Flow simulation of the effects of pressure angle to lobe pump rotor meshing characteristics

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Abstract. Lobe pump rotor profiles’ radius of base circle, addendum circle and root circle are closely connected with pressure angle. The change of pressure angle has some effect on lobe pump performance. This paper focuses on two-dimensional profile lobe pump and introduces involute rotor profiles and pressure angle parameter equation. We used geometry and two rotor mesh characteristics to establish lobe pump models of different pressure angles. Monitored the lobe pump’s pressure and velocity of input and output cross section. We used the K-Epsilon turbulence model and the dynamic meshes to compute the two-dimensional turbulence flow field of the lobe pump and obtained the pressure and velocity pulsation picture of different models and speeds. The results show with increasing pressure angle, the velocity of output decreases. The fluctuation of velocity is kept almost constant. When the pressure angle is 45°, the lobe pump has good comprehensive properties. The increasing of rotor speed makes the output flow and the oil absorption pressure increase. But the pressure fluctuation is acute. The lobe pump has vortex and leakage phenomenon in work progress. It will cause energy losses and decrease efficiency.

1. Introduction

Lobe pump belongs to one of noncontact rotor pumps. Lobe pump is efficient and energy saving, steady carrying and can ensure the reliability of continuous operation. Now, lobe pump has widely used in food processing, oil transportation, sewage treatment and agricultural production [1-2].

In recent years, with the energy saving emission reducing conception is advanced, external lobe pump has become the researching focus. Sung-Juen Jung [3] based on the involute–ellipse profiles designed multi-shape profiles with the target of smooth and continuous (ellipse-involute-ellipse). Litvin and Feng [4] have analyzed the lobe pump rotor’s a periodic motion based on meshing theory. Daniel C. H. Yang [5] has revised the involute rotor profiles with deviation function (DF) method. It can obtain high-sealing and high efficiency effect. Shih-His Tong [6] has researched amplitude periodic function based on two rotors meshing characteristics. Zhang Tie-zhu [7] has proposed the design requirements and optimization design method of rotor profiles, which based on cycloid rotor as the goal of small lightweight to establish optimization model and inner-leakage model. While, all the lobe pump designs computed theoretically without experiment and dynamic simulation.
This paper chose two external rotors lobe pump as research subjects and analyzed the parameter equation of involute rotor profiles. Pressure angle is the main design parameter and establish different two-dimensional models with different pressure angles. This paper used the K-Epsilon turbulence model and the dynamic meshes to compute the two-dimensional turbulence flow field of the lobe pump.

2. The Lobe pump rotor profile equation
The core of lobe pump is a pair of conjugate and the same shape of the rotors. The theoretical profiles of rotor not only satisfy the conjugate conditions, but also have good geometrical symmetry, interchangeability. Generally, the rotor profile of lobe pump has two models there are the involute and cycloid respectively. The following introduce rotor of the involute model. The profile of rotor consists of the involute, dedendum arc and addendum arc. Thereinto, \( R \) is the radius of pitch circle; \( r_j \) is the radius of ground circle; \( \alpha \) is angle of pressure; \( r_0 \) is the radius of addendum and dedendum arc.

2.1. The radius of ground circle \( r_j \) and the radius of addendum and dedendum arc \( r_0 \)
As shown in Figure 1, Draw a tangent of basic circle from point \( A \) and intersect at point \( F \), \( \alpha \) is the pressure angle. According to triangle relationship, it obtains following relation.

\[
R \cos \alpha = r_j \tag{1}
\]

\[ r_0 = \frac{1}{4} r_j \tag{2} \]

This type is visible that the radius of addendum and dedendum arc have nothing to do with the pressure angle, it only changes with radius of base circle.

2.2. Involute equation of lobe pump
Take any point \( Z(x, y) \) on the involute. Do the base circle tangent \( ZD \) from the point \( Z \) and cut-off point for \( D \). The angle \( \theta \) will change with the moving of the point \( Z \) on the involute \( BCE \). The coordinate equation of \( Z(x, y) \) is as follows,

\[
x = r_j \cos(\alpha + \theta) + \widehat{DZ} \sin(\alpha + \theta)
\]
\[
y = r_j \sin(\alpha + \theta) - \widehat{DZ} \cos(\alpha + \theta)
\]  \hspace{1cm} (3)

According to the properties of the involute is known,

\[
\widehat{DZ} = \widehat{DF} + \widehat{BD}
\]

Because it has

\[
\overline{AB} = \overline{PE} = \frac{\pi}{4} r_j
\]  \hspace{1cm} (4)

According to Fig. 1 shows the geometric relationship,

\[
\widehat{DZ} = \widehat{DF} + \widehat{BD}
\]  \hspace{1cm} (5)

Substituting Eq. (5) into Eq. (3) and being expressed as,

\[
x = r_j [\cos(\alpha + \theta) + (\tan \alpha - \frac{\pi}{4} + \theta) \sin(\alpha + \theta)]
\]
\[
y = r_j [\sin(\alpha + \theta) - (\tan \alpha - \frac{\pi}{4} + \theta) \cos(\alpha + \theta)]
\]  \hspace{1cm} (6)

2.3. Angle of Pressure \( \alpha \)

To make two meshing rotors do not produce interference, the meshing point of the two meshing rotors should be less than common normal and the base circle tangent point, i.e

\[
\frac{PE}{PN_1} \leq 1
\]

That is to say

\[
\frac{\pi}{4} r_j \leq r_j \tan \alpha
\]

Results show

\[
\alpha \geq 38^\circ 8'46''
\]  \hspace{1cm} (7)

In the actual involute rotor, the pressure angle often chooses from 40° to 50°. The following will be to simulate the different models.

3. Numerical calculation method for lobe pump

3.1. The main parameters of lobe pump

| Model | Pitch radius \( R \) (mm) | Pressure angle \( \alpha \) (degree) | Base radius \( r_j \) (mm) | Radius of addendum and dedendum circle \( r_0 \) (mm) |
|-------|-----------------------------|-----------------------------------|-----------------------------|---------------------------------|
| One   | 40                          | 40                                | 24.69                       | 24.05                           |
| Two   | 40                          | 45                                | 24.30                       | 22.20                           |
| Three | 40                          | 50                                | 25.71                       | 20.18                           |

When the pressure angle becomes different, the involute equation and the radius of base circle will change, causing the rotor profile changes. Here, select different pressure angles corresponding to the rotor models are set up. Based on the above theory, the parameters of the models are shown in Table 1. As the lobe pump’s two rotors and the pump wall are not contacting with each other in practical work, all the clearance of models were set as 0.4mm.
3.2. Dividing lobe pump grid
According to the different parameters set up the two-dimensional models, then import them into the grid division software Gambit. The model of lobe pump is divided into three parts, namely working area of the lobe pump, entrance passageway and outlet passageway. In the Gambit, grid type selects the triangle (Tri). Division method selects the unstructured grid (Pave). Interval size of grid selects 0.1mm in the working area, but it selects 1mm in the area of two passageways. For the inward and outward boundary choose the pressure of import and export. Set the two rotors as WALL, to import the UDF after making the rotors rotate. Due to the different specific models grid results also differ, the following is example model that pressure angle is 45°, it has 757018 cells, 7688043 faces and 43102 nodes.

3.3. Numerical calculation method
In Fluent, import the UDF and make two rotors reverse synchronous rotation. The initial conditions of import and export pressure set up a standard atmospheric pressure, and keep the outlet pressure constant. In the process of calculation, export speed and inlet pressure showed steady periodical fluctuation as calculation convergence.

Make assumptions base on principle of lobe pump: fluid is Newton fluid of constant temperature with incompressibility, and the initial state of fluid is stationary. Based on the above assumptions, the standard K-Epsilon model is used[8].

\[
\rho \frac{d \kappa}{dt} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial \kappa}{\partial x_i} \right] + G_k + G_v + \rho \varepsilon - Y_M
\]

\[
\rho \frac{d \varepsilon}{dt} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_i} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_v) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k}
\]

while \( C_1 = \max \left[ 0.43 \frac{\eta}{\eta + 5} \right], \quad \eta = Sk / \varepsilon . \)

where \( C_2 \) and \( C_{1\varepsilon} \) are constant; \( \sigma_k \) represents turbulent kinetic energy; \( \sigma_\varepsilon \) represents turbulent Prandtl number of turbulent kinetic energy dissipation rate. In Fluent, as the default constant, \( C_{1\varepsilon} = 1.44, \)
\( C_2 = 1.9, \quad \sigma_k = 1.0, \quad \sigma_\varepsilon = 1.2. \) In the calculation, adopt unsteady and implicit solver. To control the solver using PISO that is pressure-velocity coupling form, and use the two order upwind scheme, time step set up 0.0001.

4. Simulation results and analysis
In the beginning of lobe pump simulation, the fluctuation is acute. With the compute going on, the performance of lobe pump is becoming steady. After iterative 1000 steps, all the curves are going steady, as shown in the Fig.2.

As the two rotors are noncontact and the clearance changes with cyclic period in the meshing process. So the output velocity and the input pressure change in cyclic periods. The cyclic period relates to the rotor speed. With reference to Fig.2, the velocity of output shows cyclical fluctuations. With the pressure angle increasing, the average velocity of output decreases obviously. The output flow has directly related to output velocity. The velocity is greater, the flow is greater. When the pressure angle is 40°, the output flow is the maximum. Three models have similar velocity fluctuation. This shows pressure angle isn’t the major factor of influence velocity fluctuation.
Noise is caused by pressure pulsation in lobe pump working progress. As shown in Fig.3, the changing of pressure angle has great effect on oil absorption pressure. When the pressure angle is 40°, the oil absorption pressure is the maximum. When the pressure angle is 50°, the pressure is the minimum. With the oil absorption pressure increasing, the pressure pulsation amplitude is increasing and dramatic shark appears. With reference to Fig.2 and Fig.3, when the pressure angle is 45°, the lobe pump has good comprehensive property. So the pressure angle shouldn’t select too big or too small in design the rotor profiles.

When the lobe pump reaches to steady state, turbulent kinetic energy of different pressure angle modes at t=0.25s is show in Fig.4. Medium in input turbulent kinetic energy is low. Turbulence is concentrated in clearance and output. With the increasing of pressure angle, the maximum turbulent kinetic energy value decreases.

As shown in Fig.5, with the limits of two rotors inverse synchronous motion and boundary condition. Medium has great instantaneous velocity when get into and get out the lobe pump and velocity pulsation appears (as shown in point A and point C). When the medium get into the lobe pump, some parts have vortexes (as shown in point B). It caused by the action of rotors and leaded energy deficiency. When design the lobe pump, it should avoid fraction of the rotors and the lobe pump wall. So leave some clearance between the rotors and the pump wall. As shown in Fig.5, in point E and point B has medium flow. This shows that leakage has appeared in clearance. Vortexes and leakage cause energy deficiency and reduce efficiency.
Following is the different speeds which affect the lobe pump performance. Three different speeds, 300 r/min, 420 r/min and 540 r/min are selected. As shown in Fig.6, with the changing of rotor speed, the output velocity is cyclical fluctuations after the models get steady. When the speed is 540r/min, the output velocity is high and the fluctuation amplitude is great. While the speed is 300r/min, the output velocity is low and the output medium velocity is low too. This shows that output medium has some velocity fluctuation. With the increasing of rotors speed, the average velocity of output increases. The velocity of fluctuation amplitude increasing leads to large output flow and pulsation. While the speed increases to a certain extent, the change of output flow isn’t obvious.

As it shown above, speed change has obvious influence to output velocity. As shown in Fig.7, the different speeds have great affect to oil absorption pressure pulsation. When the speed is 300 r/min, the oil absorption pressure is low and the pressure pulsation is too small. This shows with the increasing of rotor speed, the input oil absorption pressure and the pressure pulsation amplitude is increasing. When the speed increases to a certain extent, the oil absorption pressure doesn’t increase.
5. Conclusions

Used the K-Epsilon turbulence model and the dynamic meshes to compute the two-dimensional turbulence flow field of the lobe pump and analysed different pressure angles and working conditions influence of lobe pump performance. The conclusions as follows:

1) Pressure angle has great influence to velocity. With the increasing of pressure angle, the velocity of output decreases. The oil absorption pressure has little relationship with pressure angle. When the pressure angle is 40°, the oil absorption pressure is the maximum but the pressure pulsation is the maximum too. When the pressure is 45°, the comprehensive property of lobe pump is the maximum.

2) In different working conditions, with the rotor speed increasing, the output velocity and input oil absorption pressure has increased obviously. But the pulsation is much more obvious. When the speed increases to a certain extent, the output velocity and the oil absorption pressure doesn’t increase.

3) Fluid in the vortex area requires amount of energy. This energy comes from the mainstream fluid, which makes the mainstream energy loss. So, this phenomenon can reduce the lobe pump efficiency.

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