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CFD Simulation and Experimental studying of a Dry Screw Vacuum Pump

K Ma, B Guo, Y H Zhou, Y B Wang

School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China; Email: monkey8023@stu.xjtu.edu.cn

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Abstract. Dry screw vacuum pumps are widely used in semiconductor, microelectronics and food industries due to their oil-free characteristics in the vacuum chamber during operation. The performance of screw vacuum pumps is usually predicted by one-dimensional numerical simulation or empirical methods. However, the above method cannot obtain the distribution of the fluid flow field inside the vacuum pump. In this paper, a three-dimensional model is established based on the experimental dry screw vacuum pump. The internal flow field of the dry screw vacuum pump was simulated by computational fluid dynamics (CFD) software using structured dynamic grid. The flow characteristics of the fluid inside the vacuum pump were analyzed. The distribution of the pressure field and velocity field inside the compressor is obtained. Comparing the P- θ indicator diagram and the performance parameters of the vacuum pump with the experimental results. It was found that the results of the three-dimensional numerical simulation were more consistent with the trends of the experimental data. On this basis, the flow field characteristics and performance of the vacuum pump are analyzed and the flow field of the vacuum pump are analyzed and the flow field of the vacuum pump can be better understood.

1. Introduction

Vacuum pumps has been widely used in different industrial processes and has become an indispensable part of production and life. With the progress of information technology, the electronic and semiconductor industries have extensive demands for vacuum pumps and higher requirements for the performance of vacuum pumps. Dry screw vacuum pump has the advantages of simple and compact structure, no oil in the working chamber, long life, environmental protection, and lower pressure pulsation. Therefore, we need to understand the working principle of dry screw vacuum pumps to guide the design and manufacture of screw vacuum pumps.

The mathematical model of the screw vacuum pump can predict the working characteristics of the vacuum pump when the structural parameters is changed. So the model is of great significance to the performance research and structural development of the vacuum pump. There are two ways to establish the mathematical model of the screw vacuum pump.

One is the chamber model. By studying the changes of volume, temperature and pressure with the rotor angle, a one-dimensional mathematical model of the working process is established. Kauder et al. [1] established a complete screw mechanical performance simulation software KaSim. The software takes the chamber volume as the research object, systematically considers the thermodynamic behavior of the fluid in the cavity and the leakage in different gaps. Janicki [2] used the chamber model to perform thermodynamic simulation on the screw machinery, and described the effect of working conditions and the gap height on the performance of the machine

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with the influence matrix. Nadler [3] took the chamber model as the research object, used the thermodynamic simulation software KaSim for theoretical research, and introduced adsorption and desorption to calculate the backflow model. Zhao et al. [4] studied the working performance of the variable pitch screw vacuum pump. The results show that the multi-stage gradual screw vacuum pump is more energy-saving, noise-reducing, and the variable pitch screw vacuum pump has better heat dissipation and gas transport performance, etc. But the article did not conduct experimental verification.

The chamber model is simple and the calculation is convenient, but it cannot reflect the change and distribution of the flow field in the chamber. The other method is to use CFD and other computational fluid dynamics software to perform three-dimensional numerical simulation of the screw vacuum pump. The model can calculate the distribution of the flow field and is very useful for calculation and design.

Few scholars have performed numerical simulation on dry screw vacuum, so the numerical simulation of screw vacuum mainly based on the CFD numerical simulation of screw pump and screw compressor. The numerical simulation of screw machinery is mainly the difference between the meshing software and the solving software. The meshing software includes SCORG, TwinMesh, Ansys Meshing, PumpLinx, etc. In addition, many scholars divide the mesh by themselves. The solution software mainly includes Fluent, CFX, Star CCM+, etc.

Kovacevic [5] used an advanced mesh generation method and applied it to the CFD program to simulate the three-dimensional flow of the screw compressor A program was developed to make the rotor get a good mesh boundary adaptation at any angle. After that, Rane and Kovacevic did a more in-depth study on the meshing and solution method of screw machinery. They [6] proposed a new algebraic mesh generation method suitable for twin-screw machinery. They [7] used algebraic transfinite interpolation to generate the deformed mesh of the twin-screw machine to generate the initial mesh. They [8] established a grid distribution program to refine the grid at the leakage triangle of the screw compressor.

Yan et al. [9] divided the grid of the screw rotor basin and applied it to the screw pump. They compared mass flow, shaft power and efficiency at various speeds and exhaust pressures, and verified the accuracy of the simulation through experiments. Lu et al. [10] proposed a grid generation algorithm. The new grid generation method can better align the calculation grid with the main leakage flow, significantly improve the quality, and reduce the numerical deviation caused by the numerical analysis of spiral machinery with larger helix angles. Ding et al. [11] used the VOF method to simulate the transient flow of an oil-injected twin-screw compressor, and evaluated the cooling and sealing effects of oil-injection by comparing the simulation results with and without oil.

Yue et al. [12] used a dynamic grid method to simulate the flow field of a two-stage dry scroll vacuum pump. When the pressure is 10000Pa, the simulation result is consistent with the experimental pumping speed. But when the pressure was reduced, the error is large. Kennedy et al. [13] compared the one-dimensional thermodynamic model with the three-dimensional computational fluid dynamics model of an oil-free twin-screw compressor, and compared the two models with experimental data. Mierka et al. [14] proposed a new calculation strategy applied to twin-screw extruders. Wu et al. [15] established a three-dimensional model of a refrigeration screw compressor, divided the internal flow field with TwinMesh software, and simulated it with CFX software. The simulation results were compared with experimental results, and the maximum error was 2.578%.

This paper establish a three-dimensional numerical model of the flow field of the dry screw vacuum pump, and simulate the working process of the dry screw vacuum pump under different loads by using CFD technology. The flow characteristics of the fluid inside the vacuum pump are analyzed, and the pressure, velocity and temperature distributions are obtained. This paper establish a performance test bench for dry screw vacuum pumps to obtain the performance of the vacuum pump under different working conditions. The simulation results were similar to the experimental

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data, which proves that the model is correct. So the model can be used for reference to the establishment of three-dimensional numerical model of dry vacuum pump.

2. Geometric Model and Meshing Generation

At present, the profile of dry screw vacuum pumps is mainly composed of curves such as points, cycloids, arcs and involutes. The profile of the driving rotor and the driven rotor are the same, but the direction of rotation is opposite. The rotor profile studied in this paper is shown in Figure 1. The composition tooth curve of the profile is smoothly connected, and the first derivative is continuous; the theoretical profile has no closed volume and leakage triangle.



Figure 1. The rotor profile of the dry screw vacuum pump



The profile studied in this paper has a sharp corner due to the existence of point A. When dividing the mesh, the curvature is too high to obtain a mesh that meets the requirements of the calculation conditions. Therefore, the profile needs to be corrected. In order to meet the grid quality required by the calculation, the sharp point is smoothly transitioned with a small arc. And the small arc is smoothly connected with the cycloid and the tooth tip arc, and the first derivative is continuous. The modified profile and partial enlarged view are shown in Figure 2.

This paper study a two-stage variable pitch vacuum pump. Two-stage variable pitch rotors generally have two equal pitch combinations or a combination of gradual pitch and equal pitch. This article selects the combination of two equal pitches. If the exhaust end surface is used as a reference, the pitch of the first section is smaller than that of the second section. The first section of the screw rotor in this paper has a pitch of 88mm and a length of 200mm; the second section of the rotor has an equal pitch of 60mm and a length of 140mm. The axial view of the two-stage screw rotor is shown in Figure 3.

The working process of dry screw vacuum pump is very complicated. In order to facilitate the simulation and reflect the working process of the compressor, this research divides the flow domain model into four parts: suction port, chamber volume, discharge port and discharge end gap. In the calculation process, these four parts connected, and exchanged data information through the interface. The fluid domain of the control volume of the vacuum pump is shown in the Figure 4.



Figure 3. The axial view of the two-stage screw rotor



Figure 4. The fluid domain of the control volume of the vacuum pump

Import the inlet and outlet flow domain model and the exhaust end gap flow domain model of the dry screw vacuum pump into ANSYS-Mesh, and mesh the inlet and outlet flow domain model and the exhaust end gap flow domain respectively. For the inlet and outlet basins, due to its complex shape, the mesh size function of Proximity and Curvature is used. For the meshing of the exhaust end face gap, the sweep method is used to generate it. In order to ensure the accuracy of the calculation, there are five layers of grids along the sweep direction, and the minimum size of the grid is 0.0001mm, which meets the calculation requirements.





Figure 5. The meshing of the cross-section

Figure 6. The flow field grid of the chamber volume

TwinMesh is a meshing tool specially designed for the simulation of internal fluid flow in twinscrew machinery. According to the profile of the compressor rotor, it can generate a high-quality hexahedral structural mesh. The grid of the rotating watershed adopts a structured division method, with 15 radial nodes, 61 Interface nodes, and 136 circumferential nodes. The meshing of the crossseciton is shown in Figure 5.

The axial distribution assigns nodes according to the value of the spiral angle. When assigning axial nodes by the value of the helix angle, the number of axial nodes should be proportional to the value of the torsion angle. After calculation, the height in the MZ direction is 0.3333333mm, the mesh expansion rate in the MZ direction is 1.001; the height in the PZ direction is 0.48899mm, and the mesh expansion rate in the PZ direction is 1.001. The flow field grid of the chamber volume show in Figure 6.

3. Simulation Setup

3.1 Governing Equation

Fluid flow and heat transfer need to follow the laws of conservation of physics, including the law of conservation of mass, the law of conservation of momentum and the law of conservation of energy. Because the flow is in a turbulent state, the system also needs to comply with additional turbulent transport equations.

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + F_i$$
(2)

$$\frac{\partial(\rho T)}{\partial t} + div(\rho uT) = div\left(\frac{k}{c_p}gradT\right) + S_T$$
(3)

3.2 Turbulence Model

The fluid movement of the vacuum pump is complicated. In the numerical simulation calculation, the selection of a reasonable turbulence model has a great influence on the accuracy of the results. For the numerical simulation of rotating machinery, the SST (Shear Stress Transport) model can obtain more accurate results.

The SST model is a low Reynolds number model, which is suitable for industrial applications. The shear pressure transmission (SST) k- ω model combines the far-field k- ε model and the near-wall k- ω model. The model also considers the transmission of turbulent shear stress, which can accurately predict the beginning of the flow and the amount of fluid separation under negative pressure gradient conditions, with higher precision and accuracy.

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left(\Gamma_k \frac{\partial \omega}{\partial x_j} \right) + G_\omega - Y_\omega + D_\omega + S_\omega$$
(4)

$$\frac{\partial}{\partial t}(\rho\omega) + \frac{\partial}{\partial x_i}(\rho\omega u_i) = \frac{\partial}{\partial x_j}\left(\Gamma_\omega \frac{\partial k}{\partial x_j}\right) + G_k - Y_k + S_k \tag{5}$$

3.3 Immersed Solid Method

In order to reduce the influence of profile correction on the calculation results, this article uses the Immersed Solid method in ANSYS CFX for reference. The immersed solid method can simulate the movement of rigid solids in the fluid domain. The momentum source acts on the fluid domain, forcing the fluid and the solid to move together. The movement of fluid outside the submerged entity is like flowing around a rigid entity.

$$S_i = -\alpha\beta C \left(U_i - U_i^F \right) \tag{6}$$

The scale factor α of the momentum source term is used to control the size of the source term, and its value is used to balance the accuracy and robustness of the simulation. By default, its value is set to 10, and its value can be modified according to the convergence. The special forcing function β is used to characterize whether there is an entering solid in the flow field.

3.4 Boundary Condition

The boundary conditions of the intake and exhaust ports of the vacuum pump simulated in this paper are derived from experimental measurements. The air inlet of the vacuum pump is set to open condition, the pressure is set to 0.04bar, and the temperature is 293.15K; the condition of the exhaust port is open condition, the pressure is set to 1.0bar, and the return temperature is 338.15K.

3.5 Independence Verification

This paper takes the inlet pressure of 0.04bar and the rotational speed of $3000 \text{ r} \cdot \text{min}^{-1}$ as an example to verify the grid independence. The different node settings and the number of grids are shown in Table 1. The verification result of grid independence of the working condition with an inlet pressure of 0.04 bar and a speed of 3000 r \cdot \text{min}^{-1} is shown in Figure 7.

Number	Radial Nodes	Circumferential Nodes	Axial Nodes	Number of Meshes/ten thousand
1	15	300	680	424
2	15	333	680	497
3	16	333	680	513
4	16	333	829	665
5	16	333	1020	860



Table 1 and Figure 7 show that with the subdivision of the grid and the increasing number of grids, the solution result will be more accurate. For the last three grids, the volume flow rate and input power vary little with the grid. Considering the time cost of calculation and the accuracy of calculation, this paper finally adopts the fourth set of grids as the calculation grid.

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Figure 7. The results of grid independence verification

For rotating machinery, the time step is often calculated based on the speed. Since the dynamic mesh of the rotation domain in this paper is generated by the commercial rotating machinery meshing software TwinMesh, the number of mesh generation is related to the angular step of rotation. Therefore, in the simulation of this article, the time step is not only related to the rotation speed, but also related to the angle step.

$$\Delta t = \frac{n/360}{N/60} \tag{7}$$

At the same speed, the smaller the angle step, the smaller the corresponding time step. The time step requires trial calculations to obtain a suitable value. This paper tries to calculate the influence of different angle steps on the results under the same speed and the same working conditions. It is found that a time step of 2° can meet the calculation requirements and greatly improve the calculation efficiency. In the end, the time step selected in this paper is about $1.1111 \cdot 10^{-4}$ seconds.

4. Experiment Studying

This paper use a two-stage dry screw vacuum pump as a prototype to build a vacuum pump performance test bench. The system diagram is shown in Figure 8. The whole system is mainly composed of dry screw vacuum pump, muffler, motor, frequency converter and test acquisition system. The test acquisition system is composed of pressure sensor, temperature sensor, torque sensor and NI acquisition system.



Figure 8. Vacuum pump performance test system

This experiment use a ASC510 frequency converter to change the speed of dry screw vacuum pump. The screw vacuum pump connect to the variable frequency motor through a coupling. By adjusting the frequency of the inverter to change the motor frequency, the speed of the vacuum pump can be adjusted.

Under normal circumstances, each pressure sensor can measure the pressure change of one revolution of the rotor. But considering that the sensor will sweep across the top of the screw, the measured pressure will be deviated. Therefore, there will be overlaps in the data between two adjacent pressure sensors to eliminate the above influence.

5. Results

5.1 Model validation

In order to verify the accuracy of the three-dimensional flow field model of the dry screw vacuum pump, this paper compares the experimental and simulated values of the p- θ diagram of the internal working process. As shown in Figure 9, the figure shows a comparison between the simulated value and the experimental value when the rotation speed is 3000° min⁻¹ and the suction pressure is 4kPa. There is an error between the experimental value and the simulated value, but the pressure change trend is consistent.

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The first part is the intake process, and the initial angle is 0° at the beginning of the inhalation process. For screw vacuum pumps, the suction orifice is generally designed to have a larger shape to ensure sufficient suction, and the suction resistance loss is relatively small. And the experimental data of the intake process cannot be obtained in this paper, so the pressure in the intake process of the experiment in this paper is always equal to the intake pressure.

The second part is the isometric process. At this time, the suction orifice has been closed, and due to the impact of the high-pressure chamber leakage, the gas pressure will slowly rise during this process. The third part is the internal compression process. In this process, the volume of the chamber will decrease with the decrease of the pitch. At the same time, considering the impact of the leakage of the high-pressure chamber, the pressure rises faster. The fourth part is the second stage of isometric process. The gas in the chamber will still rise due to the leakage of the high pressure chamber. The fifth part is the second stage of the compression process. The working chamber reaches the exhaust end surface but is not connected to the exhaust orifice. The reduction in the volume of the chamber and the end surface leakage will cause the gas pressure to rise. Similarly, here is the difference between simulation and experiment. There are three main reasons for the error. First, this article modified the original profile, which resulted in a larger fluid area at the sharp point and increased leakage from the high-pressure chamber to the low-pressure chamber. Although this article draws on the solid immersion method, it does not completely eliminate the effects of leakage. Secondly, the gap value selected in this paper is deviated from the gap value during actual operation. Third, due to the large helix angle of the dry vacuum pump rotor, a relatively orthogonal grid cannot be obtained, which leads to errors in numerical calculations. Fourth, there is a water-cooling cavity between the vacuum pump and the front cover. This article did not consider the effect of water cooling in the simulation.

The last part is the exhaust process. At this time, the chamber connect to the exhaust orifice. The over-compression phenomenon can be observed from the figure, and both simulations and experiments have such phenomena.

5.2 Simulation Result

The pressure distribution in the vacuum pump is calculated by CFD software, and the pressure change in the flow field of the vacuum pump is analyzed in detail. Choose the axial section of the vacuum pump to reflect the pressure distribution in the working chamber of the vacuum pump. Because the vacuum pump is used in this simulation, the rotor profile of the driving rotor and the driven rotor are the same, and they are both single-tooth rotors. Therefore, the pressure change cycle is periodically once every 360°. Since the angle step used in this paper is 2° when generating the rotating watershed, every 180 result files is a cycle. At 0° and 360° rotation angles, the pressure distribution in the vacuum pump chamber is the same. With 60° intervals, Figure 10 shows the changes in the internal pressure of the vacuum pump at different angles.

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Figure 10. The pressure distribution in the vacuum pump

The pressure gradually increases along the spiral surface of the rotor from the suction port to the discharge port, and the pressure at the discharge port reaches the maximum. The exhaust port of the dry vacuum pump is only opened on one side, and only on the side of the driven rotor. When the rotor chamber is not connected to the exhaust, the rotor chamber will be over-compressed, and the pressure will be higher than the atmospheric pressure. The highest pressure is on the exhaust end side of the active rotor. When the rotor chamber is connected to the exhaust end side of the active rotor. When the rotor chamber is connected to the exhaust gas, the pressure in the rotor chamber is discharged and the pressure is reduced.

Figure 11 shows the velocity distribution in the rotor basin under different angles. The flow velocity in the rotor chamber is less than $10 \text{m} \cdot \text{s}^{-1}$, and the velocity in the tip leakage channel is higher than the velocity in the chamber. The highest speed in the rotor chamber is located in the clearence where the two rotors mesh. The speed in the meshing clearence is generally higher than $100 \text{m} \cdot \text{s}^{-1}$, in some places as high as $240 \text{m} \cdot \text{s}^{-1}$. The speed is unreasonable in some places in the velocity counter is mainly due to the quality of the grids. The reason for the excessively high flow velocity at the meshing gap is that the gap at this position is too small, and the velocity is affected by the leakage from the high-pressure chamber to the low-pressure chamber and the rotation speed, resulting in a higher velocity than other places.

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Figure 12. The pressure distribution on the rotor surface

Figure 12 shows the pressure distribution on the rotor surface. There is a very distinct color boundary on the pressure counter, and this boundary is the dividing line of different chamber. The suction chamber of the rotor occupies the first two chambers. After going through multiple processes, the gas is finally discharged. The pressure change range of the front part of the rotor is small, and the pressure at the rear end of the rotor changes drastically. This is also the place where the leakage is the most serious.

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6. Conclusions

In this paper establish a three-dimensional numerical model of the dry vacuum pump and numerically simulate the internal flow field of the vacuum pump by the fluid analysis software CFX. Numerical simulation has obtained the pressure and velocity distribution of the flow field inside the vacuum pump. The rotor meshing line divides the rotor flow field into different chambers. Because the meshing clearence between the rotors along the contact line is too small, and with the increase of the pressure difference between the high-pressure chamber and the low-pressure chamber and the influence of the speed, the leakage effect becomes more and more obvious. The leakage velocity at the gap of the vacuum pump is greater than the leakage velocity between the teeth. The clearence is the most important factor affecting the performance of the vacuum pump, and the maximum leakage velocity of the clearence exceeds 240 m/s. Therefore, various leakage clearences of the vacuum pump are reasonably reduced during the design.

References

- [1] Kauder K and Janicki M 2003 Adiabatic modelling and thermodynamic simulation af rotary displacement machines with the program KaSim
- [2] Janicki M. 2007 Modellierung und Simulation von Rotationsverdrängermaschinen Dissertation, Universität Dortmund
- [3] Nadler K. 2017 Modellierung und Analyse von Schraubenvakuumpumpen im Blower-Betrieb. Dissertation, Universität Dortmund
- [4] Zhao F, Zhang S and Sun Kun 2018 Thermodynamic performance of multi-stage gradational lead screw vacuum pump. Applied Surface Science 432 97-109
- [5] Kovacevic A 2010 Boundary adaptation in grid generation for CFD analysis of screw compressors International Journal for Numerical Methods in Engineering 64 401-426
- [6] Rane S and Kovacevic A 2017 Algebraic generation of single domain computational grid for twin screw machines Advances in Engineering Software 107 38-50.
- [7] Rane S, Kovacevic A and Stosic N 2015 Analytical Grid Generation for accurate representation of clearances in CFD for Screw Machines British Food Journal 90
- [8] Rane S, Kovacevic A and Stosic N 2016 Computational Fluid Dynamics in Rotary Positive Displacement Screw Machines International Symposium on Transport Phenomena & Dynamics of Rotating Machinery
- [9] Di Y, Kovacevic A and Qian T 2016 Numerical modelling of twin-screw pumps based on computational fluid dynamics Journal of Mechanical Engineering Science 1989-1996 (vols 203-210) 231.24(2016).
- [10] Lu Y, Kovacevic A and Read M 2019 Numerical Study of Customised Mesh for Twin Screw Vacuum Pumps
- [11] Ding H and Jiang Y 2017 CFD simulation of a screw compressor with oil injection Iop Conference 232
- [12] Yue X, Zhang Y and Su Z 2017 CFD-based analysis of gas flow in dry scroll vacuum pump Vacuum 139 127-135
- [13] Kennedy S, Wilson M and Rane S 2017 Combined Numerical and Analytical Analysis of an Oil-free Twin Screw Compressor IOP Conference Series: Materials Science and Engineering 232
- [14] Mierka O, Theis T and Herken T 2014 Mesh Deformation Based Finite Element Fictitious Boundary Method (FEM-FBM) for the Simulation of Twin-screw Extruders
- [15] Wu H, Huang H and Zhang B 2019 CFD Simulation and Experimental Study of Working Process of Screw Refrigeration Compressor with R134a Energies