

Thermal-Structural Coupling Analysis of Variable Pitch Screw Rotors

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Abstract: The assembly accuracy of the variable pitch screw rotor has a significant control effect on the vacuum performance of the system. The assembly clearance directly affects the stability of the equipment operation, and the temperature load is an important factor in the rotor deformation. Aiming at the problem of rotor clearance balance, this paper accurately describes the heat exchange process between yin and yang rotors by establishing a thermodynamic model. The three-dimensional simulation model is constructed, and the thermal-structural coupling simulation is completed by combining the physical properties of the material and the boundary conditions. The simulation results show that the axial direction of the rotor has a nonlinear temperature gradient, and the suction end increases from 25°C to the exhaust end. The maximum temperatures of the right and left rotors are 125°C and 122°C, respectively. The thermal deformation is consistent with the temperature field distribution, and the deformation of the exhaust end is concentrated. The radial thermal deformation of the right and left rotor addendum circle is 0.011-0.0475mm and 0.0082-0.0418mm, respectively. The research results provide numerical support for the vacuum performance optimization of the pump body, clarify the reasonable assembly clearance range, and provide a theoretical basis for the improvement of the rotor structure, which has important engineering guidance value.

Keywords: Variable Pitch, Screw Rotor, Thermodynamic Model, Thermal-structure Coupling

1. Introduction

Variable pitch screw vacuum pump has become the core vacuum equipment in key industries such as semiconductor, medicine and chemical industry due to its wide pumping speed range, compact structure and no oil pollution [1]. In the process of its operation, the yin and yang rotors are the core working parts, and the assembly accuracy between the two directly determines the operation stability, sealing reliability and pumping efficiency of the pump body, which is the key technical link affecting the performance of the whole machine [2]. Under the actual working conditions, the rationality of the rotor assembly clearance is very important to the regulation of the system performance. If the clearance is too large, it is easy to cause the gas leakage inside the pump chamber to intensify and significantly reduce the pumping efficiency. If the gap is too small, it is difficult for the rotor to adapt to the deformation caused by the thermal load during operation, which in turn induces the friction loss between the rotors, and even the stuck fault occurs in severe cases, which directly affects the service life of the equipment [3-5]. Through the systematic analysis of the overall performance of the variable pitch screw rotor, it can be seen that the temperature load is the dominant factor inducing the deformation of the rotor, and the effect of the pressure load can be ignored [6]. Therefore, accurately grasping the temperature distribution law and thermal deformation characteristics of the internal yin and yang rotors of the variable pitch screw vacuum pump has become the core premise to ensure the rationality of the assembly gap and improve the performance of the whole machine [7-8]. However, the working temperature of the rotor is difficult to measure directly, which brings great technical challenges to the analysis of thermal deformation characteristics [9]. The systematic research on the coupling effect of assembly clearance and thermal deformation is relatively scarce, and the cognition of rotor deformation mechanism and clearance dynamic regulation law under

thermal load is still insufficient, which restricts the technical process of assembly precision optimization and performance improvement of variable pitch screw vacuum pump [10].

In recent years, scholars at home and abroad have carried out continuous research on the thermal-structural coupling characteristics of variable pitch screw rotors. Based on the thermal-structural coupling simulation, Li Ming et al [11]. analyzed the influence of different parameters on the temperature field and stress field distribution of the rotor by optimizing the structural parameters of the variable pitch screw rotor, which effectively improved the operation stability of the vacuum pump. Wang Xiaodong et al [12]. used a combination of numerical simulation and experiment to carry out thermal-structural coupling analysis of the rotor. Through structural optimization, the synergistic improvement of leakage control and thermal deformation suppression was achieved. Based on the multi-physics coupling simulation framework, Zhang et al [13]. focused on the thermal-structural coupling analysis, and proposed a rotor structure design scheme that takes into account low leakage and low vibration. Through thermal-structural coupling calculation and experimental verification, Smith et al [14]. discussed the thermal deformation law of the rotor under different working conditions and the influence of structural parameters on the coupling characteristics, which provided a basis for the long-term stable operation of the variable pitch screw rotor. In summary, the thermal-structural coupling characteristics of the variable pitch screw rotor are directly related to the pumping efficiency, ultimate vacuum and working stability of the screw vacuum pump. However, the existing research has not yet formed a systematic understanding of the synergistic influence mechanism between key factors such as temperature field, stress field and assembly clearance. The thermal-structural coupling analysis of the rotor not only helps to improve the working efficiency and reliability of the pump, but also provides theoretical support for the low leakage and low noise design of the variable pitch screw

vacuum pump, which is of great significance to promote the development of technology in this field.

Aiming at the optimization of assembly accuracy of variable pitch screw rotor, this paper focuses on the research of thermal deformation characteristics. In this paper, by constructing a three-dimensional model that fits the actual working conditions, combined with the thermal physical properties and boundary conditions of the rotor material, a thermal-structural two-way coupling simulation is carried out to systematically obtain the thermal deformation law of the rotor and the dynamic change characteristics of the assembly gap. The research results can provide reliable numerical support for optimizing the overall performance of variable pitch screw vacuum pump, clarify the reasonable range of assembly clearance, provide important theoretical basis for the improvement of rotor structure parameters, and have important engineering guiding significance for promoting the efficient and stable operation of variable pitch screw vacuum pump.

2. Establishment of Thermodynamic Model

The new variable pitch screw rotor proposed in this study adopts a two-stage spiral guide line. Based on the Fourier heat conduction theory and the basic equations of thermoelastic mechanics, the finite element numerical method is used to analyze the thermodynamics of the variable pitch screw rotor. The thermal-mechanical coupling model of the rotor system is established, and the temperature field distribution characteristics of the rotor under the working state and the corresponding thermal deformation law are obtained. At the same time, the thermal deformation results under the thermal-mechanical coupling are obtained.

The steady-state thermodynamic equation is expressed as:

$$[K]\{I\} = \{Q\} \quad (1)$$

In the formula: $\{Q\}$ represents the node heat flow vector, $[K]$ represents the conduction matrix, $\{I\}$ represents the node temperature vector.

In the steady-state thermal analysis, the temperature field of the system does not change with time, and its control equation satisfies the law of conservation of energy, that is, the sum of the net heat flow into the system and the heat generation rate in the system is zero. In Cartesian coordinate system, the temperature field can be expressed as a function of temperature T with respect to spatial coordinates and time:

$$T = f(x, y, z, t) \quad (2)$$

In the formula, T denotes temperature; x, y, z represent three-dimensional space coordinates; t represents time.

Under the above conditions, assuming that the variable pitch screw rotor medium is continuous, uniform and isotropic, and is in a steady state without internal heat source, the three-dimensional heat conduction differential equation can be simplified to the form of Laplace equation:

$$\nabla \cdot (k \nabla T) = 0 \quad (3)$$

Considering the isotropic material, the material used in this paper is 304 stainless steel, and the thermal conductivity k is a constant. Therefore, the equation can be simplified as:

$$\nabla^2 T = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = 0 \quad (4)$$

Under the condition of steady state and no internal heat source, the temperature distribution at any point inside the

variable pitch screw rotor satisfies the Laplace equation, and the spatial second derivative of the temperature field is zero. This simplified form provides a theoretical basis for the subsequent solution of the steady-state temperature field of the variable pitch screw rotor by the finite element method, and can be used as an input condition for the thermal-structural coupling analysis.

When there is a temperature gradient between two completely contacted objects or different parts of the same object, internal energy exchange will occur due to the thermal motion of microscopic particles. This process is called heat conduction. For the variable pitch screw rotor system, the energy transfer caused by temperature difference in each shaft section follows the Fourier heat conduction law formula:

$$q = -k \cdot A \cdot \frac{dT}{dx} \quad (5)$$

In the formula : q is the heat flux rate of the variable pitch screw rotor; k is the thermal conductivity of the variable pitch screw material; A is the cross-sectional area perpendicular to

the heat flow direction; $\frac{dT}{dx}$ is the temperature gradient of the variable pitch screw rotor along the heat flow direction.

The negative sign in the formula indicates that the direction of heat flow is opposite to the direction of temperature gradient, that is, the heat flows spontaneously from the high temperature region to the low temperature region. The basic law of the internal heat conduction process of the variable pitch screw rotor is revealed, which provides a theoretical basis for the subsequent numerical simulation of the temperature field.

Because the gas medium transported by the screw vacuum pump itself has a certain temperature, the forced convection heat transfer process will occur when it flows through the rotor surface. This heat exchange phenomenon can be quantitatively described by Newton's cooling law:

$$q = h \cdot A \cdot (T_s - T_f) \quad (6)$$

In the formula : q is the heat flux rate of the variable pitch screw rotor; h is the convective heat transfer coefficient between the variable pitch screw rotor and the air; A is the effective heat transfer area ; T_s is the surface temperature of the variable pitch screw rotor; T_f is the characteristic temperature of the gas medium.

The formula shows that the heat flux rate of the variable pitch screw rotor is proportional to the heat transfer area and the temperature difference between the surface and the fluid. In the variable pitch screw rotor system, the value of heat transfer coefficient h is mainly affected by factors such as gas flow rate, physical parameters and rotor surface geometry.

Based on the Hamiltonian principle in mechanics, the motion equation of the variable pitch screw rotor system can be established. Its mathematical expression is:

$$M\ddot{X} + C\dot{X} + KX = f(t) \quad (7)$$

In the formula: M represents the mass matrix of the variable pitch screw rotor; C represents the damping matrix of the variable pitch screw rotor; K represents the stiffness coefficient matrix of the variable pitch screw rotor; $\ddot{X}$ represents the motion acceleration vector of the variable pitch screw rotor; $\dot{X}$ represents the velocity vector of the variable pitch screw rotor, and X represents the displacement vector of

the variable pitch screw rotor.

The motion equation and the heat conduction equation together constitute a complete set of equations describing the thermodynamic model of the variable pitch screw rotor in the thermo-mechanical coupling field, which constructs a complete theoretical framework for the analysis and research of the dynamic characteristics and temperature field distribution of the variable pitch screw rotor system.

3. Simulation Analysis of Temperature Field of Variable Pitch Screw Rotor

3.1. Thermal Boundary Conditions

The solution of the heat conduction partial differential equation must depend on the complete definition of the thermal initial condition and the thermal boundary condition at the same time. The thermal initial condition stipulates the spatial distribution of the initial transient temperature of the variable pitch screw rotor, and the thermal boundary condition determines the heat transfer law between the rotor surface and the external environment. In the numerical simulation of thermodynamics, the reasonable setting of thermal boundary conditions not only affects the numerical stability of the calculation process, but also directly determines the degree of agreement between the final temperature field simulation results and the real physical phenomena.

Based on the energy transfer mechanism of thermodynamic systems, thermal boundary conditions are usually classified into three categories in engineering heat transfer analysis. The first type of boundary conditions (Dirichlet conditions) directly gives the spatial and temporal distribution of temperature on the boundary surface, which is suitable for thermal systems with definite temperature boundary, and can also be a constant temperature field. The parameter equation is expressed as:

$$t_w = f(x, y, z, \tau) \quad (8)$$

Where t_w denotes the surface temperature of the object.

The second type of boundary condition (Neumann condition) mainly applies to the working scene where the external heat source power is known or the surface heat flux can be accurately measured by defining the heat flux distribution of the boundary, and expresses the heat transfer rate through the unit area boundary in unit time. The heat flux density can be a function of space coordinates and time, or a constant value. The parameter equation is expressed as:

$$q_w = f(x, y, z, \tau) \quad (9)$$

Where q_w denotes the heat flux at the boundary of the object.

The third type of boundary condition (Robin condition) establishes the thermal coupling relationship between the solid surface and the fluid medium. This boundary condition is mainly applicable to the working scene with convective heat transfer mechanism, and expresses the energy balance mechanism between the solid surface heat conduction and the fluid convective heat transfer. The governing equation is expressed as:

$$-\lambda \left(\frac{\partial t}{\partial n} \right)_w = h(t_w - t_f) \quad (10)$$

Here, $-\lambda \left(\frac{\partial t}{\partial n} \right)_w$ denotes the internal heat flux of solid with Fourier's law; $h(t_w - t_f)$ represents the surface convection heat transfer of Newton's law of cooling; in the third boundary condition, h is the surface heat transfer coefficient; t_f is the fluid temperature.

It is very important to construct accurate thermal boundary conditions for finite element thermal analysis of objects with complex curved surface structures such as variable pitch screw rotors. In this paper, the combination of Dirichlet boundary and Robin boundary is used to simulate the rotor temperature field. The first type of boundary condition is used at the inlet end, and the fixed temperature of 25°C is set. The third type of boundary condition is used at the exhaust end. Using Formula (10), it is concluded that the gas is compressed by the variable pitch screw rotor, forming a high temperature of 120°C and inter-tooth turbulence effect. It is calculated by Formula (6) that the convective heat transfer coefficient of stainless steel 304 selected by the rotor body is 16.2W/(m²°C). In the actual working environment, the middle section of the variable pitch screw rotor is in a vacuum closed environment, only considering the heat conduction mechanism and ignoring the convection effect.

3.2. Mesh Subdivision

Due to the complex spatial surface characteristics of the variable pitch screw rotor, this paper studies the use of unstructured grid division, using ten-node tetrahedral elements for discretization. In order to improve the calculation accuracy, the patch conformal algorithm is selected for mesh generation, and the global element size is set to 0.5mm. The local refinement of the area with significant curvature change is carried out by the size function. In terms of boundary layer treatment, the expansion layer option is enabled and set to a smooth transition mode, and the smoothing level is adjusted to medium, so as to enhance the grid quality in the near-wall region. The meshing model of the variable pitch screw rotor obtained by the above parameter optimization is shown in Fig.1. This meshing effectively controls the number of elements while ensuring the calculation accuracy.

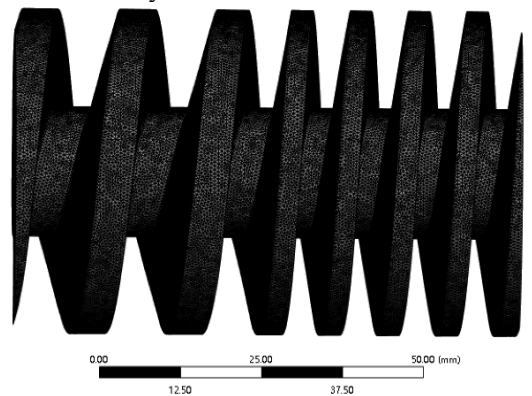
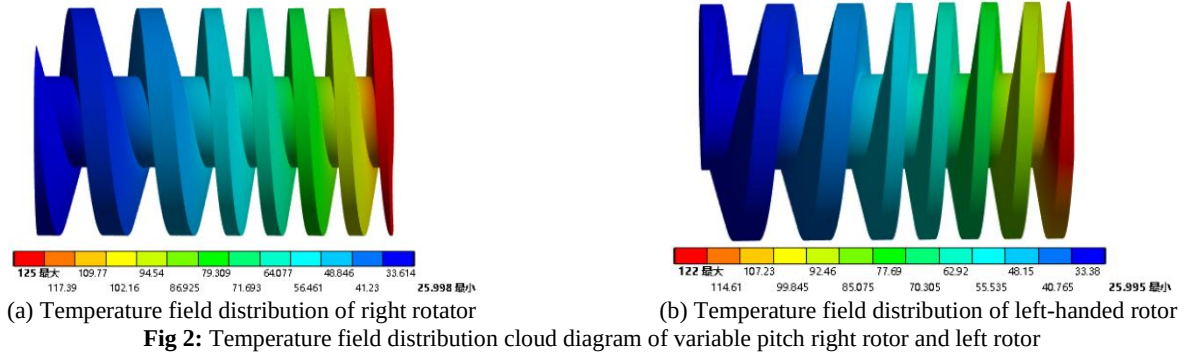


Fig 1: Grid division model of variable pitch screw rotor

3.3. Temperature Field Simulation

According to the temperature field distribution cloud diagram shown in Fig.2, the variable pitch screw rotor shows obvious axial temperature gradient. From the suction end to the exhaust end, the variable pitch left-handed rotor and the right-handed rotor both show a trend of increasing

temperature.

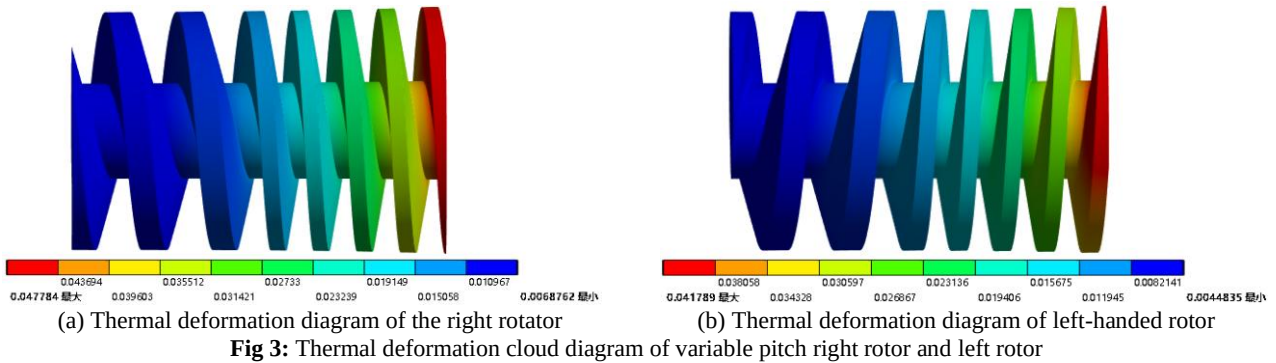


This nonlinear temperature distribution will directly lead to different degrees of thermal deformation of the variable pitch screw rotor. Through the analysis of the temperature field, it can be seen that the temperature gradient from the inlet end to the exhaust end is approximately trapezoidal distribution. This distribution characteristic makes the thermal deformation of the variable pitch screw rotor at different axial positions significantly different, which has the greatest influence on the fit clearance between the rotor and the pump chamber. The design of the meshing clearance of the variable pitch screw rotor should fully consider the influence of thermal load under actual working conditions to ensure the best operating performance under thermal conditions.

3.4. Thermal Deformation Simulation

Based on the analysis method of thermal-structural coupling, the calculation results of steady-state temperature

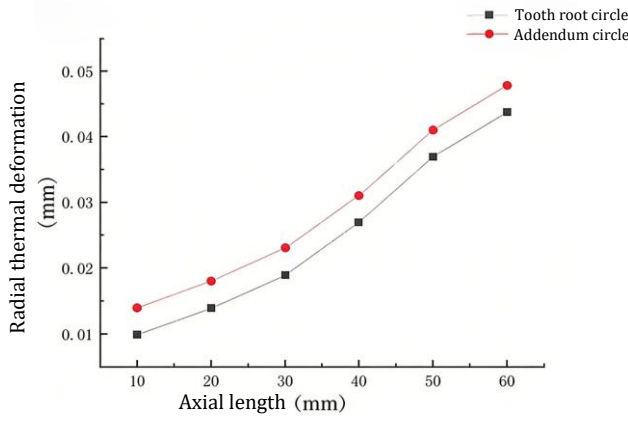
field are imported into the static structural mechanics model as load data. The thermal deformation field distribution of the variable pitch right rotor and the left rotor is obtained by finite element solution, as shown in Fig.3. Whether it is right-handed or left-handed, the thermal deformation of the variable pitch screw rotor shows significant nonlinear axial distribution characteristics: as the rotor temperature gradually increases from the suction end to the exhaust end, the thermal deformation increases gradually, and the thermal deformation growth is relatively slow; due to the internal compression of the intermediate variable pitch conveying section, the gas temperature rises steadily, and the thermal deformation growth is relatively stable. The area of the exhaust section is affected by the recoil compression effect, and the sharp rise of temperature leads to a significant increase in thermal deformation, forming an obvious deformation concentration area.



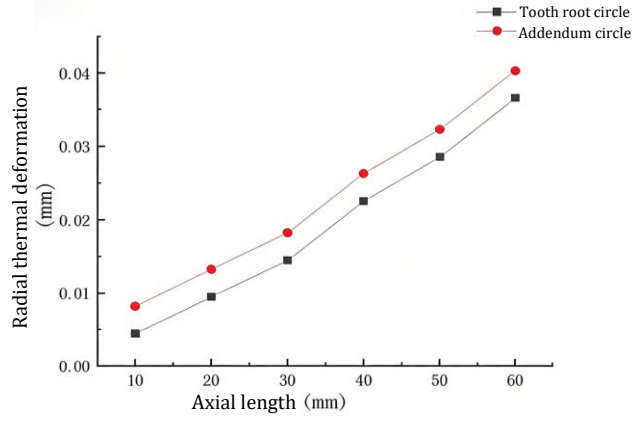
3.5. Analyzed and Discussed

The thermal deformation distribution of the variable pitch screw rotor in the working state is obtained by solving the static structural mechanics with the temperature field analysis

results as the thermal load. Fig.4 shows the distribution of radial thermal deformation of addendum circle and dedendum circle along the axial direction of variable pitch right rotor and left rotor.



(a) Radial thermal deformation of the right rotator



(b) Radial thermal deformation of left-handed rotor

Fig 4: The radial thermal deformation of the addendum circle and the dedendum circle of the variable pitch right rotor and the left rotor

In the working process of the variable pitch screw vacuum pump, the temperature field distribution of the suction end is relatively uniform, which is mainly affected by the inlet temperature and does not undergo the internal compression process, so that the thermodynamic parameters of the extracted gas remain relatively stable. In the middle variable pitch section, due to the internal compression effect, the gas temperature rises steadily. Due to the recoil gas compression effect at the exhaust end, the external atmosphere enters the exhaust cavity and causes the instantaneous compression of the working medium, which makes the temperature in this area increase significantly to the peak area. The highest temperature on the surface of the right rotor reaches 125°C, and the highest temperature on the surface of the left rotor is 122°C. The numerical results of Fig.4 show that the radial thermal deformation of the addendum circle and the dedendum circle show an obvious increasing trend from the intake end to the exhaust end. Among them, the radial thermal deformation of the addendum circle of the right rotator is 0.011-0.0475mm, and the root circle is 0.0069-0.0437mm; the radial thermal deformation of the addendum circle of the left-handed rotor is 0.0082-0.0418mm, and the dedendum circle is 0.0045-0.0381mm. This axial distribution feature is highly consistent with the gradient change of the rotor temperature field, indicating that the thermal deformation of the variable pitch right rotor and the left rotor is controlled by temperature.

Based on the above analysis results of thermal-structural coupling, in order to fundamentally solve the matching problem between rotor thermal deformation and assembly clearance under thermal conditions, it is necessary to adopt the precise design strategy of axial variable clearance to realize the dynamic matching of structural design and thermal deformation characteristics. Firstly, according to the characteristics that the thermal deformation of the rotor increases along the axial direction, it is necessary to set a taper angle of 0.1°-0.3° along the axial direction of the rotor tooth top profile. By constructing a taper structure consistent with the thermal deformation trend in advance in the cold state, the active compensation of the thermal deformation of the tooth top in the hot state is realized. Secondly, on the basis of taper design, the axial distribution of assembly clearance needs to be optimized synchronously, so that the clearance along the axial direction increases by 30%-50% according to the simulated thermal deformation, and the dynamic balance between sealing performance and operation safety is realized. Finally, due to the maximum thermal deformation at the exhaust end and the influence of recoil compression effect,

the temperature fluctuation and deformation impact in this area are more significant, and special compensation gaps need to be reserved in this area. Further buffer the severe thermal deformation of the exhaust end, avoid structural damage caused by excessive local deformation, and compensate the axial deformation gradient generated by the variable pitch screw rotor under thermal load. Ensure the reliability of the vacuum pump under hot conditions.

4. Conclusion

In this paper, aiming at the core problem that the coupling of assembly clearance and thermal deformation of variable pitch screw rotor affects the performance of pump body, the two-stage screw guide line variable pitch screw rotor is taken as the research object, and the systematic research is carried out through thermal-structural coupling simulation. The main conclusions are as follows:

(1) The synergistic distribution law of rotor temperature field and thermal deformation is clarified. There is a nonlinear temperature gradient along the axial direction of the rotor. The temperature increases gradually from the suction end (25°C) to the exhaust end. The maximum temperature of the right rotor is 125°C, and that of the left rotor is 122°C. The thermal deformation is highly compatible with the temperature field, and gradually increases along the axial direction. The deformation concentration area is formed at the exhaust end. The radial thermal deformation of the right-rotating sub-tooth top circle is 0.011-0.0475mm, and the left-rotating rotor is 0.0082-0.0418mm, which provides the core data support for the gap design.

(2) The optimization design scheme of axial variable clearance is proposed. According to the characteristics of thermal deformation gradient, the strategy of setting 0.1°-0.3° taper angle along the axial direction of the rotor tooth top contour, increasing the fit clearance by 30%-50% according to the thermal deformation, and reserving additional compensation clearance at the exhaust end can effectively avoid the leakage caused by too large clearance and the friction stuck caused by too small clearance, and realize the synergistic improvement of sealing performance and operation safety.

(3) The engineering practical value of thermal-structural coupling analysis is verified. By constructing a three-dimensional model suitable for the actual working conditions and simulating the composite boundary conditions, the problem that the rotor temperature in the closed pump chamber is difficult to measure directly is solved, and the

correlation between the temperature field, thermal deformation and assembly clearance is quantified. It provides a reliable theoretical support for the structural optimization and assembly precision control of variable pitch screw rotors, and has important guiding significance for the design and upgrading of similar vacuum equipment.

Acknowledgements

This research was funded by the Tianjin Education Commission Research Program Project [Project No. 2022ZD027], the Tianjin.

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