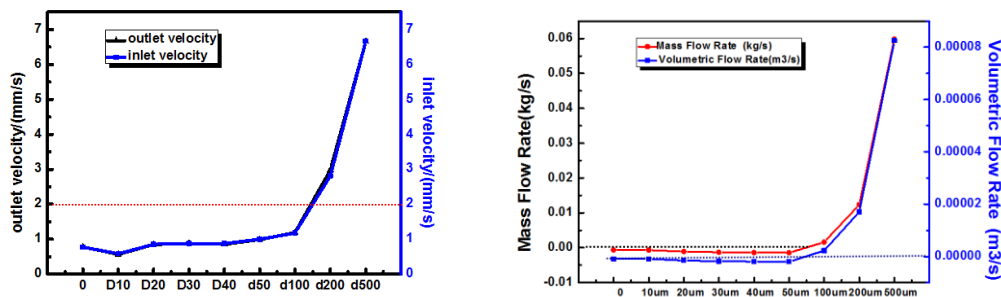


Figure 12. The average velocity and flow rate for the case II

4.3.3 *Case III: Inlet pressure is equal to outlet pressure.* Figure 13 shows the average velocity of the outlet and inlet for Case III. The average velocity of depth of $10\mu\text{m}$ is smaller than the one of traditional. The micro-V-groove depth between $20\mu\text{m}$ and $50\mu\text{m}$, the average velocity increases with the increasing micro-V-groove depth. But, when the depth exceeds $50\mu\text{m}$, the average speed decreases quickly. So the average speed of micro-V-groove with $50\mu\text{m}$ is the largest and the average velocity of depth $500\mu\text{m}$ is the smallest. This is because, the oil in the micro-V-groove is more for larger micro-depth, then the inertia force becomes larger, which may exceed the interface pressure difference. However, the oil inside the micro-V-groove of $50\mu\text{m}$ almost keeps stationary in the process of the rotation (see figure 11).

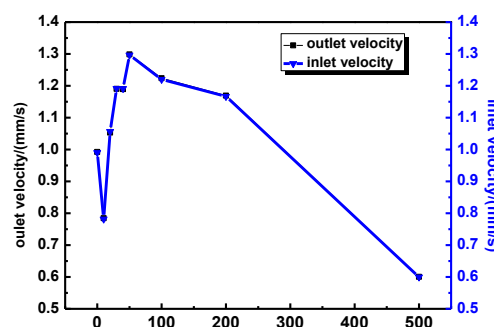


Figure13. The average velocity of the outlet and the inlet for case III

5. Conclusion

(1) Micro-V-groove arrays on the vane tip can improve the lubrication efficiency and mechanical efficiency of the oil pump. The pump overall efficiency increased as the decrease of micro-groove depth from $500\mu\text{m}$ to $50\mu\text{m}$ and not be affected by the rotate speed and working frequency of the pump rotator.

(2) The simulation results of computational fluid dynamics (CFD) method were consistent with the experiment results. The fluid dynamic characteristics and internal flow field of the vane pump were analyzed.

(3) The micro-V-groove depth of $50\mu\text{m}$ is the optimal size. The vane pump with the $50\mu\text{m}$ depth of micro-V-groove array has larger fluid velocity, larger mechanical efficiency and minimum inner leakage compared with traditional vane pump.

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