Study on effect of surface roughness on resistance based on results from experiments and simulation with CFD and LBM

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Abstract. In this paper, the rotating disk with a diameter of 50mm is selected as a simplified object to study the effect of surface roughness on resistance. The accuracy of different CFD models is studied to reduce the simulation error through rheometer experiment of smooth disk. Then, optimized models are used to calculate the torque of rough disks with different roughness. Compared with results from rheometer experiment, it’s found that smooth disk doesn’t have pressure drag, but rough disk has pressure drag. And the disk surface with roughness of 90μm has the maximum drag reduction rate of 3.26% at speed of 400rpm. There is an uncertain and irregular relationship between drag reduction effect and surface microgroove under different Reynolds number, so, the flow in microgrooves on rough surfaces is simulated for further analysis by LBM. Compared with channel without microgroove, channel with microgroove reduces the velocity gradient on bottom wall and there is vortex in each microgroove. The velocity gradient on bottom wall attains a minimum when the height of microgroove is 90μm, which has the minimum viscous friction, however, the pressure difference between inlet and outlet of channel with microgroove height of 90μm doesn’t reach a minimum. Therefore, when applied to macroscopic objects, the microgrooves, which can reduce the viscous friction, probably increase the total resistance due to the pressure drag.

1. Introduction

The fluid machinery is widely used in the marine, energy, water conservancy and other industries, such as propellers, pumps and turbines. These fluid machines rotate in the fluid to meet certain operational needs. However, the surface roughness varies during fluid mechanical process and will change in the using term, which will certainly affect the resistance and flow field. In order to predict the resistance and flow field, CFD simulation is applied mostly. However, the flow of rotating machinery is rotational, transient, pulsating and non-linear, the exact nature of laminar-turbulent transition and turbulence in the rotating-disk flow is still major problem [1,2], which makes it difficult to obtain accurate simulation results, therefore, the selection of computational model is very important for the accuracy of simulation. Because the disk is the representative basic component of these machines, for example, chemical vapour deposition (CVD) reactors often used in the semiconductor industry are one of the applications of the rotating-disk flow [3]. Moreover, the torque rheometer can
easily and accurately measure torque value of the disk, so we choose the rotating disk as a simplified study object of this paper.

At present, CFD software FLUENT provides many computational models, including laminar model, k-ε model, k-ω model, k-kl-ω model, Transition SST model, RSM and DES model. In this paper, these models are used to simulate the flow field of a smooth rotating disk with a diameter of 50mm at different rotating speeds on the free surface of a cylindrical flume, and the torque of the rotating disk is calculated respectively. What’s more, we make aluminum alloy disks for rheometer experiments, and the torque rheometer uses air bearings, which can measure more precise torque values. By comparing the experimental data with the simulation results, we can analyze the accuracy of simulation of those computational models. The rotating disks used in the above simulation and experiment are smooth, but the study on rough surfaces with microgroove is interesting and popular, which is closely related to the study on drag reduction.

Shintaro Imayama, et al. compare the laminar–turbulent transition processes with and without artificial surface roughnesses by experimental study [4]. However, in this paper, we choose the best computational model to simulate the torque of the disk with different surface roughness parameters when rotating in water at different rotating speeds. Moreover, the structure of the rough surface is considered as uniformly distributed and similar to rectangular microgrooves, which is different from that of Shintaro Imayama et al. Then, because LBM has advantages in simulating micro-scale flow, the accuracy of calculation is satisfied and the computing resources are saved at the same time, so, D2Q9 model in LBM is introduced to simulate the flow of microgrooves on rough surface in this paper, and the flow field in microgrooves on rough surfaces is further analysed, so as to provide some suggestions for surface processing in the field of fluid machinery and reduce the adverse effects of surface roughness on resistance.

2. Theoretical basis of CFD and LBM

This paper is not an attempt to make a contrastive study on the traditional CFD method and lattice Boltzmann method, they are mainly used to simulate and analyse the problems on roughness and resistance. Therefore, their theoretical basis is simply introduced.

In a cylindrical coordinate system, the continuity equation and the NSE can be decomposed radial, azimuthal and axial components. The position vector is given as \( r = (r^* \cos \theta, r^* \sin \theta, z^*) \). The instantaneous velocity vector is represented by \( \mathbf{v} = (\hat{u}^*, \hat{v}^*, \hat{w}^*) \). The position vector is given as \( r = (r^* \cos \theta, r^* \sin \theta, z^*) \). The instantaneous velocity vector is represented by \( \mathbf{v} = (\hat{u}^*, \hat{v}^*, \hat{w}^*) \). The rotation vector is given by \( \mathbf{\omega} = (0,0, \Omega^*) \). The continuity equation and Navier-Stokes equation in a uniformly rotating co-ordinate system are written as

\[
\nabla \cdot \mathbf{v} = 0
\]

\[
\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} + 2 \mathbf{\omega} \times \mathbf{v} + \mathbf{\omega} \times (\mathbf{\omega} \times \mathbf{r}) = -\frac{1}{\rho} \nabla p^* + \nu^* \nabla^2 \mathbf{v}
\]
that of Reynolds time-averaged method. Therefore, this model needs extensive computer resources, but it has advantages in solving transient and separable flows, especially when the flow of fluid machinery deviates from the design conditions [7].

However, the LBM is a different approach to fluid simulation than standard Navier-Stokes solvers: while the latter start with a set of fluid conservation equations and discretize them, the LBM discretizes another equation, which means that it is less obvious that it works as a method for simulating fluids [8]. By discretizing the force-free form of the Boltzmann equation in velocity space, physical space, and time, the lattice Boltzmann equation was found:

\[ f_i(x + c_i \delta_x, t + \delta_t) - f_i(x, t) = \Omega_i(x, t) \]  

(3)

This expresses that particles \( f_i(x, t) \) move with velocity \( c_i \) to a neighboring point \( x + c_i \delta_i \) at the next time step \( t + \delta_t \). At the same time, particles are affected by a collision operator \( \Omega_i \), the simplest one that can be used for Navier-Stokes simulations is the Bhatnagar-Gross-Krook (BGK) operator:

\[ \Omega_i(x, t) = -\frac{1}{\tau} [f_i(x, t) - \langle f_i^{eq} \rangle (x, t)] \]  

(4)

By learning the theoretical basis of LBM, the simple two-dimensional microgroove flow codes are written, then, the programming steps are executed, and the results are obtained.

3. Simulation

In this paper, CFD is used to simulate the flow of smooth rotating disk in water from macro scale, after studying the accuracy of CFD models by comparing with experimental data, then the wall roughness correction function is introduced to simulate the flow of rotating disk with different surface roughness in water. Finally, LBM is used to simulate the flow of microgrooves on the surface of rough rotating disk from micro scale.

3.1. Simulation with CFD

The mesh model is divided into the stationary region and the rotating region. The rotating region is a cylinder with a diameter of 50 mm and a height of 1 mm and refers to the volume surrounded by the red area in figure 1.a, whose upper surface acts as a rotating disk and rotates with the rotating region. As shown in Figure 1.b, the stationary region is the volume that removes the rotating region from the cylinder with a diameter of 70 mm and a height of 3 mm, the solid wall boundary without slip is adopted on the bottom and side face. And the two regions are meshed separately and the data of the two regions are processed by using the interface. Furthermore, it’s verified that the grid density is reasonable, the simulation results are almost unchanged with the increase of the grid density.
The Reynolds number \( (Re = \frac{\omega r^2}{v}) \) is in the range of 392.7-3927 at speeds of 60-600rpm. For rotating disks, the critical Reynolds number of the transition from laminar flow to turbulent has not yet been determined. So the laminar model is also used to simulate besides the turbulence model. It's worth mentioning that solution results of Transition SST model serve as the initial condition in DES model calculation. Torque values of rotating disks are obtained by different CFD models. The comparison with experimental data measured by torque rheometer is shown in Table 1 below.

| Model       | Speed/rpm | 60  | 100  | 200  | 400  | 500  | 600  |
|-------------|-----------|-----|------|------|------|------|------|
| realizable k-\( \varepsilon \) |           | 5.57719E-06 | 1.33764E-05 | 4.33703E-05 | 1.34687E-04 | 1.90390E-04 | 2.50819E-04 |
| k-\( \omega \) |           | 5.28782E-06 | 1.1914E-05 | 3.3170E-05 | 9.61372E-05 | 1.35208E-04 | 1.78577E-04 |
| laminar     |           | 5.28567E-06 | 1.17159E-05 | 3.36350E-05 | 9.55158E-05 | 1.33611E-04 | 1.75923E-04 |
| RSM         |           | 5.46026E-06 | 1.26010E-05 | 3.94654E-05 | 1.24763E-04 | 1.78491E-04 | 2.37239E-04 |
| SST k-\( \omega \) |       | 5.28748E-06 | 1.17159E-05 | 3.36564E-05 | 9.61833E-05 | 1.34818E-04 | 1.78125E-04 |
| Transition SST |         | 5.28742E-06 | 1.17159E-05 | 3.36664E-05 | 9.61719E-05 | 1.34818E-04 | 1.77819E-04 |
| DES         |           | 5.25785E-06 | 1.16130E-05 | 3.31170E-05 | 9.33524E-05 | 1.31285E-04 | 1.73829E-04 |
| experiment  |           | 5.58311E-06 | 1.13969E-05 | 3.07886E-05 | 8.86349E-05 | 1.24241E-04 | 1.63925E-04 |

Compared with the experiment, realizable k-\( \varepsilon \) model has the minimum relative error of only 0.106% at a speed of 60rpm, but the relative error achieves maximum at other speeds, with the maximum error reaching 53.242%. However, DES model has the maximum relative error of only 5.826% at a speed of 60rpm, but the relative error achieves minimum at other speeds, with the minimum error reaching 1.896%. Table 1 shows that the torque values calculated by SST k-\( \omega \) and Transition SST models are almost the same, and the accuracy of RSM is not ideal, which is related to the introduction of more equations and assumptions into RSM. It is worth noting that the relative error of laminar model is less than 10% at rotational speeds of 60-600rpm. Therefore, it is not accurate enough to judge the flow state only by Reynolds number.

In CFD software FLUENT, when the roughness constant is in the range of 0.5-1, it shows that the surface has grooved structure, and the roughness height represents the common roughness. In fact,
FLUENT simulates the flow field near the surface with different roughness by introducing a wall roughness correction function.

After finding out the models, by which simulation results are most consistent with the experimental values at various rotating speeds, the flow of rotating disks with different surface roughness is simulated by realizable k-ε model and DES with setting up roughness parameters. The torque values of the rotating disks are obtained, as shown in Table 2.

At speed of 60rpm, the torque value of the rotating disk increases with the increase of roughness. At speeds of 100rpm and 200rpm, the torque value of rotating disks decreases with the increase of roughness. However, at speeds of 400rpm, 500rpm and 600rpm, the torque value of rotating disk decreases firstly and then increases with the increase of roughness.

| Roughness /μm | 60 rpm | 100 rpm | 200 rpm | 400 rpm | 500 rpm | 600 rpm |
|---------------|--------|---------|---------|---------|---------|---------|
| 10            | 5.6432E-06 | 1.15966E-05 | 3.30791E-05 | 9.29571E-05 | 1.30452E-04 | 1.72566E-04 |
| 20            | 5.70E-06   | 1.15734E-05 | 3.29606E-05 | 9.22986E-05 | 1.29289E-04 | 1.70786E-04 |
| 30            | 5.74888E-06 | 1.15428E-05 | 3.28158E-05 | 9.14639E-05 | 1.27868E-04 | 1.68705E-04 |
| 40            | 5.78906E-06 | 1.15057E-05 | 3.26075E-05 | 9.04897E-05 | 1.26290E-04 | 1.67218E-04 |
| 50            | 5.82142E-06 | 1.14626E-05 | 3.23847E-05 | 8.94284E-05 | 1.24721E-04 | 1.65370E-04 |
| 60            | 5.84684E-06 | 1.14139E-05 | 3.21377E-05 | 8.83145E-05 | 1.23812E-04 | 1.71212E-04 |
| 70            | 5.86482E-06 | 1.13608E-05 | 3.18722E-05 | 8.71893E-05 | 1.24430E-04 | 1.73586E-04 |
| 80            | 5.87701E-06 | 1.13032E-05 | 3.15903E-05 | 8.61917E-05 | 1.25877E-04 | 1.74990E-04 |
| 90            | 5.88354E-06 | 1.12383E-05 | 3.12967E-05 | 8.57467E-05 | 1.27204E-04 | 1.75768E-04 |
| 100           | 5.88497E-06 | 1.11724E-05 | 3.09927E-05 | 8.59661E-05 | 1.28141E-04 | 1.76201E-04 |
| 0(smooth)     | 5.58311E-06 | 1.13969E-05 | 3.07886E-05 | 8.86349E-05 | 1.24241E-04 | 1.63925E-04 |

**Table 2.** Torques of rotating disks with different roughness.

![Figure 2](image.png)

**Figure 2.** Curve about torque, roughness and speed.

Figure 2 is drawn from the datas in Table 2, compared with the torques of smooth disks measured by rheometer experiment, it’s found that there is no drag reduction effect of the disk surface with
different roughness at speeds of 60 rpm, 200 rpm and 600 rpm. The disk surface with roughness of 70, 80, 90 and 100μm reduces drag at speed of 100 rpm, the disk surface with roughness of 60, 70, 80, 90 and 100μm at speed of 400 rpm produce the drag reduction effect, and the disk surface with roughness of only 60μm at speed of 500 rpm produces drag reduction effect. In short, the effect of drag reduction isn’t ideal. At 400 rpm speed, the disk surface with roughness of 90μm has the maximum drag reduction rate of 3.26%.

According to the simulation results, the torque of smooth disk doesn’t contain component of pressure drag, but the torque of rough disk contains component of pressure drag. That is to say, microgrooves on rough surface can reduce the velocity gradient on the wall, thus reducing the viscous friction, however, it will produce pressure drag and may increase total drag, which is difficult to predict. The rotation effect in rotating turbulence changes the near-wall turbulent pulsation curl and enhances the turbulent intensity around the circumference. Moreover, for fluid machinery, due to the strong rotation, large curvature and multi wall, which combine to affect rotating turbulence, the anisotropy of rotating turbulence is more prominent, and it is more vulnerable to tiny disturbance and flow separation is more likely to occur, which demonstrates that there is an uncertain and irregular relationship between drag reduction effect and surface microstructures under different Reynolds number. So, in the next section, we simulate the flow of microgrooves on rough surface for further analysis.

3.2. Simulation with LBM
In order to simulate the flow in microgrooves on rough surface, C++ programs are written by D2Q9 model of lattice Boltzmann method. The length and width of the channel are 30 mm and 3 mm, respectively, and the flow is driven by pressure at the entrance, so that the maximum velocity at the cross section is 0.2 m/s at low Re, and the Kn number is less than 0.01 by adjusting the relaxation time. The standard bounce-back method is applied in the upper wall and the bottom wall without slip.

It should be noted that the simulation results of pressure driven flow of tunnel without microgrooves agree well with the theoretical analytical solutions, and the results with D2Q9 model of velocity profile in near the wall has slight errors.

The width and spacing of the microgrooves are the same. The groove spacing is 60μm and the width is 30μm. The effects of different height of the microgrooves on flow field are compared. Contours of velocity magnitude of microgrooves with different height are shown in Table 3.

When heights of the microgroove are 10μm, 30μm and 90μm, shape of the boundary line with velocity of 0 is similar to a parabola with only one trough. However, when heights of the microgroove are 50μm and 70μm, the boundary line with velocity of 0 is similar to a wave line, with a peak and a trough. There is only one clockwise vortex in a microgroove with different heights, and the shape and area of the vortices are somewhat different.

Compared with channel without microgroove, channel with microgroove reduces the velocity gradient on bottom wall. The velocity gradient on bottom wall attains a minimum when the height of microgroove is 90μm, which has the minimum viscous friction, however, the pressure difference between inlet and outlet of channel with microgroove height of 90μm doesn’t reach a minimum. Therefore, the microgrooves, which can reduce the viscous friction, probably increase the total resistance when applied to macroscopic objects, due to the pressure drag.
Table 3. Contours of velocity magnitude with different microgroove height.

| Height/um | Contours of velocity magnitude | U/(m/s) |
|-----------|--------------------------------|---------|
| 10        | ![Contour 10]                  | ![U scale] |
| 30        | ![Contour 30]                  | ![U scale] |
| 50        | ![Contour 50]                  | ![U scale] |
| 70        | ![Contour 70]                  | ![U scale] |
| 90        | ![Contour 90]                  | ![U scale] |

4. Conclusion
In this paper, the rotating disk with a diameter of 50mm is selected as a simplified study object. In order to reduce the simulation error, the accuracy of different CFD models to simulate the torque of smooth disk was analyzed by rheometer experiment. Then, the Realizable k-ε model and DES are used to simulate and calculate the torque of rough disks with different roughness, it’s showed that the torque value of the rotating disk increases with the increase of roughness at speed of 60rpm. At speeds of 100rpm and 200rpm, the torque value of rotating disks decreases with the increase of roughness. However, at speeds of 400rpm, 500rpm and 600rpm, the torque value of rotating disk decreases firstly and then increases with the increase of roughness.
Compared with the torques of smooth disks measured by rheometer experiment, it’s found that there is no drag reduction effect of the disk surface with different roughness at speeds of 60rpm, 200rpm and 600 rpm. The disk surface with roughness of 70, 80, 90 and 100μm reduces drag at speed of 100rpm, the disk surface with roughness of 60, 70, 80, 90 and 100μm at speed of 400rpm produce the drag reduction effect, and the disk surface with roughness of only 60μm at speed of 500rpm produce drag reduction effect. In short, the effect of drag reduction is not ideal. At speed of 400rpm, the disk surface with roughness of 90μm has the maximum drag reduction rate of 3.26%.

According to the simulation results, the torque of smooth disk doesn’t contain component of pressure drag, but the torque of rough disk contains component of pressure drag. That is to say, when the fluid flows on rough surface, microgrooves on rough surface can reduce the velocity gradient on the wall, thus reducing the viscous frictional drag, however, it will produce pressure drag and may increase total drag, which is difficult to predict. There is an uncertain and irregular relationship between drag reduction effect and surface microstructures under different Reynolds number. Therefore, the flow in micro-grooves on rough surfaces is simulated for further analysis by LBM in this paper.

Compared with channel without microgroove, channel with microgroove reduces the velocity gradient on bottom wall. The velocity gradient on bottom wall attains a minimum when the height of microgroove is 90μm, which has the minimum viscous friction, however, the pressure difference between inlet and outlet of channel with microgroove height of 90μm doesn’t reach a minimum. Therefore, when applied to macroscopic objects, the microgrooves probably increase the total resistance due to the pressure drag, which can reduce the viscous friction.

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