A numerical CFD simulation method using static grid based on momentum compensation for screw pumps

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Abstract. Three-dimensional CFD numerical simulation is the most powerful tool for performance analysis of screw machines. This paper compares and analyzes two CFD numerical calculation methods based on moving and static grid, and proposes a static grid calculation method based on momentum compensation, which takes into account the wall velocity and fluid momentum on the rotor surface when the screw rotor rotates. That is, while the static grid is used, the rotation characteristics of the fluid domain between the rotors are considered. Compared with the commonly used static grid method, this method greatly improves the accuracy of the calculation, the calculation error of mass flow rate is reduced from 2.32% to 1.14%. At the same time, it is simple and easy to implement. It is also suitable for modelling screw machines with special-shaped rotors, which are still challenge for moving grids. The accuracy and reliability of the method are verified by comparison with the calculation results of the moving grid and the experiments.

1. Introduction
Due to the complexity of geometry and working process of screw machines, there are higher requirements for the grid when performing 3D CFD numerical simulation. The generation and processing of the grid for the fluid domain has always been a thorny problem. With the development of numerical methods and grid technology, the CFD numerical simulation of screw pumps has evolved from a static grid generated directly from the pump chamber to a structured moving grid generated by dividing the geometric domain by a special algorithm. The moving grid can be updated and changed in real time with the rotation of the screw rotors, which can reflect the real working process of the screw pump. It is also the hotspot and frontier of the numerical simulation of screw machines [1]. Since the emergence of structured moving grid technology that can reflect the dynamic meshing process of screw rotors, it has been widely used in the analysis of screw machines, especially for screw compressors, and
can accurately simulate the fluid dynamics and thermodynamics characteristics during the internal compression process.

Now the most powerful tool for analysing screw pumps is the three-dimensional CFD modelling based on the structured moving grid. However, although the moving grid method is accurate and reliable, it also has some shortcomings. First of all, special algorithms and programs are needed to realize the meshing and dynamic update of the geometry, which is difficult to realize on the current general commercial meshing software. In the calculation process, due to the need to update and iterate a large amount of dynamic grid data, a lot of computing resources are required, and it takes a long time to complete a simulation calculation case, the calculation efficiency is relatively low. Moreover, for some complex screw machines, such as variable pitch and variable cross-section screw pumps and claw-type screw rotors with pointed hooks, the generation of accurate and reliable moving grids is still a huge challenge. In addition, in the three-dimensional CFD numerical simulation of the screw vacuum pump, the calculation based on the moving grid is often difficult to converge due to the low inlet pressure and the rarefied gas. In these cases, the moving grid method cannot show its advantages. In these cases, the static grid method is a practical option. It is easy to operate the calculation and the convergence is easy to achieved. Especially when modelling screw pumps, such as multiphase pumps and vacuum pumps, the static grid method are simple and easy to use. It is very practical for evaluating the performance of screw pumps. Since the static grid is generated by directly dividing the geometric model of the flow channel extracted from the pump chamber, the CFD numerical simulation based on the static grid can obtain the leakage, pressure distribution, rotor torque, rotor axial force and radial force, power consumption, etc. Before the structured dynamic grid technology was developed, a large number of simulation calculation cases were based on static grids. Compared with the thermodynamic chamber mathematical models which neglect kinetic energy and simplify the analysis of the main and leakage flow, the CFD numerical simulation based on static grid can be used to investigate the influence of the geometric characteristics of the pump and rotors on the pump performance, and the pressure analysis and leakage situation of different rotation positions can be obtain. The CFD method is more intuitively. These static grid-based calculation examples have played a good role in the introduction of CFD numerical simulation methods into the analysis and research of positive displacement screw machines, and have also enabled researchers to further improve the understanding of performance characteristics and internal flow of the screw machines.

However, CFD models based on static grids have certain limitations when simulating screw pumps. By using static mesh, approximate pressure gradients and the leakage velocity field can be obtained; but such results do not take into account the velocity field of the main flow and neglect the transient nature of the working process in a screw pump. Some important parameters cannot be obtained, such as the real-time mass flow rate, rotor torque and pressure fluctuation. More so, in the case of a multiphase pump the pressure field will differ significantly from the result obtained on a static mesh and therefore power calculation will be inaccurate. Compared with the moving grid calculation method, the static grid method has larger calculation errors.

Although there are many calculation cases based on static grids and moving grids, there is no comparative analysis of the calculation results and errors of these two methods. This paper performs...
CFD simulation on the same screw pump with static grids and moving grids of the same cell number and cell size. By comparing and analyzing the calculation results of the dynamic and static grids, the difference of these two methods is obtained. At the same time, a static grid simulation method based on momentum compensation is proposed to improve the accuracy and feasibility of static grid CFD simulation in the analysis of screw pumps. The proposed method is aimed to improve the accuracy and feasibility of static grid CFD simulation in the analysis of screw pumps, and provide a reliable method for the analysis of special-shaped screw rotors and the screw pumps under special working conditions.

2. Numerical Methods

Positive displacement screw pumps operate on the basis of changing the size and position of a working domain which consequently causes change in the pressure of the domain which causes transports of the fluid. To calculate performance of such a pump, quantities such as mass, momentum, energy etc. need to be modelled. Conservation of these quantities can be represented by a general transport equation for a control volume.

In order to account for the deformation of the working domain, the conservation equation needs to account for the velocity of the domain boundary. This could be done by replacing the velocity in the convective term with the relative velocity \((\mathbf{v} - \mathbf{v}_b)\), where \(\mathbf{v}_b\) is the velocity vector at the cell face [10]. The grid velocity \(\mathbf{v}_b\) and the grid motion are independent of the fluid motion. However, when the grid velocities are calculated explicitly and used to calculate the convective fluxes, the conservation of mass and other conserved quantities may not necessarily be preserved. To ensure full conservations of these equations, the space conservation law needs to be satisfied. Space conservation can be regarded as mass conservation with zero fluid velocity. The unsteady terms in the governing equations involving integration over a control volume \(\Omega\), which is now changing with time, need to be treated in a way consistent with the space conservation equation with a deforming and/or moving grid [10, 11].

Figure 1 shows the flow charts of CFD modelling based on moving mesh and static mesh. It can be
observed that compared with moving mesh method, one key step is missed —— solve the grid displacement. The CFD modelling flow chart of based on moving mesh includes the momentum calculation of the grid cell and the data transfer. The static mesh method neglects the flow of fluid in the pump chamber driven by the rotation of the rotors [12, 13].

When using static mesh method, a rotation speed was added to the rotor surfaces according the real rotation of rotors. However, when the screw rotors rotate, the rotational speed of the entire fluid domain is ignored, that is, the momentum of the fluid is not considered.

The velocity decomposition of the fluid in the screw pump is shown in Figure 2. Its momentum term is

\[ M_S = \rho v_z \]  

The velocity of the fluid in the axial direction \( v_z \) is related to the rotation speed \( n \) of the rotors and the lead \( S \),

\[ v_z = \frac{n}{60} S \]  

**Figure 2** Velocity of infinitesimal fluid element with the rotating of rotors: (a) axial direction; (b) circumferential direction

When the screw rotor rotates, the infinitesimal fluid element rotates around the axis relative to the screw rotor. Its speed is

\[ v_r = r \omega \]  

Among them, \( r \) is the radial distance between the position of the fluid element and the centre of the rotor, \( \omega \) is the rotation speed of the screw rotor, and the rotation speeds of the male and female screw rotor are respectively

\[ \omega_1 = \frac{2\pi n}{60}, \quad \omega_2 = -\omega_1 \frac{z_1}{z_2} \]  

3. Geometry and Grid Generation

3.1. Geometry of Screw Pump

The rotor profile of the screw pump is involute-cycloid profile. Table 1 shows the geometry parameters of rotors.
Table 1 Geometry parameters of screw rotors used in study

|                | Male Rotor | Pitch Radius (mm) | Root Radius (mm) | Tip Radius (mm) |
|----------------|------------|-------------------|------------------|-----------------|
| Number of Lobes| 2          | 42                | 35               | 70              |
| Female Rotor   | 3          | 63                | 35               | 70              |
| Centre distance|            |                   | 105mm            |                 |
| Thread pitch   |            |                   | 61mm             |                 |
| Radial clearance|           |                   | 0.24mm           |                 |
| Inter-lobe clearance|  |                   | 0.12mm           |                 |

3.2. Grid Generation

In order to compare the numerical calculation results based on moving and static mesh, six different rotation positions are taken to generate the static mesh, while keep the same size and cell number as the moving mesh, as shown in Figure 3. At the same time, this grid generation method can be used to investigate how the rotor position influences the calculation results when using static mesh.

4. Simulation results and discussion

By using the same numerical scheme and parameter settings, it is found that the pressure distribution of the flow field calculated by using the static mesh is very close to the calculation result of the moving mesh, and the pressure gradient of the pump chamber calculated by these two methods are completely consistent. Therefore, it is an accurate and reliable method to use static mesh to calculate the pressure distribution inside the screw pump.

The main difference in the calculation results of these two methods is reflected in the velocity field distribution. Figure 4 shows the velocity distribution on cross section of rotors based on static and moving grid. It can be observed that the rotor section velocity calculated by static grid is lower than the result of moving grid calculation, among them, the maximum velocity calculated by the static grid is 15.390m/s, and the maximum velocity calculated by the moving grid is 23.147m/s. The high-velocity area corresponding to the static grid is mainly distributed on the wall of the rotor, which is caused by the rotation speed of the screw rotor set by the boundary conditions, and the velocity in the area far away
from the rotor wall in the pump chamber is extremely low. However, the high-speed area calculated by moving grid is distributed throughout the pump chamber.

![Figure 4](image_url)

**Figure 4** Velocity distribution on cross section of rotors: (a) based on the static grid and rotating wall; (b) based on moving grid

It can also be observed from Figure 4 that the velocity distribution close to the wall of the casing calculated by two methods are consistent, and due to the main effect of viscosity, the fluid velocity near the wall is close to zero. At a far distance from the wall of the pump casing, the inertial force is much larger than the viscous force and plays a major role. Therefore, there is an obvious velocity gradient along the normal direction of the inner wall of the casing.

Because the rotors in the pump chamber are static when the static grid method is used for calculation, the fluid passage in the pump is fixed, mainly composed of the leakage passage of the screw rotors, including the interlobe clearance, the radial clearance and the blow-hole area. At this time, the fluid velocity direction is mainly along the axial direction of the screw rotors. When using the moving grid method for calculation, in addition to pumping fluid from the inlet to the outlet in the axial direction, there is also a rotation speed relative to the casing wall as the screw rotor rotates. Among them, the flow situation close to the inner wall of the casing can be analyzed by the boundary layer theory, which is not detailed here.

![Figure 5](image_url)

**Figure 5** Velocity distribution on axial cross section: (a) based on the static grid and rotating wall; (b) based on moving grid
It can be seen from Figure 5 that the velocity in axial section of the rotor calculated by the static grid is smaller than the calculation result of the moving grid. Among them, the maximum velocity on the rotor axial section calculated by the static grid is 15.390m/s, while it is 23.678m/s when calculated by the moving grid. It can also be observed from the figure that the velocity gradient in the inlet and outlet ports of the screw pump calculated by the static grid is almost zero, while there are obvious velocity gradients and vortex flow in the inlet and outlet area by the moving grid.

Refer to the JB/T 8091-1998 screw pump test method [14], the experimental setup is shown in Figure 6. A pressure gauge is installed at the outlet of the pump. A flow meter and a throttle valve are installed in the pipeline. The real-time flow rate and outlet pressure can be measured in this hydraulic system [15].

![System performance test bench](image)

**Figure 6.** System performance test bench (a) schematic diagram; (b) test rig

Since the flow channel in static grid calculation is the leakage channel of the screw pump, the flow rate calculated by using the static grid is the leakage volume, and the flow rate of the screw pump can be obtained by subtracting the leakage amount from the theoretical flow rate. The flow rate of the screw...
pump calculated by static grid at different rotation angle positions is shown in Figure 7. From the calculation results, it can be seen that the instantaneous leakage of the screw pump changes with the change of the screw rotation angle, and it also shows periodicity. It can also be observed from Figure 7 that the flow rate of the screw pump calculated by the static grid at different rotation angle is larger than that by the moving grid. According to the comparative analysis of these two velocity fields, this is due to the fact that the momentum of fluid transmission is ignored when using static grid in calculations. The calculated flow rate in pump chamber is low, and the corresponding leakage rate is also low, so the calculated flow rate is high.

Figure 8 flow chart of static grid CFD method based on momentum source compensation

In order to improve the accuracy of calculation, a compensation momentum source term is added in the static grid CFD calculation, shown as Figure 8. The calculation results show that the velocity of the flow field obtained by this method is higher than the static grid calculation result, and the value is close to the result by the moving grid.

Figure 9 Mass flow rate under different rotation angle calculated by three calculation methods
Figure 9 shows the flow rates of the screw pump at different rotation angles calculated by three different methods. It can be seen from the figure that the period and amplitude of the flow fluctuation calculated by the static grid are basically consistent with the calculation results of the moving grid, but the average value is higher than the calculation result of the moving grid. When the momentum compensation source term is added, the calculated leakage is increased and the flow rate is reduced, which is closer to the result of moving grid calculation, and it is also closer to the real flow situation. If assuming the mass flow rate calculated by moving grid as standard, the calculation error is reduced from 2.32% to 1.14% when adding the momentum source in static grid. This result shows that adding momentum compensation source term can improve the accuracy and feasibility of the static grid calculation method.

5. Conclusions
This paper conducted comparative study of the moving and static grid CFD numerical simulation methods. The calculation process and errors of these methods were analyzed. A momentum compensation method based on the static grid calculation was proposed. It can be concluded that,

• The pressure distribution of the flow field in the screw pump calculated by the static grid and the moving grid are consistent, so the method of using the static grid method to solve the pressure distribution of the screw pump is reliable.

• The velocity of the flow field calculated by static grid is smaller than that by using the moving grid. Among them, the velocity gradient of the inlet and outlet ports in the screw pump calculated by static grid is zero, and the velocity of the rotor flow field region far away from the rotor wall is also extremely small. However, there are obvious velocity gradients and vortices in the inlet and outlet ports of the pump when calculated by moving grid.

• The period, frequency and fluctuation trend of the pump flow rate calculated by static grid at different rotation angles are the same as those of the moving grid, but the average value is higher than that of the moving grid. This is due to the ignoring of the fluid momentum during rotation when using static grid calculations. The calculated velocity in the pump chamber is low, and the corresponding calculated leakage is also low, so the calculated flow rate is high.

• By adding the momentum compensation source term on the basis of the static grid method, the calculation error of mass flow rate is reduced from 2.32% to 1.14%, the calculation accuracy and feasibility of the static grid method are greatly improved, and it provides a method reference for the analysis of the difficult-to-handle special-shaped screw rotors.

Acknowledgments: The authors wish to thank Prof. Kovacevic in City University of London for providing the license of SCORG, which is used in this study.

Funding: The authors wish to acknowledge the support of grant No. 2020CFB114 and grant No.2018A07.

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