

Article

Research on Motor Rotor Loss of High-Speed Air Compressor in the Application of Hydrogen Fuel Cell Vehicle

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Abstract: As an important component of hydrogen fuel cell vehicles, the air compressor with an air foil bearing rotates at tens of thousands of revolutions per minute. The heat generation concentration problem caused by the high-speed motor loss seriously affects the safe and normal operation of the motor, so it is very important to clarify the loss distribution of the high-speed motor and adopt a targeted loss reduction design for air compressor heat dissipation. In this paper, for an air compressor with a foil bearing with a rated speed of 80,000 rpm, an empirical formula and a three-dimensional transient magnetic field finite element model are used to model and calculate the air friction loss, stator core loss, winding loss and permanent magnet eddy current loss. The accuracy of the analytical calculation method is verified by torque test experiments under different revolutions, and the average simulation accuracy can reach 91.1%. Then, the distribution of the air friction loss, stator core loss, winding loss and eddy current loss of the air compressor motor at different revolutions is obtained by using this method. The results show that the proposed method can effectively calculate the motor rotor loss of a high-speed air compressor with air foil bearing. Although the motor efficiency increases with the increase in motor speed, the absolute value of loss also increases with the increase in motor speed. Stator core loss and air friction loss are the main sources of loss, accounting for 55.64% and 29% of the total motor loss, respectively. The electromagnetic loss of winding, the eddy current and other alloys account for a relatively small proportion, which is 15% in total. The conclusions obtained in this paper can effectively guide calculations of motor loss the motor heat dissipation design of a high-speed air compressor with an air foil bearing.

Keywords: motor loss distribution; finite element simulation; 3D magnetic field analysis; loss separation

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1. Introduction

With the increasingly critical problems of energy shortage and environmental damage, the new energy field has attracted growing attention. In the automotive industry, hydrogen fuel cell electric vehicles provide kinetic energy through the reaction of hydrogen and oxygen on the electrode with the chemical production of only water, for truly zero emissions and zero pollution [1]. Additionally, the energy conversion efficiency of hydrogen fuel cells can reach 60~80% because the reaction is not limited by the Carnot cycle [2,3]. Vehicles containing hydrogen fuel cells also have the advantages of a long driving range and a short refueling time, making these vehicles highly promising as new energy vehicles [4,5]. In the automotive industry, hydrogen fuel cell electric vehicles are considered to be one of the important directions in the development of new energy vehicles.

The air supply system in hydrogen energy vehicles has a significant impact on the dynamic performance of the hydrogen energy vehicles. The air compressor is a key component used to enhance the reaction efficiency. According to the research of Argonne and the DOE in the United States, the cost of the air compressor ranks second in the

total cost of the entire fuel cell system [6,7]. Its performance directly affects the overall efficiency and power density of the fuel cells. Therefore, it is of great significance to develop a miniaturized, wide working condition compressor suitable for the vehicles' working environment. At present, the air compressors used in fuel cell vehicles mainly include roots compressors, screw compressors, vortex compressors, sliding vane compressors and centrifugal compressors. Among them, scroll, screw and centrifugal air compressors have the best comprehensive performance. However, there is friction between the blades of the scroll and screw compressors, and the noise and impact on quality are considerable. In contrast, the centrifugal compressor is the first choice among air compressors for fuel cell vehicles. Internationally famous automobile companies have gradually adopted high-speed centrifugal compressors as vehicle mounted air compressors, and using a single-stage centrifugal compressor has gradually become a trend.

Nowadays, fuel cell air compressors for vehicles are constantly being developed towards the goal of ultra-high speed to meet the air supply demand of high-power fuel cell systems, while achieving the goal of having a small volume and thus reducing the land occupation. Increasing the rotor speed is the key way to ensure that the air compressor can supply air with a high pressure ratio and a large flow rate while having a small volume and light weight [8,9]. In 2010, the U.S. Department of Energy cooperated with Honeywell to develop a gas supply management system based on a centrifugal compressor, which was applied to an 80 kW PEMFC with a maximum speed of 1.1×10^5 rpm [10]. Zhao et al. applied the rated speed to a 2.5×10^5 rpm ultra-high-speed centrifugal compressor in a 10 kW PEMFC system, driven by a speed sensorless permanent magnet synchronous motor with the maximum pressure and flow of 1.6×10^5 Pa and 20 g/s, with a weight of only 0.6 kg [11,12]. The above research shows that this kind of compressor has great potential for use in fuel cell vehicles.

As a driving part, the motor drives the compressor to rotate, which is source of the power for compressing gas. For a high-speed air compressor, the motor loss will increase with an increase in speed. In order to reduce the motor loss and carry out targeted energy conservation and emission reduction, it is necessary to clarify the distribution of the various losses of the motor. Soong W. L. et al. created an electromagnetic and mechanical design for a high-speed and efficient induction motor for centrifugal compressor, and compared the electromagnetic characteristics, loss and mechanical characteristics of three different types of motors (switched reluctance motor, permanent magnet synchronous motor, induction motor) [13]. Seok Mayeong Jang et al. introduced the design and performed an analysis of a high-speed, 50 kW, 700,000 rpm centrifugal compressor. The structural design criteria and power loss of the high-speed motor are analyzed using the theoretical analysis method, and the results are verified using the finite element method [14]. Baek [15] analyzed the iron loss and compared the iron loss of three different magnet shapes (single V type, single flat type and double triangle type) in the rotor structure of a built-in permanent magnet synchronous motor. Yang [16] studied the iron loss and eddy current loss of different voltage harmonics and revealed the change of loss, the temperature rise and the change mechanism for eddy current loss. According to the double "V" curves of the power and current with respect to voltage, Zhang Yongping [17] optimized the no-load loss and load loss separation experiments to separate each part of the loss. However, this method separates the winding loss, mechanical loss, iron loss and stray loss, but does not separate the loss of the rotor. At present, the research on motor loss is mostly focused on the electromagnetic loss, and the overall loss distribution of the motor, including the air friction loss, is lacking. In addition, the loss separation has only been carried out under the rated working conditions. The loss for each part of the motor under the condition of variable speed is lacking.

As mentioned above, small centrifugal air compressors have great potential for use in vehicle mounted fuel cell systems. Reducing the loss of high-speed air compressors to save resources and reduce costs is an urgent problem to solve. At present, the research on the loss distribution of the high-speed motors of hydrogen fuel cell air compressors is limited. Most studies focus on the electromagnetic loss and lack the overall loss distribution

of the motor, which would include the wind and friction losses. In addition, the loss separation is only carried out under the rated working conditions. The loss of each part of the motor under the condition of variable speed is lacking. It is very important to define the loss distribution of a high-speed motor and adopt a targeted loss reduction design for air compressor heat dissipation design. Based on this, the air friction loss, stator core loss, winding loss and permanent magnet eddy current loss of a foil bearing air compressor with a rated speed of 80,000 rpm are modeled and calculated using an empirical formula and a three-dimensional transient magnetic field finite element model. The accuracy of the analysis and the calculation method are verified using torque test experiments at different speeds. On the basis of the existing effective calculation methods, this paper proposes a method of motor loss separation that can be applied to the high-speed air compressors in hydrogen fuel cell vehicles. Using this method, the distributions of the air friction loss, stator core loss, winding loss and eddy current loss of an air compressor motor at different speeds are obtained. The changes in the various losses of the motor with the increase in speed are also analyzed. In subsequent designs aimed at loss reduction and heat dissipation, specific and targeted solutions can be proposed for those losses that account for a large proportion of the total loss and change with increases in speed according to the methods and conclusions proposed in this paper. This study can therefore effectively guide the motor loss calculation and motor heat dissipation design of high-speed air compressors with air foil bearings.

2. Analytical Calculation of Air Friction Loss

When a rotor rotates at a high speed, there is a large relative motion between the rotor and the air, resulting in tangential friction and air friction loss. There are two main types of rotor air friction loss: cylinder surface air friction loss and disk surface air friction loss. The air friction loss on the cylinder surface is the friction loss between the cylindrical surface of the rotor and the air, and the disk surface friction loss is the friction loss between the surfaces on both sides of the disk structure of the end face of the rotor thrust plate and the air.

2.1. Cylinder Surface Air Friction Loss

The cylinder surface air friction loss of the rotor can be calculated according to Formula (1) [18–20]:

$$P_a = k_1 C_{fa} \pi \rho \omega^3 r^4 l \quad (1)$$

where k_1 is the roughness coefficient, and k_1 of smooth surface is taken as 1; C_{fa} is the cylinder surface air friction coefficient; ρ is the gas density, ω is the angular velocity of the cylinder, and r and l are the radius and axial length of the cylinder, respectively.

The air friction coefficient C_{fa} can be calculated using Formulas (2) and (3) [21]:

$$C_{fa} = 0.515 \frac{\left(\frac{\delta}{r}\right)^{0.3}}{\text{Re}_\delta^{0.5}} \quad (500 < \text{Re}_\delta < 10^4) \quad (2)$$

$$C_{fa} = 0.0325 \frac{\left(\frac{\delta}{r}\right)^{0.3}}{\text{Re}_\delta^{0.2}} \quad (\text{Re}_\delta > 10^4) \quad (3)$$

where δ is the radial air gap thickness and Re_δ is the tangential Reynolds number. The tangential speed is determined by the rotor speed, and the tangential Reynolds number can be calculated using Formula (4):

$$\text{Re}_\delta = \frac{\rho u_1 \delta}{\mu} \quad (4)$$

$$u_1 = \omega r \quad (5)$$

where μ is the dynamic viscosity of the gas and u_1 is the tangential velocity of the shaft.

For a rotating body in free space, the axial Reynolds number is calculated as follows:

$$\text{Re}_r = \frac{\rho u_1 r}{\mu} \quad (6)$$

2.2. Disk Surface Air Friction Loss

The shaft surface air friction loss of the rotor can be calculated according to Formula (7):

$$P_e = \frac{1}{2} C_{fe} \rho \omega^3 (r_2^5 - r_1^5) \quad (7)$$

where P_e is the sum of the loss values of the two disk surfaces, C_{fe} is the air friction coefficient of the disk surface, r_1 is the inner radius of the thrust plate and r_2 is the outer radius of the thrust plate, as shown in Figure 1a.

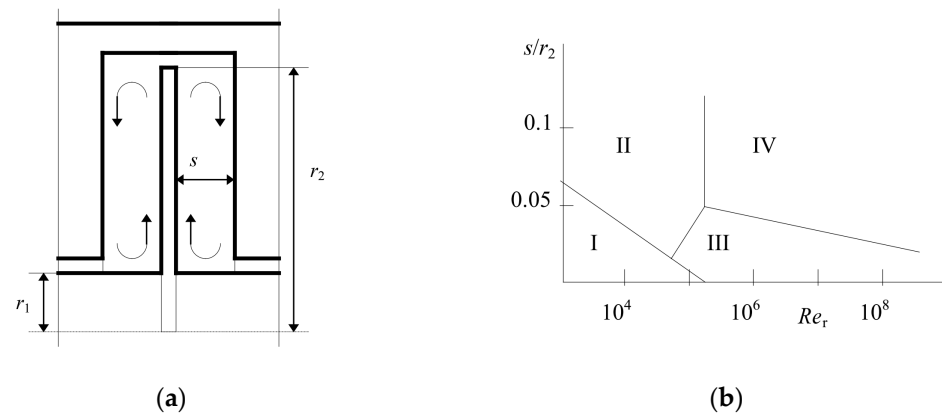


Figure 1. Zoning method of end face wind friction loss calculation. (a) Schematic diagram of rotating end face. (b) Approximate fluid region division of closed rotating disk.

According to the relationship between the spacing ratio (s/r^2 : the ratio of the distance from the thrust plate to the thrust bearing to the outer diameter of the thrust plate) and the Reynolds number, four regions are defined in a schematic diagram as shown in Figure 1b. Regions I and II are laminar flow zones and regions III and IV are turbulent flow zones, while only tangential velocity is reflected in regions I and III and there is a radial pumping effect in regions II and IV. The C_{fe} calculation formula of the disk surface friction coefficient of each region is as follows [22]:

$$C_{fe} = \frac{2\pi}{\left(\frac{s}{r_1}\right) \text{Re}_r} \quad (8)$$

$$C_{fe} = \frac{3.7 \left(\frac{s}{r_1}\right)^{0.1}}{\text{Re}_r^{0.5}} \quad (9)$$

$$C_{fe} = \frac{0.08}{\left(\frac{s}{r_1}\right)^{0.167} \text{Re}_r^{0.25}} \quad (10)$$

$$C_{fe} = \frac{0.0102 \left(\frac{s}{r_1}\right)^{0.1}}{\text{Re}_r^{0.2}} \quad (11)$$

For a body rotating in free space, the empirical formulas of friction coefficient are:

$$C_{fe} = \frac{3.87}{\text{Re}_r^{0.5}} \quad (\text{Re} < 3 \times 10^5) \quad (12)$$

$$C_{fe} = \frac{0.146}{Re_r^{0.2}} \quad (Re > 3 \times 10^5) \quad (13)$$

The above C_{fe} formulas are applicable to the Reynolds number in the range 10^3 to 10^7 , and the spacing ratio (s/r^2) in the range of 0.0127 to 0.217.

2.3. Calculation of Air Friction Loss of Air Compressor

The above formulas can be used to construct a model to calculate the air friction loss caused by the high-speed rotation of the rotors of ultra-high-speed air compressors with air foil bearings. The calculation model is shown in Figure 2. In this model, the rotor mainly includes a spindle and thrust plate. The clearance of each air foil bearing is assumed to be consistent with δ_1 in the process of movement. The specific parameter values are listed in Table 1.

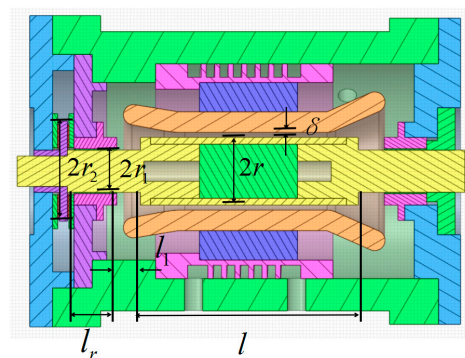


Figure 2. Simplified model sectional view of air compressor.

Table 1. Calculation parameters.

Physical Quantity	Numerical Value
Outer diameter of spindle r (mm)	20
Inner diameter of spindle r_1 (mm)	12.5
Outer diameter of thrust bearing r_2 (mm)	29
Air gap of spindle δ (mm)	3
Air gap of air bearing δ_1 (mm)	0.03
Length of spindle outer diameter l (mm)	119
Length of spindle inner diameter l_1 (mm)	15
Radial length of bearing l_r (mm)	25
Thickness of thrust disc l_t (mm)	5
Density of air ρ (kg/m ³)	1.205
Dynamic viscosity of air μ (kg/(m·s))	18.1×10^{-6}

3. Simulation Calculation of Electromagnetic Loss

When the motor is running, the motor no-load loss includes stator core loss, permanent magnet eddy current loss (in some cases this may be considered stray loss) and air friction loss. Motor load loss includes winding loss and stray loss. In this work, the air friction loss of the motor was assessed using a combination of simulation and measurement. The formula is as follows:

$$P_{fw} = P_{Loss} - P_{Fe} - P_{Cu} - P_{Solid} \quad (14)$$

where P_{Loss} is the total loss of the motor measured in the experiment, while P_{Fe} , P_{Cu} and P_{Solid} are the core loss, winding loss and eddy current loss, respectively, obtained using finite element simulation.

3.1. Maxwell Theoretical Equations

For simulation, it is necessary to analyze the mechanical movement within a certain period of time. Here, the excitation input is mostly a three-phase sine wave current, which

can be solved using a transient magnetic field. The formula of the vector and scalar magnetic potential in the three-dimensional transient state is [23]:

$$\begin{cases} \nabla \times \mathbf{H} = \mathbf{J} \\ \mathbf{B} = \nabla \times \mathbf{A} \\ \mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} \end{cases} \quad (15)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (16)$$

where $\mathbf{H}$ is the magnetic field intensity, $\mathbf{J}$ is the current density, $\mathbf{B}$ is the magnetic induction intensity, $\mathbf{E}$ is the electric field intensity and $\mathbf{A}$ is the magnetic potential. Using the above equation, the following two identities can be obtained.

$$\begin{cases} \nabla \times \frac{1}{\sigma} \nabla \times \mathbf{H} + \frac{\partial \mathbf{B}}{\partial t} = 0 \\ \nabla \cdot \mathbf{B} = 0 \end{cases} \quad (17)$$

This theoretical equation is used to solve a three-dimensional transient magnetic field. For a mechanical transient solution, the discrete displacement or angle must be calculated, and its equation can be expressed as follows.

$$\left\{ \frac{dx}{dt} \right\}^{t+\Delta t} = \frac{\{x^{t+\Delta t}\} - \{x^t\}}{\Delta t} \quad (18)$$

where x represents the mechanical displacement, i.e., the displacement or angle that is discretized [24].

The Bertotti separation model is typically used to solve for the stator core loss using the finite element method, which decomposes the core loss into three parts: hysteresis loss, eddy current loss and additional eddy current loss [25]. The loss formula of the motor core per unit mass is as follows:

$$P_{Fe} = P_h + P_c + P_e \quad (19)$$

By refining the iron loss calculation model, a calculation formula based on loss coefficient and magnetic flux density maximum can be obtained.

$$P_{Fe} = k_h f B_m^\alpha + k_c f^2 B_m^2 + k_e f^{1.5} B_m^{1.5} \quad (20)$$

$$B_m^x = \sum_{k=1}^{\infty} k (B_{k\max}^x + B_{k\min}^x) \quad (21)$$

where k_h , k_c , k_e are the hysteresis loss coefficient, eddy current loss coefficient and additional loss coefficient of stator materials, respectively. B_m is the magnetic density amplitude of each point in the stator; α is the Steinmetz coefficient, which ranges from 0.7 to 2.2 according to the properties of the material properties.

The simulation simplifies the skin effect of copper wire, so only the traditional DC loss is needed to calculate the winding loss [26]:

$$P_{Cu} = P_{DC} = m I^2 R \quad (22)$$

where m is the coefficient. When R represents the phase resistance, m of the three-phase motor is 3.

In the finite element time domain, the magnetic field equation can be expressed as:

$$\nabla \times \frac{1}{\mu} (\nabla \times A_s) = J_s - \sigma \left(\frac{\partial A_s}{\partial t} + \nabla E \right) + \nabla \times H_c \quad (23)$$

where A_s is the magnetic vector potential, J_s is the source current density, E is the potential scalar and H_c is the permanent magnet coercivity. When the magnetic field in the magnetic steel and the magnetic steel sheath changes, the induced current generated is eddy current.

The eddy current loss is calculated using the z-direction component J_z of current density, and its finite element simulation equation can be expressed as follows:

$$P_{\text{Solid}} = \int \left(\frac{|J_z|^2}{\sigma} \right) ds \quad (24)$$

3.2. Basic Assumptions and Model Building

Here, ANSYS Maxwell finite element software was used to solve the three-dimensional machine model. To facilitate calculation, the following assumptions were made for the motor model without affecting the results:

- The core loss model adopted the classical calculation formula and ignored any loss change caused by the stacking times of the stator cores;
- The non-uniformity of the permanent magnet structure and the influence of the motor temperature change on the calculation of the motor loss were not considered in this model;
- To avoid mutual interference between the motion domain and the bearing, the gap between the bearing and the rotating shaft was enlarged to 0.9 mm. The windings were treated as stranded winding, and the effect of skin effect was not considered.

The main parameters of the motor are shown in Table 2. The motor body structure includes an 18 slot stator, double-layer winding and the magnetic steel and sheath. The screw holes and chamfers of shell, diffuser and bearing were simplified in the model. The winding modeling was refined to exhibit axial asymmetric distribution. The Dirichlet boundary condition was given in the model, with shaft–rotor–magnetic-steel–sheath as the motion domain. Using the air gap length as the grid standard, the grid of motion domain and stator was refined to 1/2 of the air gap length, and the boundary layer of magnetic steel and sheath was generated. The resulting high-speed permanent magnet motor model established using the above reasonable assumptions, and the model processing is shown in Figure 3.

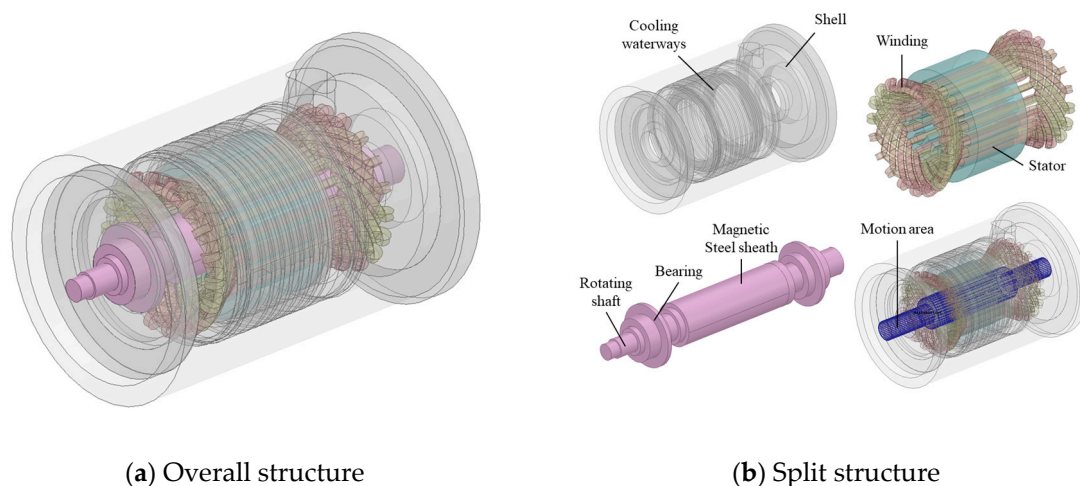


Figure 3. Structural diagram of 3D complete machine.

Table 2. Main geometric parameters of motor.

Parameter	Numerical Value
Number of grooves	18
Number of poles	2
Outer radius of stator	50 mm
Radius of rotor core	16 mm
Length of stator and rotor core	58 mm

Silicon steel B27AV1400 was selected as the stator core material of the prototype. According to the alternating magnetization loss curve of silicon steel, the loss coefficient of the model can be fitted using the least square method. Using simulation analyses of different speed conditions, the B-P curve at multi-frequency was selected during fitting. The specific curve and fitting results are shown in Figure 4 and Table 3.

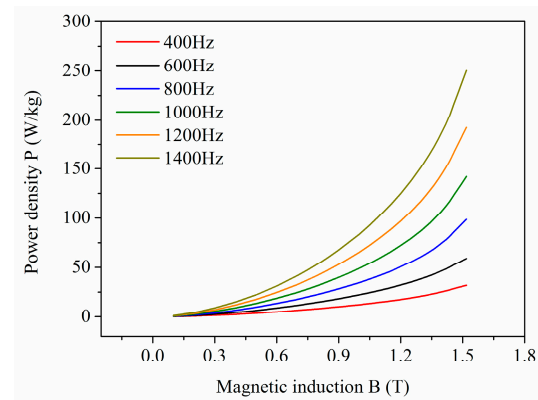


Figure 4. B-P curves of silicon steel B27AV1400 at different frequencies.

Table 3. Calculation results of iron loss coefficient of silicon steel sheet B27AV1400.

Loss Coefficient	Numerical Value
k_h	80.85
k_c	0.24
k_e	6.47

4. Experimental Verification

4.1. Test Method

To measure the loss and efficiency of the motor, the loss separation method was used. The voltage of the rated frequency was applied to the tested motor, and the input power p_1 was recorded. The experimental platform is shown in Figure 5, with a 540 V output DC power source, variable-frequency drive, power meter and motor. The voltage port of the power meter is connected between the frequency converter and the motor through the terminal, and the current data is clamped with AC current pliers. The output torque of the motor can be measured using a torque-measuring instrument, and the output power p_2 of the motor is:

$$p_2 = \frac{T \cdot n}{9.549} \quad (25)$$

where T is the output torque of the motor and n is the synchronous rotation speeds of the motor. Motor efficiency η and Loss P_{loss} are:

$$\eta = \frac{p_1}{p_2} \times 100\% \quad (26)$$

$$P_{Loss} = p_1 \times (1 - \eta) \quad (27)$$



Figure 5. Experimental device diagram of air compressor motor.

To further verify the accuracy of the winding model, the phase resistance of the motor was measured experimentally. During measurement, the motor was at room temperature and the rotor was stationary. A DC resistance tester was used, as shown in Figure 6. Since the Y-connection three-phase winding of the motor is internally connected, there are only three outgoing terminals. The resistance value of each phase was calculated according to the following formula:



Figure 6. Photo of motor DC resistance test.

$$\begin{cases} RR_{aa} = RR_{medmed} - RR_{bcbc} \\ RR_{ba} = RR_{medmed} - RR_{cabc} \\ RR_{ca} = RR_{medmed} - RR_{abbc} \end{cases} \quad (28)$$

where R_{ab} , R_{bc} and R_{ca} are the terminal resistance values measured between outgoing terminals A and B, B and C, and C and A, respectively, and R_{med} is the calculated value. The expression is as follows:

$$R_{med} = \frac{R_{ab} + R_{bc} + R_{ca}}{2} \quad (29)$$

4.2. Simulation Model Verification

Under the 540 V rated voltage, the motor operating frequency was adjusted, and P_1 and T were measured when the readings of power meter and torque meter became stable. The experimental data are shown in Table 4. The torque comparison results from the simulation and test data from 50,000 rpm to 80,000 rpm are shown in Figure 7. The simulation gave torque values slightly higher than the test values, but with consistent trends and average accuracy of 91.1%.

Table 4. Test results of air compressor motor.

Revolutions/rpm	p_1/kW	$T/\text{N}\cdot\text{m}$	$\eta/\%$
50,000	3.20	0.61	93.11
60,000	5.58	0.88	94.38
70,000	8.69	1.19	95.12
80,000	13.00	1.55	95.62

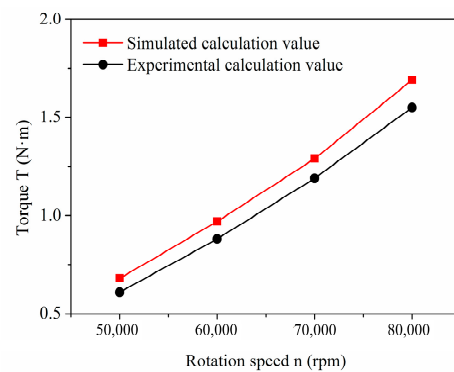


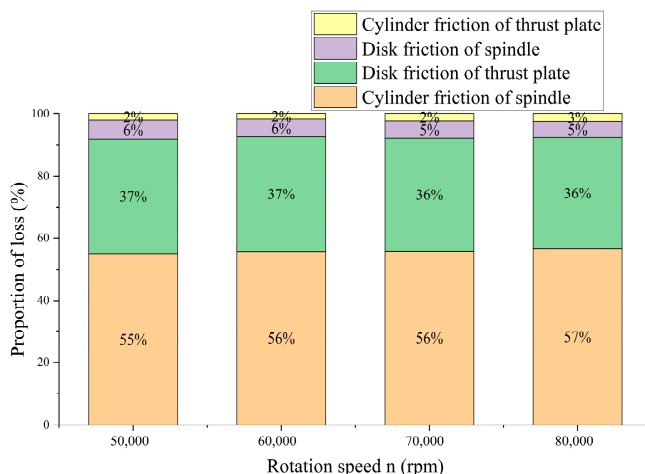
Figure 7. Comparison diagram of experimental test torque and simulation calculation torque.

Finally, the measured phase resistance of the motor at 25 °C is $R_{25} = 0.00187 \, \Omega$, which can be converted to $0.0227 \, \Omega$ at 75 °C. The simulation data for the winding loss allowed the calculation of a phase resistance of $0.0256 \, \Omega$, which is close to the measured value, demonstrating good modeling accuracy.

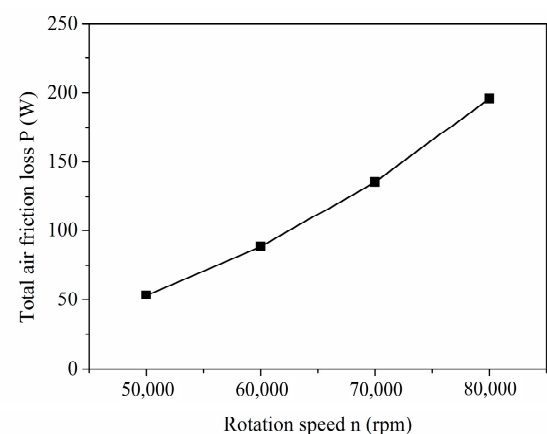
5. Results and Discussion

5.1. Analysis of Air Friction Loss

As can be seen from Figure 8a, when the rotation speeds range from 50,000 rpm to 80,000 rpm, the largest proportion of air friction loss is the cylinder surface loss of the main shaft, at about 55%, followed by the disk surface loss of the thrust plate, at about 36%. The cylinder surface and disk surface loss of the thrust plate account for only a relatively small proportion, about 9% in total. Given the small volume of the thrust plate, the heat flux generated by the wind friction loss here is large, and this is a difficulty addressed in the heat dissipation design. As shown in Figure 8b, the overall air friction loss increases exponentially with increases in the rotation speeds, reaching 195.84 W at the rated 80,000 rpm.



(a)



(b)

Figure 8. Relationship between air friction loss and revolution of air compressor rotor. **(a)** Relationship between air friction loss and revolutions of each part. **(b)** Relationship between air friction loss and revolutions.

Due to the complexity of the air compressor structure, the analytic method theory was used to estimate the air friction loss and the change trend in the rotation speed for the analysis of the overall heat flow density distribution. The loss separation method was used to determine the specific numerical air friction loss, and this information was used in the subsequent cooling scheme design, which utilized accurate input parameters.

According to the experimental test, the total loss at 50,000 rpm to 80,000 rpm is obtained, and, combined with the simulation calculation results, the air friction loss at different revolutions is separated, as shown in Figure 9. The loss is generally on the rise, and the air friction loss accounts for about 29% of the total loss.

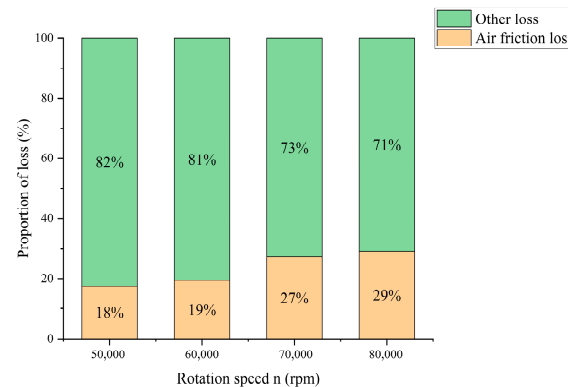


Figure 9. Comparison diagram between calculated wind friction loss and measured total loss by loss separation.

5.2. Analysis of Electromagnetic Loss Simulation Results

Maxwell 3D cannot use adaptive mesh generation in transient analysis, so it was necessary to verify the mesh independence to eliminate the potential for error arising from differences in mesh generation. The motor model was divided into four kinds of meshes with different degrees of refinement: 101,517, 387,980, 504,933 and 1,133,367. The losses obtained from these different meshes were determined as shown in Figure 10. The curved surface and boundary layer meshes had large influences on the magnetic field solution, and the core loss and eddy current loss fluctuated greatly, but there were few changes in winding loss and torque. From 504,933 to 1,133,367 grids, there were loss differences of 0.8%, 0.9% and 1%, respectively, with no change in torque. Considering the grid error and computer simulation cost, 504,933-grid division was finally selected based on the results.

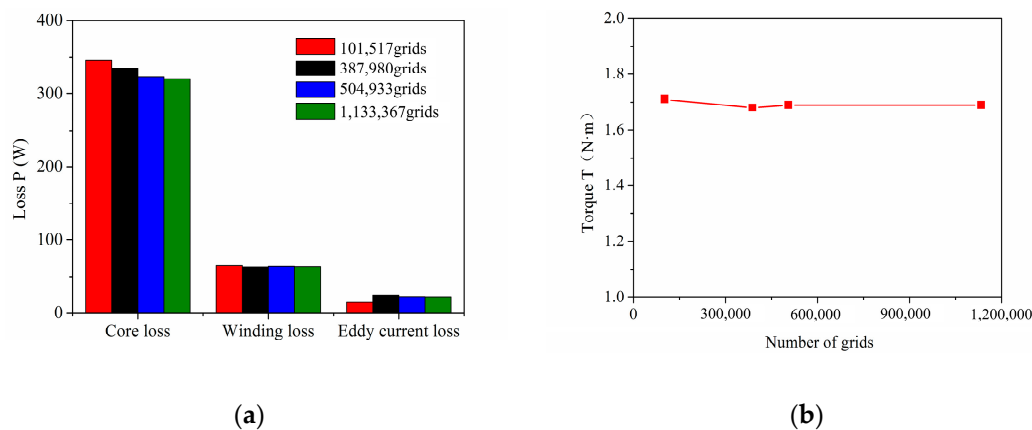


Figure 10. Grid independence verification. (a) Comparison of loss changes of various components under different grid numbers. (b) Torque variation under different grid numbers.

The calculated stator core loss distribution results for 80,000 rpm are shown in Figure 11.

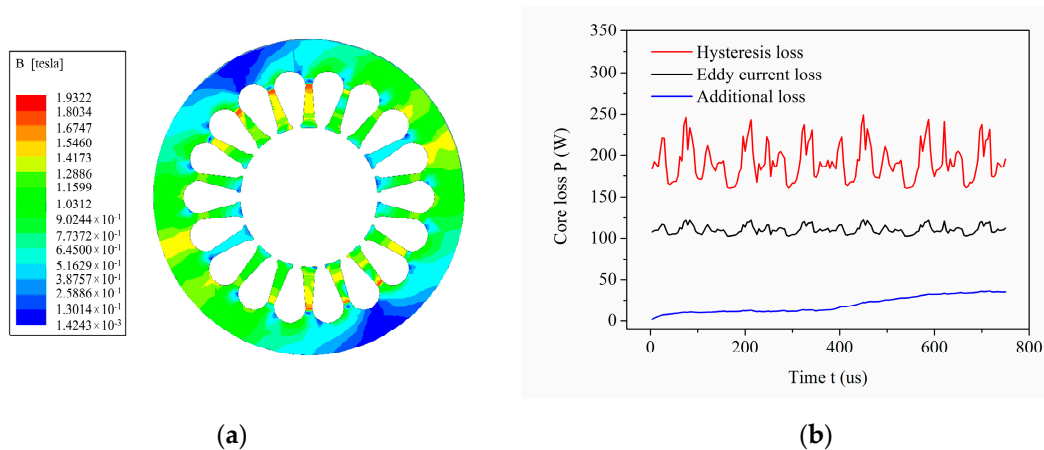


Figure 11. Magnetic induction distribution at 80,000 rpm. (a) Nephogram of magnetic induction. (b) Loss curve.

As shown in Figure 11, the maximum magnetic induction intensity occurs at the junction between the stator gear and the yoke. After one power cycle, the core loss value does not rise or show periodicity, but fluctuates stably between 270 W and 500 W. Here, the end winding of the motor accounted for 72.7% of the total length, with losses of asymmetric end winding of 26.1 W and 21.2 W. Other losses determined using three-dimensional simulation are shown in Table 5 and Figure 12. The electromagnetic loss of the whole machine is 410.93 W, and core loss accounted for the highest proportion of the total loss, 78%. The external alloy material of the motor will also be affected by the magnetic field and cause loss, but this loss is too low to be considered.

Table 5. Simulation results of electromagnetic losses of motor components at 80,000 rpm.

Components	Loss	Numerical Value/W
Basic loss	Iron loss of stator	322.6
	Copper loss of winding	64.6
	Eddy current loss of rotor	23.4
Eddy current loss of other alloys	Bearing	9.4×10^{-6}
	Rotating shaft	6×10^{-3}
	Diffuser	8.3×10^{-4}
	Cooling waterways	6.6×10^{-3}
	Shell	0.33
Sum		410.93

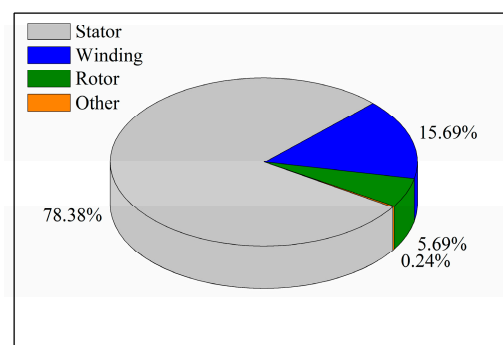


Figure 12. Overall loss distribution of motor at 80,000 rpm.

To compare the air friction loss results more comprehensively, we varied the rotation speeds and excitation for the same motor model, and solved for the motor data at

50,000 rpm, 60,000 rpm and 70,000 rpm, as shown in Figure 13. With increased rotation speeds, the total output power of the motor increased, and the rotating magnetic field became stronger, so the output torque exhibited an upward trend. The stator core loss and winding loss changed greatly. With the change in the rotation speeds, the magnetic field-related parameters in the stator core also change, such as the frequency f and maximum magnetic induction B_m . Overall, increased rotation speeds increased the excitation and copper loss with the increase in current.

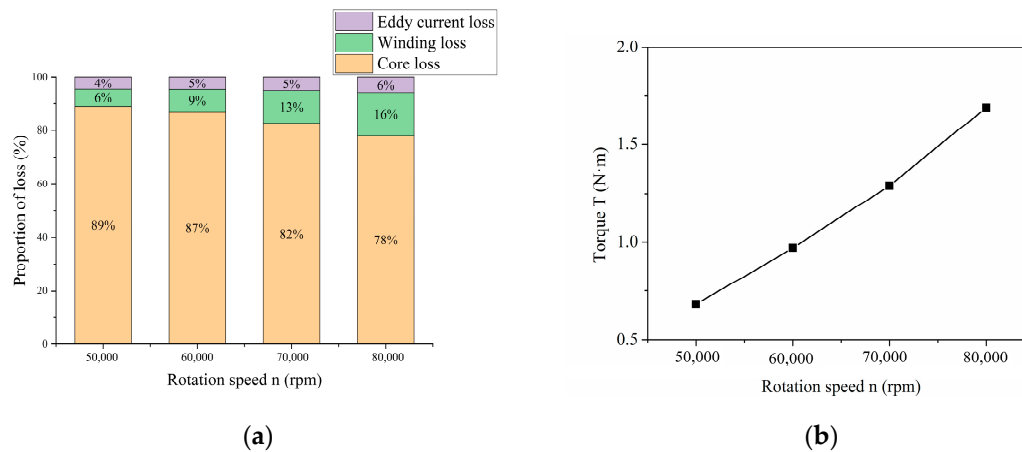


Figure 13. Motor simulation results under different revolutions. (a) Relationship between electromagnetic loss and Revolution. (b) Relationship between torque and Revolution.

5.3. Overall Analysis of Motor Loss

After the losses of each part of the motor are separated, the loss values for each part are calculated, respectively, when the speed is 50,000 rpm, 60,000 rpm, 70,000 rpm, 80,000 rpm. As the speed increases, the motor efficiency increases from 93.11% to 95.62%. However, at the same time, the absolute value of the loss value also increases, from 280 W to 760 W. Among the losses, the proportion of the stator iron loss decreases relatively with the increase in speed, from 73% to 56%, but it still accounts for a large proportion of the total loss, more than 50%. Therefore, it is crucial to study the loss distribution in order to reduce the loss as much as possible to improve the motor rotor efficiency of the high-speed air compressor with an air foil bearing. The proportion of motor air friction loss increases from 18% to 29% as the speed increases. Therefore, it is of great significance to study the distribution of the motor rotor air friction loss of the air compressor with an air foil bearing at high speeds to avoid a high air friction loss. Stray losses, such as winding copper loss, eddy current loss and the electromagnetic loss of other alloys, increase slightly with the increase in rotating speed, and their proportion in the total loss is low. At the high rotating speed of 80,000 rpm, it is about 15%.

In our future work, we will create a targeted loss reduction design for a high-speed air compressor motor for fuel cell vehicles based on the above methods and results. Since the stator core loss accounts for the largest proportion, we can take measures to reduce it: increase the stator slot sectional area, increase the stator slot filling factor, etc. The air friction loss of the motor accounts for about one quarter to one third of the loss and changes greatly with the increase in the speed. Great attention must thus be paid to it at high speeds. The air friction loss is mainly caused by the bearings and seals, and the following measures can be taken to reduce it: use high-efficiency shafts, use high-efficiency lubrication systems and lubricants and use advanced sealing technology, etc. Other losses account for a small proportion and do not change significantly with speed. If conditions permit, relevant measures can be taken to reduce these losses. In order to improve the efficiency of loss reduction and save costs, we should give priority to reducing the components of the loss with the highest proportions and with obvious changes with increases in speed.

6. Conclusions

In this work, the air friction loss, stator core loss, winding loss and permanent magnet eddy current loss of a foil bearing air compressor with a rated speed of 80,000 rpm are modeled and calculated using an empirical formula and a three-dimensional transient magnetic field finite element model. The accuracy of the analysis and calculation method are verified using torque test experiments at different speeds. Using this method, the distributions of the various losses of an air compressor motor at different speeds are obtained. The following conclusions are obtained:

1. The air friction loss was solved for different rotating cylinder and disk surfaces of the rotor using analytical method. The distribution of the air friction loss of the rotor was determined, and the magnitude of the total air friction loss was estimated. As the rotation speed increases, the overall loss shows an upward trend, and the air friction loss accounts for about 29% of the total loss.
2. The winding ends of the motor are long and asymmetrically distributed, so to fully consider the three-dimensional structure of the motor and more accurately calculate loss, a whole machine model was established. The results for the model matched the experimental results well, indicating that the model has a good accuracy.
3. The motor efficiency increases with the increase in the rotation speed, but the absolute value of loss also increases with the increase in the rotation speed. Stator core loss and air friction loss are the main sources of loss, accounting for 55.64% and 29% of the total motor loss, respectively. The electromagnetic loss of the winding, eddy current and other alloys accounts for a relatively small proportion, which is 15% in total.

In subsequent designs for loss reduction and heat dissipation, specific and targeted solutions can be proposed for those losses that accounts for a large proportion of the total and that change with increases in the speed according to the methods and conclusions proposed in this paper. The stator core loss can be reduced by increasing the stator slot sectional area and the stator slot filling factor, etc. The air friction loss can be reduced by using high-efficiency shafts, using high-efficiency lubrication systems and lubricants and using advanced sealing technology, etc. The conclusions obtained in this paper can effectively guide the motor loss calculation and motor heat dissipation design of a high-speed air compressor with an air foil bearing.

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