3D Dynamic Simulation Analysis of Single Screw Expander

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Abstract: The simulation of this type of expander generally adopts empirical formula or one-dimensional numerical simulation due to the complicated meshing curves of single screw expander (SSE). However, these existing methods cannot obtain the distribution of pressure field and velocity field of fluid in the expander. In this paper, 3D solid modelling and dynamic grid technology are used to carry out numerical simulation of intake, expansion and exhaust process of single screw expander by CFD software. Besides, the distribution laws of pressure field and velocity field of single screw expander are acquired. This paper provides a new idea for the optimal design of single screw expander.

1. Introduction

In recent years, with sharply increasing pressure from energy consumption and environmental governance, the development of renewable energy and the improvement of energy efficiency are significant ways to solve energy problems[1,2]. Up to now low-grade heat energy recovery and power generation technologies mainly include Organic Rankine Cycle (ORC), water vapor Rankine Cycle and Karina Cycle[3]. Expander is a core component, which directly affects the efficiency of power generation. Single screw expander is a modified expansion machine with single screw compressor, mainly composed of case, rotor and star wheel. In addition to the advantages of positive displacement expander, single screw expander has many attractions, such as simple structure, long service life, force balance, high volume efficiency, low noise, etc.[4-9]. It is an ideal expander for industrial waste heat and pressure recovery.

Ziviani and Giuffrida et al.[10,11] studied the performance of SSE by experiments, and further established the mathematical model of the expander. Simultaneously the influence law of internal leakage and friction loss of the expander on the system performance was analyzed. Guo Zhiyu[12] numerically optimized the intake and exhaust structure of SSE and verified it through the ORC experimental system. Shen Lili[13] conducted the leakage process of a SSE, analyzed profoundly the change of leakage line with the angle of the screw. Followed a leakage model applicable to the expander was given. Because the actual working process of SSE is affected by many factors, the energy equation and mass equation are mostly applied to establish the mathematical model. It is extremely difficult to get the flow field distribution inside the expander, ignoring the momentum equation.

In this paper, CFD dynamic grid technologies and adaptive grids based on pressure and temperature gradient are applied to the numerical simulation of the working process of single screw expander, which provides guidance and help for the design and optimization of SSE.

2. Structure and Working Principle

The structure of the single screw expander is shown in the Figure 1. Inside the shell of the single screw expander, a screw and two symmetrically distributed star wheel planes constitute a meshing pair. The screw groove, star wheel teeth and the inner cavity of the shell form an enclosed working space. The working substance with a certain pressure expands in the volume of the basic element, then pushes the screw and star wheel to do rotation and work. The working process of a SSE is divided into three steps including intake process, expansion process and exhaust process. A common single screw expansion power machine usually has six screw slots, which are separated into two spaces by two star wheels, upper and lower. The intake, expansion and exhaust processes are completed respectively[14]. The structural parameters of the SSE employed in this paper are shown in Table 1.

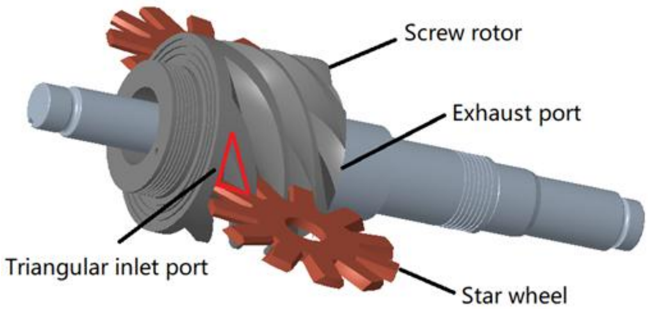

Figure 1: Single screw expander schematic diagram.

Table 1: The geometric parameters of screw rotor and star wheel.

Parameter	Value
Screw rotor diameter	117 mm
Star-wheel diameter	117 mm
Internal volume ratio	2.95
Central distance	93.6 mm
Number of screw grooves	6
Number of star-wheel teeth	11

3. Fluid Dynamics Simulation

3.1. Geometric Modelling and Mesh Generation

The screw star wheel meshing surface of a SSE is relatively complex. In this paper, CREO software with the powerful 3D surface modeling capability is used to build a 3D solid model, and Converge CFD software does the numerical analysis. On account of the complexity of flow field of SSE, screw and star wheels are defined rotors. The grids around the rotors change with the rotating of rotors. this article adopts the formidable Cartesian grid partitioning of converge software, and basic mesh size is 5mm. Level 3 mesh refinement processing is carried out on screw and star wheels' surfaces, at the same time grid adaptive encryption function based on velocity and temperature gradient is taken timely. In order to exponentially reduce the number of grids, level 3 and level 2 refinement are employed in temperature gradient, and pressure gradient respectively.

3.2. Mathematical Model

According to the working state and internal flow field of SSE, the transient calculation is selected. The continuity equation, energy equation and momentum equation are used in this paper. RNG K-Epsilon turbulence model and PISO algorithm are used to simulate the SSE unsteadily [15]. The dissipation rate equation and turbulent kinetic energy equation are solved by first-order upwind scheme, while the energy and momentum equation are solved by central difference scheme.

3.3. Setting of Boundary Conditions and Calculative Parameters

Based on the basic theory of CFD, it is necessary to set the boundary conditions and initial conditions of the mathematical model when simulating the dynamic characteristics of internal fluids of SSE through Converge.

The inlet and outlet both are pressure boundaries, meanwhile, the wall is set as adiabatic wall and medium is air. The specific parameters are illustrated in Table 2.

Table 2: Boundary condition.

Parameter	Value
pressure-inlet	0.74 MPa
Temperature-inlet	293.15 K
pressure-outlet	0.15 MPa
Temperature Backflow	190 K
Wall boundary	Adiabatic, No slip
Screw speed	3000 rpm

4. Results

4.1. Pressure Field

Pressure contour plot of SSE is shown in Figure 2. High-speed rotating screw form the negative pressure in the screw groove, and subsequently gas from triangular inlet port is sucked until the exhaust port is opened to force the gas out. It can be seen from the pressure contour plot that the pressure value on the screw surface increases successively from the suction end to the exhaust end, and the pressure on the exhaust end reaches the maximum point. The screw and star wheel meshing area is above the star wheel, and the pressure value is larger. While the below belonging to the non-meshing area, the pressure is smaller. The pressure changes in the adjacent grooves of the expander can be clearly observed because each groove is 60 degrees apart and has periodic changes.

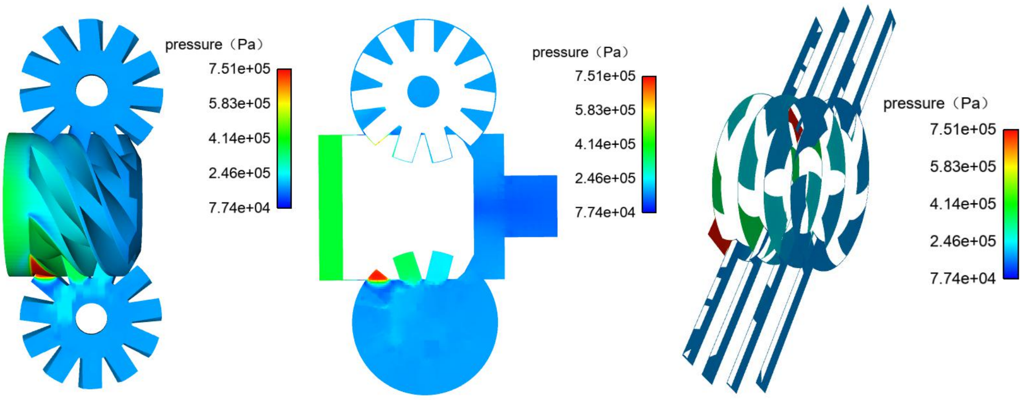

Figure 2: Pressure contour plot on the rotor.

4.2.Velocity Field

Velocity contour plot of SSE is shown in Figure 3. The velocity of the whole flow field is comparatively stable from the velocity distribution diagram of SSE, and the velocities are bigger at the intake and exhaust ports, the clearance between screw and shell, and the meshing clearance between star wheels and screw. According to the velocity figure, the gas velocity in the clearance between the screw grooves and shell and the clearance between the star wheels and the screw grooves is far greater than that in the screw grooves. There is an evident leakage of working gas. The greater the pressure differential between the high and lower pressure area, the more evident leakage caused by the gap. And the fluid velocity in the gap is considerably higher than that in the grooves.

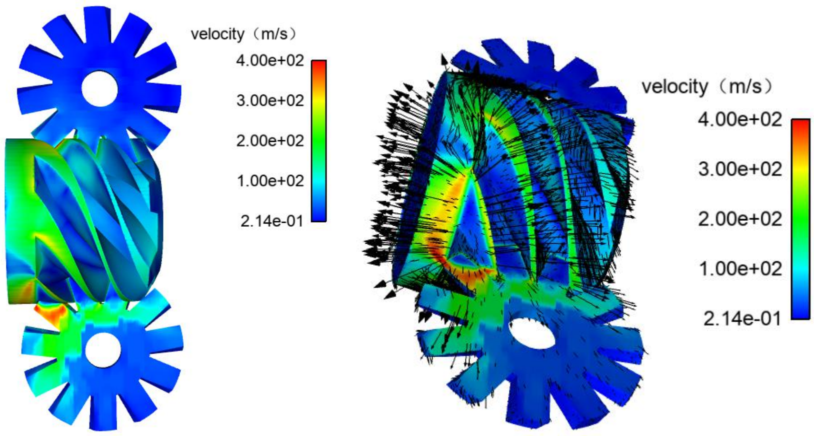

Figure 3: Velocity contour plot and vector diagram on the rotor.

4.3.Variation of Intake Pressure and Velocity

The single screw expander achieves air intake through periodic connection between triangular inlet port and spiral grooves, which leads to the unavoidable fluctuation of velocity and pressure at the air inlet. Figure 4 and Figure 5 show the fluctuation and periodic change of pressure and velocity at the triangular inlet port. Therefore, the periodic opening and closing of triangular inlet port and spiral grooves inevitably leads to pressure loss, which is an essential part of the pressure intake loss of SSE.

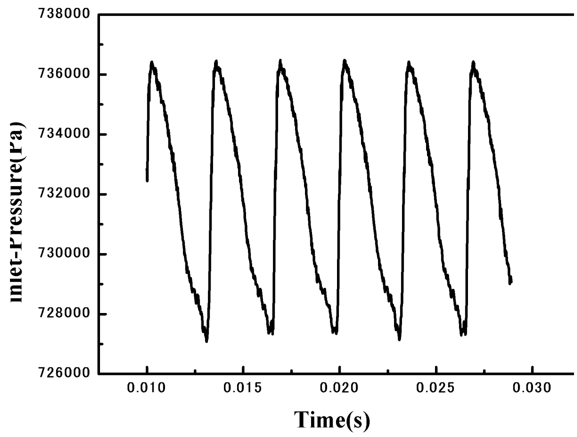

Figure 4:Velocity trends at triangular inlet ports.

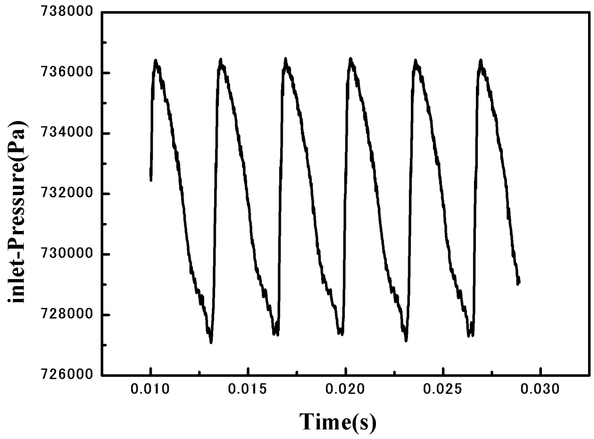

Figure 5:Pressure trends at triangular inlet ports.

4.4. Variation of Output Torque of Screw Rotor

As can be seen from Figure 6, the torque of the single screw expander shows periodic changes. The intake and exhaust periodically in the screw grooves, and the periodic expansion of gas in the screw grooves lead to the regular change of the screw output torque, which is consistent with the actual situation.

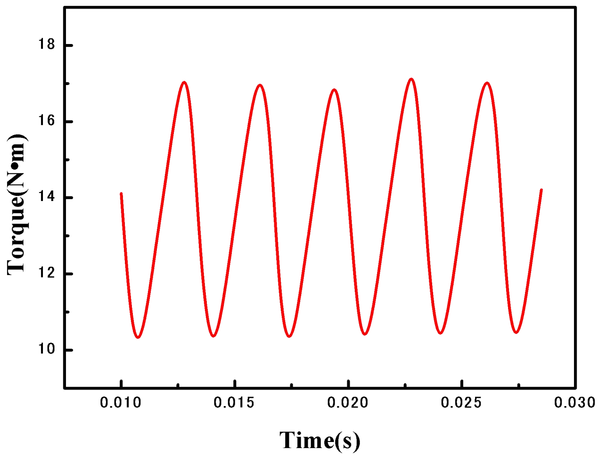

Figure 6: The torque at the SSE shaft according to the time.

5. Conclusion

By RNG K-Epsilon turbulence model and PISO algorithm, the three dimensional transient numerical simulation of internal flow field of SSE is finished using the Converge software. Then the pressure, velocity distribution of whole working process of the air intake, expansion and exhaust are obtained. The pulse of velocity of intake and exhaust ports over time and internal small gaps leaks of expander are comprehensively summarized. The above results indicate that by establishing an effective and reliable numerical calculation model and selecting reasonable initial conditions, boundary conditions and parameter settings, the simulation of SSE and other rotating machinery can be carried out effectively and accurately. This paper could provide a significant idea for the optimization and design of fluid machinery.

Acknowledgments

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