Design of magnetic brush composite seal

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Abstract: Brush seal is a mechanical sealing method that achieves sealing by the relative high-speed friction between brushes and the sealed object. It is a non-contact sealing method that overcomes some of the disadvantages of traditional mechanical seals in different media conditions, axial offset, and temperature changes. Brush seals are generally installed at both ends of the shaft or on the sealing surface of pumps, valves, and other equipment. When the equipment is working, the sealed object and the brush ring form relative motion, forming a sealed space inside the brush ring, and the pressure inside the sealing ring gradually rises, thus achieving sealing. Brush seals have good adaptability, can adapt to different working conditions, and have a simple structure, easy maintenance, and long service life. Therefore, they are widely used in some special industries such as petroleum, chemical, pharmaceutical, and food industries. Although brush seals have unique advantages, there are also some shortcomings. For example, due to the difficulty in maintaining the perfect high-quality surface matching between the bristles and the shaft, brush wear may occur, resulting in a decline in sealing performance. In this study, a new type of magnetic brush seal was designed and manufactured. The magnetic force was used to ensure the high-quality surface between the bristles and the shaft. The brush seal was tested and analyzed on a bearing seat test bench. The main research contents are as follows: Firstly, the materials and manufacturing processes required for the magnetic brush seal were studied, mainly through ANSYS Electronics. Then, a brush seal sample was made, and finally, the experimental device was designed and applied.

Key words: Brush seal; aero engines; ANSYS Maxwell; leakage characteristic experiment

1 Introduction

Seal technology is extremely important for applications in heavy industry and aerospace, and it provides indispensable support for the development of these fields. Brush seal can greatly improve work efficiency and reliability, reduce leakage and prolong life[1,2] Contact seal is divided into two types: static seal and dynamic seal[3]. The dynamic seal refers to the sealing structure used on the rotating shaft, in which the sealing component rotates with the rotation of the shaft. It is essentially a friction seal, which achieves the sealing effect by the sealing contact between the sealing component and the shaft surface. The dynamic seal is suitable for places where the rotating shaft needs to be sealed, such as the rotor and bearing box of mechanical equipment such as pumps and compressors. Brush seal is one of the most commonly used dynamic seals in aero-engines and gas turbines[4,5]. Its sealing performance will have an important impact on engine efficiency. Brush seal is a new type of contact seal, which originated from the labyrinth seal[6]. It is an efficient damping seal with the characteristics of high efficiency, energy saving and flexible seal. Compared with the labyrinth seal, the leakage of brush seal is only 1/5-1/10[7]. Nowadays, brush seal technology has become one of the indispensable technologies in modern advanced turbine machinery, such as aero-engines, gas turbines and steam turbines.

Brush seal has become a key technology and an indispensable part of important components such as aero-engines, gas turbines and steam turbines. However, there are some problems in the brush seal of the traditional structure. Specifically, the traditional structure mostly uses two baffles to hold the arranged brush hairs, and the roots of the brush hairs and the baffles are connected by welding process. However, there are several problems in this way, such as: the thermal stress of welding[8] will make the brush seal ring deformed; internal stress release may also occur after welding, resulting in deformation of the workpiece; the grain size of the material in the heat affected zone of welding is coarse, and the properties, especially the corrosion resistance are poor. The traditional brush seal ring has a high requirement for the weldability of the brush material, and it is difficult to meet the needs of non-metallic and polymer material brush wire in some occasions. To solve these problems, MTU company in Germany developed a new type of hoop brush seal technology[9], which avoids these problems caused by welding and can apply non-metallic brush wire.

Magnetic fluid seal[10]is a device that uses the rheological properties[11] and magnetic viscosity effect[12] of magnetic fluid to achieve sealing. The magnetic circuit composed of a circular permanent magnet, a pole shoe and a rotating shaft concentrates the magnetic fluid placed between the shaft and the gap at the top of the pole shoe under the action of the magnetic field generated by the magnet[13], so that it forms a so-called 'O' ring, which blocks the gap channel to achieve the purpose of sealing. This sealing method can be used in two cases where the shaft is magnetic, and the shaft is non-magnetic. The former magnetic beam is concentrated in the gap and runs through the shaft to form a magnetic circuit, while the latter magnetic beam ratio does not pass through the shaft, but only through the magnetic fluid in the sealing gap to form a magnetic circuit. The use of magnetic fluid seals also has certain limitations, and it performs poorly under high temperature conditions and when dealing with the eccentricity of some shafts[14,15].

This paper further discusses the non-welding brush seal technology, aiming to reduce the wear effect[16] of brush seals through magnetic force, eliminate the hysteresis effect[17.18], and cope with greater shaft eccentricity[19].

2 Structure design of magnetic brush composite seal

2.1 Basic magnetic brush seal structure

To add magnetic force on the basic of the original brush seal to achieve the purpose of strengthening the sealing performance, the basic requirement is to make the magnetic induction line pass through the whole magnetic brush seal device completely. The preliminary idea of the magnetic brush seal structure is to change the material of the front plate, the back plate, the core wire and the wire to the paramagnetic material on the base of the new brush seal structure designed by us. The special size magnet is processed and adsorbed in the middle of the secondary brush seal, so that the closed magnetic induction line of the magnet-back plate-core wire-axis-core wire-front plate-magnet is completed.

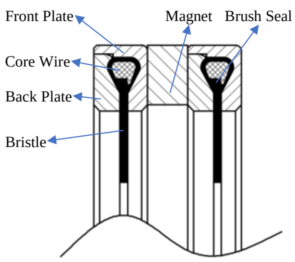

Figure 1 Magnetic brush seal (left) and structure (right)

2.2 Ansys Maxwell magnetic response simulation

Maxwell of Ansys[20]is an embedded magnetic field simulation software. Maxwell can model and simulate magnetic or ferromagnetic materials, which is very important for the design and analysis of many electromagnetic systems. Maxwell is solved by the finite element method, which considers the material nonlinearity and the field-matter coupling effect and has high accuracy. Its visualization tools are rich, which can display information such as magnetic field distribution, magnetic flux density, and induced potential, which is convenient for analysis and observation.

2.2.1 Set the Solver Type

There are three types of Solver : Megnetostatic[21], Electrostatic, and Eddy Current. As well as other electric field related solvers, we choose Megnetostatic static magnetic field.

2.2.2 Establish the model

Because the material of the front plate back plate is the same and does not affect the magnetic induction line, we simplify the front plate and the back plate into one. The software does not support the modeling of the wire, so the brush wire is simplified as a entirety. The Draw command in Modeler is used to create 2D objects, the rectangle option in the software is used to draw the approximate model, and then the irregular model (core and thread) is drawn by Boolean operation.

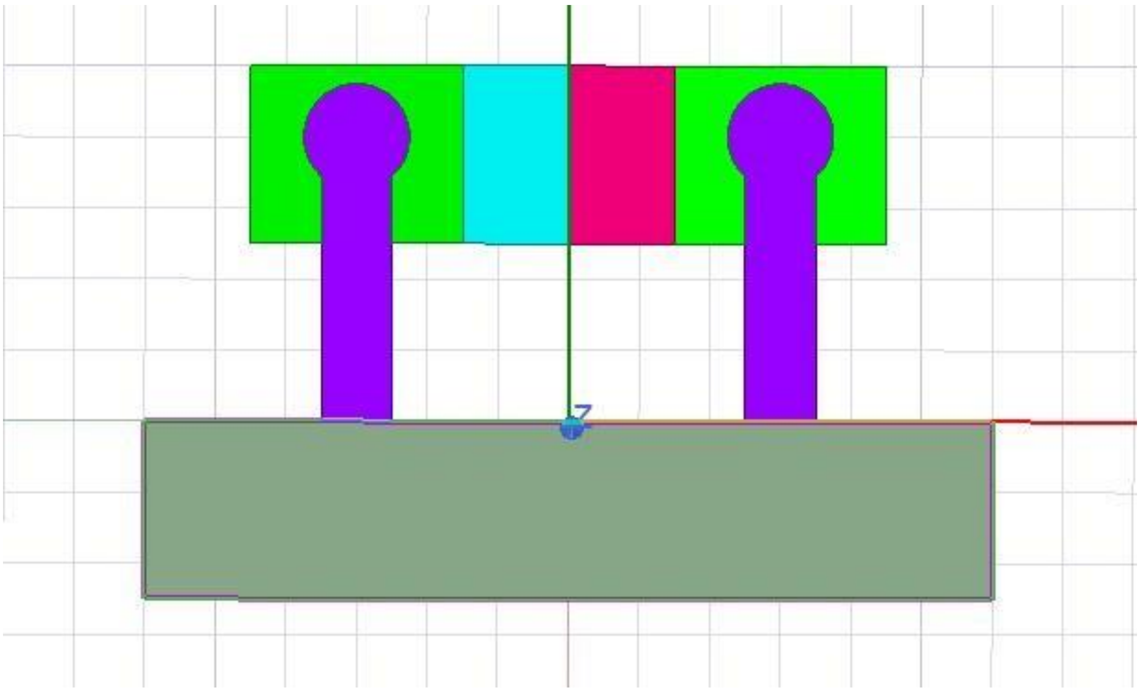

Figure 2 Magnetic brush seal model

2.2.3 Investigate and select brush wire materials

Because of the special use characteristics of the brush wire, the use requirements are: high rigidity, magnetic conductivity, fine wire diameter and so on. Therefore, we selected several wire that meet the requirements for comparison:

Table 1 material comparison

Parameters	1J22	1J79	1J85	1Cr13
Chemical Constituents (%)	Ni67.5-70.0, Fe29.0-30.0, Co4.5-5.2, Mo≤0.8, Mn≤0.50, Si≤0.30, C≤0.03	Ni80.0-82.0, Fe≤1.0, Mn≤1.0, Si≤0.3, C≤0.05	Ni80.5-82.5, Fe≤1.0, Mn≤1.0, Si≤0.5, C≤0.05	Cr12.5-14.5, Mn≤1.00, Si≤1.00, S≤0.03, P≤0.04, C≤0.15
magnetic(al) behavior	Ferromagnetism	Ferromagnetism	Ferromagnetism	Micro-magnetism
Resistivity (μΩ·cm)	43-49	128-140	46-52	-
Relative permeability	4000-8000	200-500	1000-4000	-
Coercivity (A/m)	1200-2000	200-400	800-1600	-
Curie Temperature (℃)	550	280	450	-
Thermal Conductivity (W/m·K)	11-17	10-14	10-20	24.9-26.2
Melting Point(℃)	1420-1460	1350-1380	1380-1420	1480-1530
Coefficient of thermal expansion (/℃)	11.7	11.8	11.3	10.4
corrosion resistance	Medium	Normal	Normal	Better
Magnetic Hysteresis loss	Low	Medium	Low	None
Thermal Conductivity performance	Medium	Medium	Medium	Better
Welding performance	Poor	Poor	Poor	Better

2.2.4 Set material properties

Since Maxwell 's own material library does not have the materials we need, we need to add the materials we need to the material library. Find the required conductivity, dielectric constant, permeability, etc., input into the material library.

2.2.5 Set boundary conditions and excitation sources

Because it is to simulate the static magnetic field, and the magnetic field can be extended to infinity, it is necessary to set a boundary as an infinity boundary, otherwise the simulation will continue to run. We choose Balloon Boundary to simulate the infinite boundary conditions, and the results of Balloon Boundary are closer to the actual situation.

2.2.6 Setting Solution Options

In Maxwell, the generation and change of magnetic field need various excitation sources to occur. Among them, the current is the most basic and main excitation source to generate the magnetic field. When the electron moves in the conductor, the current and the magnetic field will be generated. In addition, the magnetic moment of the object is also a common excitation source, which is the ratio between the magnetic field strength of the object and its own magnetic strength. In addition, when there is a changing electric field or magnetic field in a closed loop, an induced magnetic field around the loop or an induced electric field along the direction of the loop will also be generated respectively. Since the magnet is a permanent magnet in our model, our excitation source does not need to select the current, etc., and the permanent magnet itself is an excitation source.

2.2.7 after-treatment

After setting the above conditions, click check, and after the computer check is correct, click analyze to run the simulation. After the operation, the results are post-processed. Visualization is a major feature of post-processing. The calculation results can be displayed in a graphical way, including magnetic field distribution, electric field distribution, physical quantity, etc., which is intuitive and convenient to understand the magnetic field distribution.

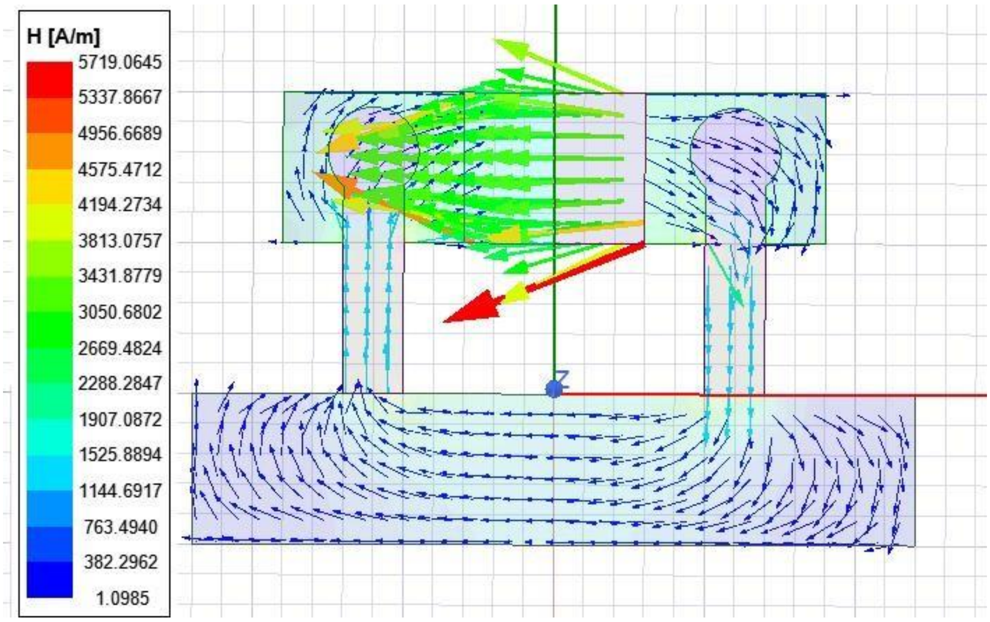

Figure 3 Magnetic field vector diagram

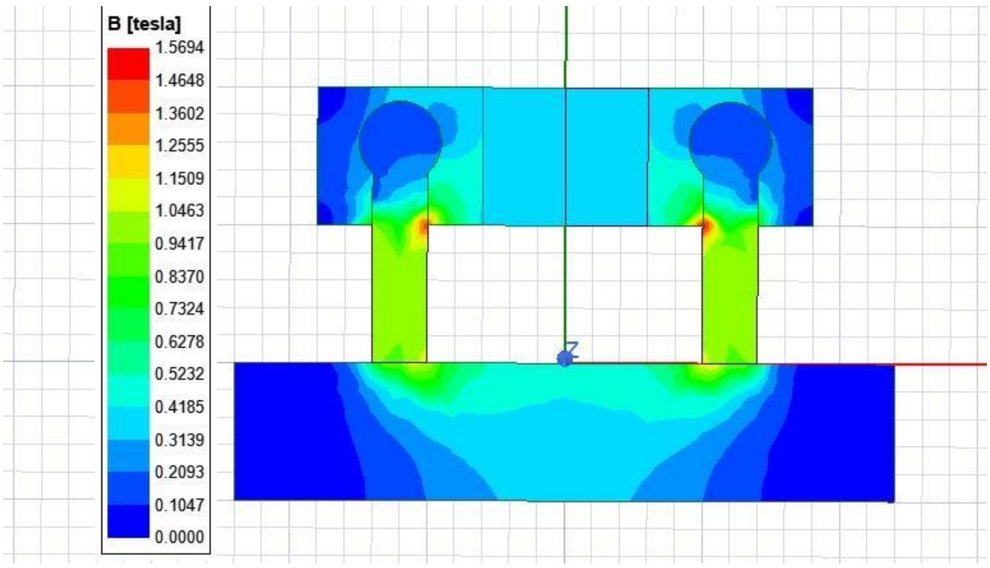

Figure 4 Magnetic induction intensity cloud diagram

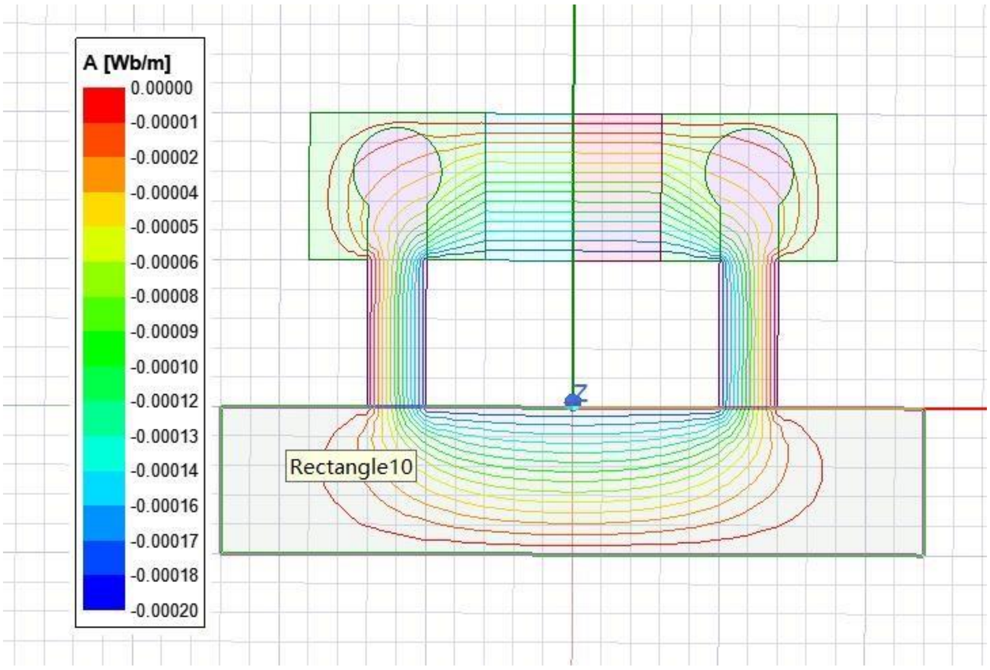

Figure 5 Magnetic induction line diagram

2.3 The influence of various materials on the calculation of magnetic field

2.3.1 The influence of brush wire material on magnetic field

This section mainly compares the influence of different brush wire materials on the number of magnetic induction lines and whether they are closed. Ferromagnetic materials are more conducive to the closure of magnetic induction lines. When the magnetic induction line is closed, the magnetic brush wire will be attracted towards the axis direction, which makes it possible to quickly restore the original position when dealing with the axial beat and reduce the leakage caused by the hysteresis effect.

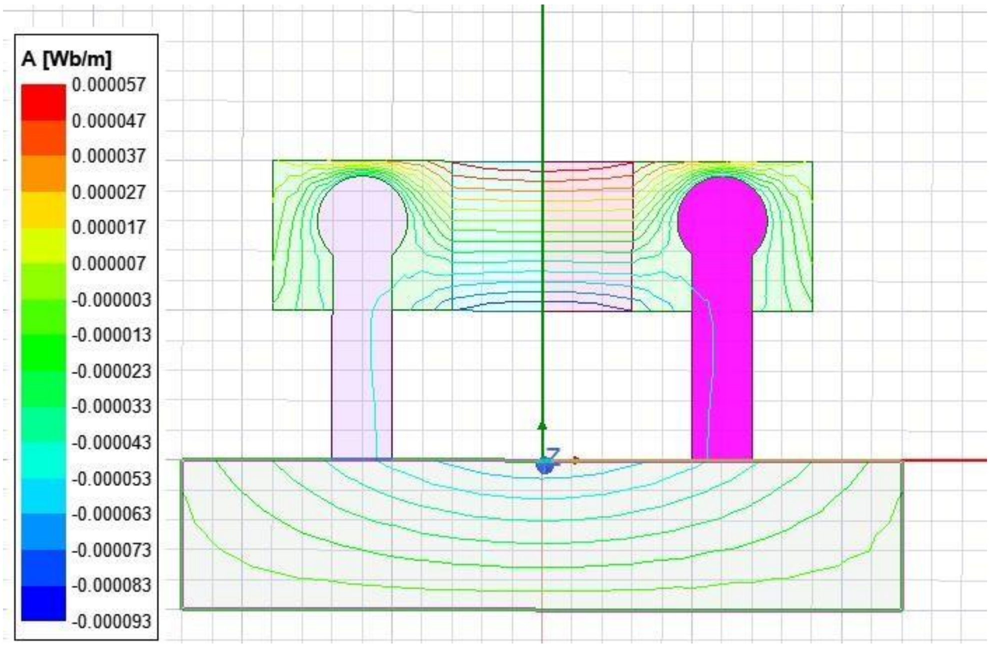

Figure 6 Magnetic induction line diagram: copper brush wire material

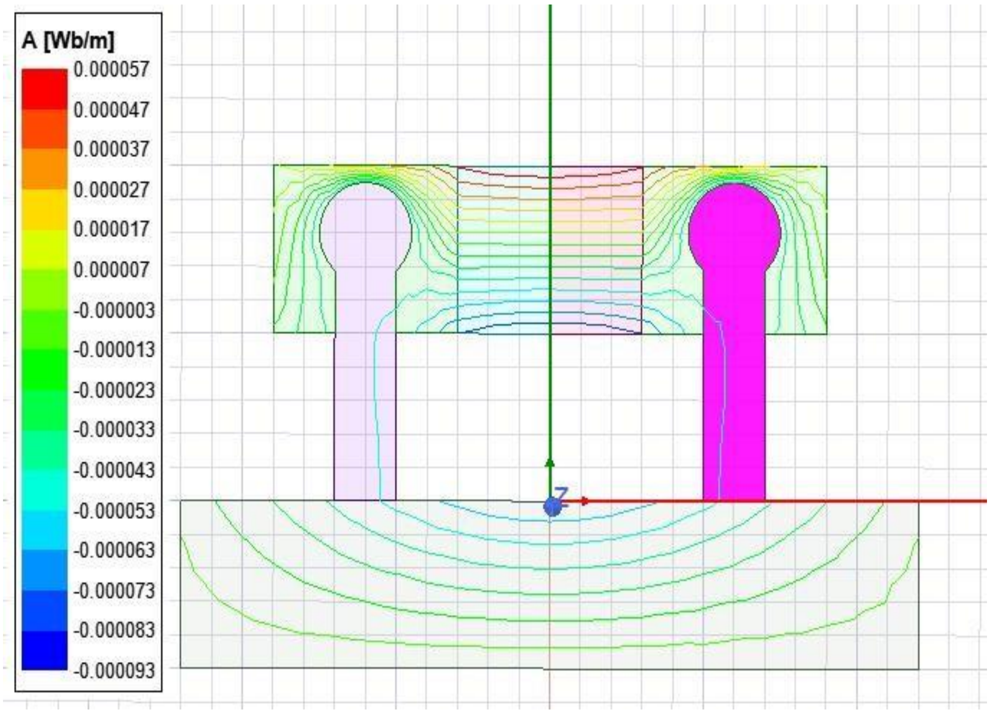

Figure 7 Magnetic induction line diagram: molybdenum brush wire material

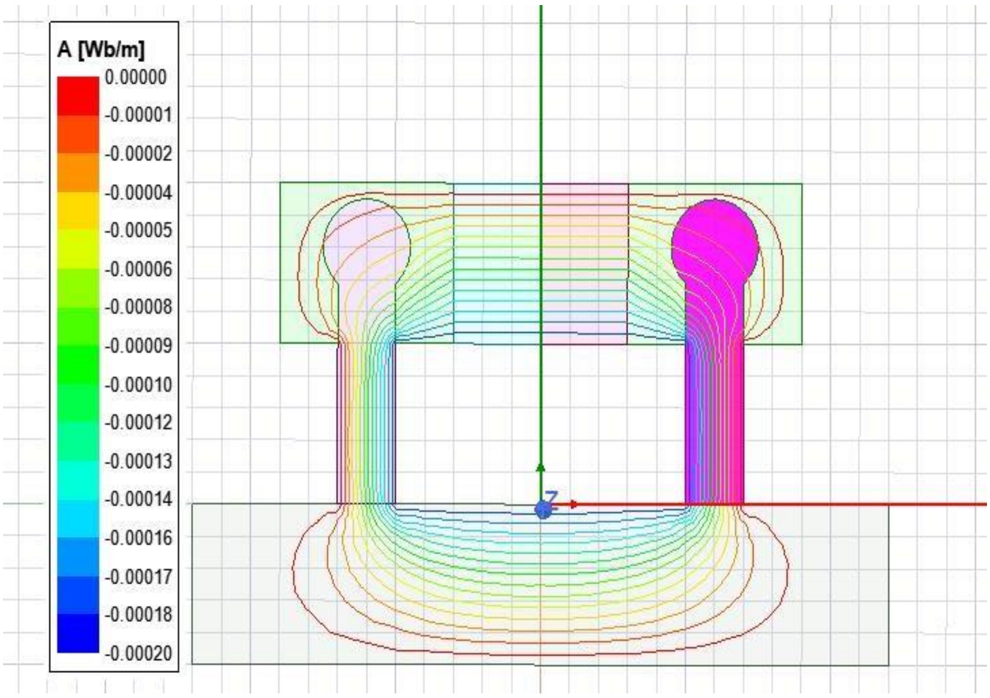

Figure 8 Magnetic induction line diagram: nickel brush wire material

2.3.2 The influence of shaft material on magnetic field

This section mainly compares the influence of different brush wire materials on the number of magnetic induction lines and whether they are closed. The magnetic induction line closure is better when the axis of the ferromagnetic material such as steel is used.

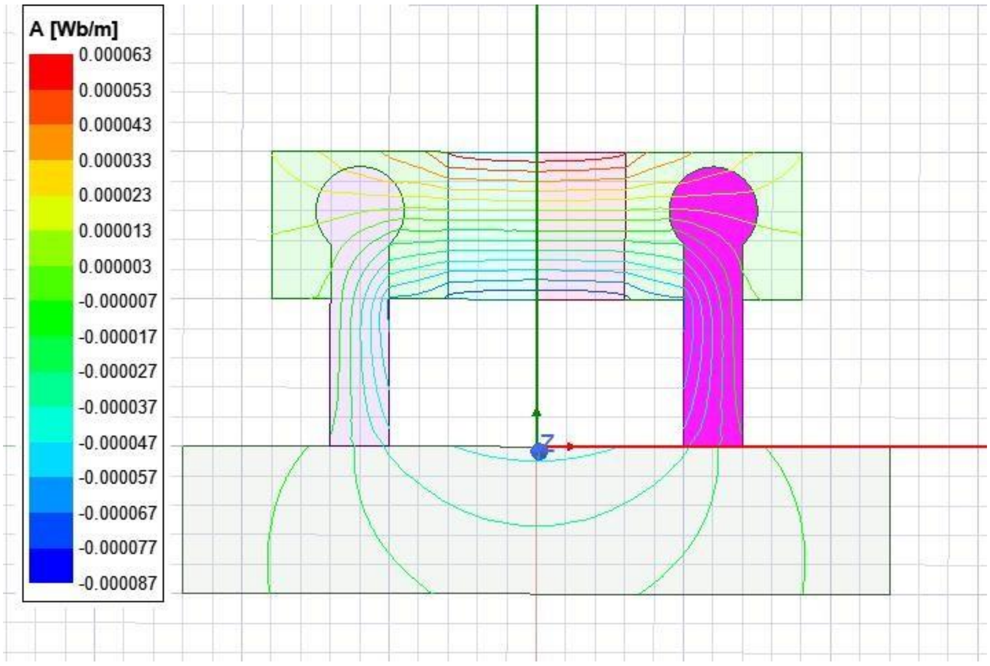

Figure 9 Magnetic induction line diagram: chromium shaft and iron brush wire

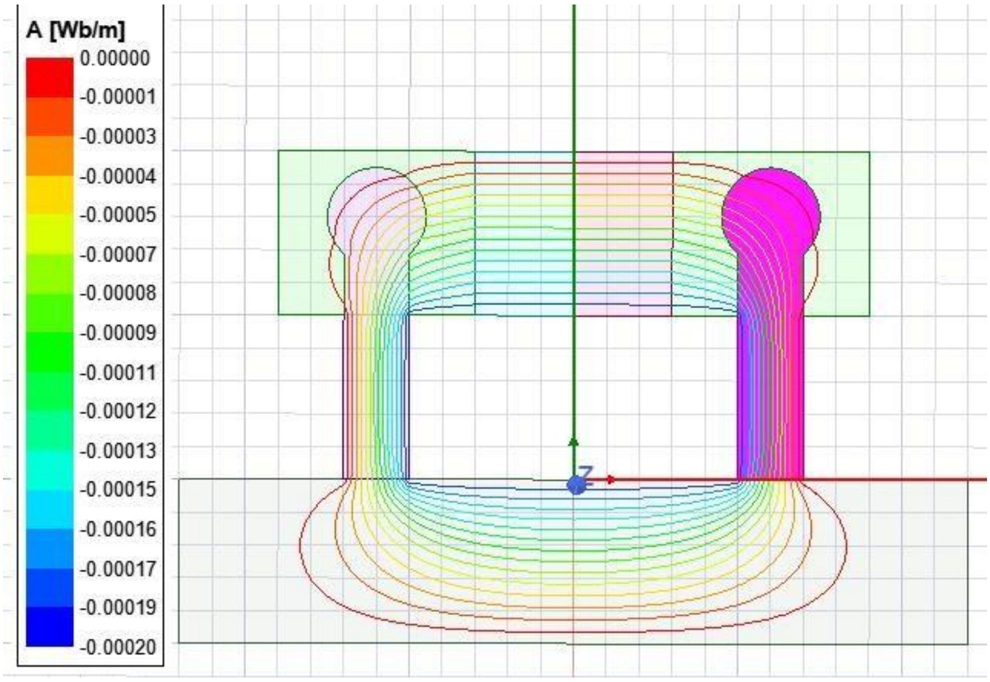

Figure 10 Magnetic induction line diagram: steel shaft and iron brush wire

2.4 Maxwell simulation conclusion

Brush wire is an important part of brush seal. For the material selection requirements of brush seal brush wire, there are generally the following aspects:

Wear resistance: The brush wire needs to constantly contact and rub with the sealed object when it is working, so it needs to have good wear resistance to ensure long-term service life.

Elasticity: The brush wire needs to have a certain elasticity to adapt to the surface deformation during sealing and maintain the stability and consistency of the sealing effect.

Thermal conductivity: In the process of sealing friction, the brush wire needs to be able to withstand the high temperature generated, and it also needs to have good thermal conductivity to effectively dissipate heat during the sealing process.

Antistatic: In some special application environments, such as the flow of liquid or air, the brush wire needs to have certain antistatic properties to ensure the reliability of use.

Temperature and pressure: different brush material is limited by temperature and pressure is different, need according to the specific work.

On this basis, we add the special material selection requirements of this topic, requiring the brush wire to be a paramagnetic material. After comparison in all aspects, we decided to use 45 steel for the front plate, back plate and core wire, and the brush wire material is a hard-magnetic alloy wire of 1J79. At the same time, since the shaft material in the laboratory is 40Cr, the material is not a paramagnetic material, so we have a diameter of a 45-steel expansion sleeve is added to the shaft of 50 mm, so that the magnetic flux path is closed.

3 Brush seal brush ring manufacturing

Brush seal manufacturing is commissioned by Beijing Haibao Sealing Technology Co., Ltd. and meet the design requirements.

3.1 Finished brush seal product

Figure 11 Brush seal product

Figure 12 Brush wire state

4 Brush seal test bench design and assembly

To verify the sealing effect of the new brush seal, we decided to build a brush seal test bench, which is composed of a bearing seat and a motor. At the same time, it is necessary to design various experimental accessories suitable for the bearing seat.

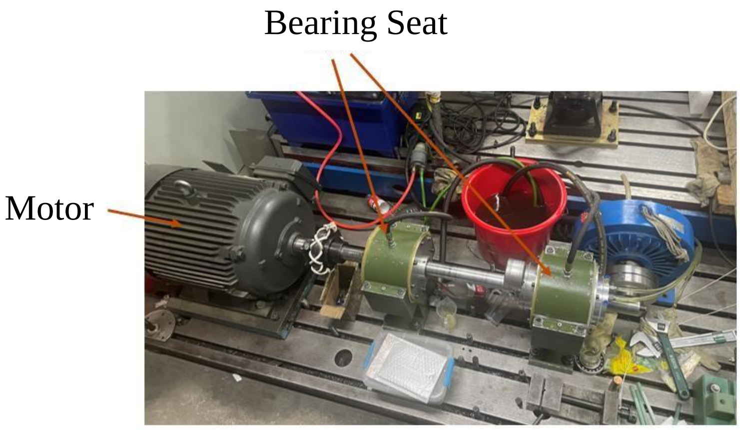

Figure 13 Brush seal test bench

4.1 Brush seal test bench end cover design

The end cover is installed on the end surface and connected with the bench body. It is a key component of the bearing seat, which is mainly used to ensure the safety and sealing of the bearing, usually installed on both sides of the bearing to seal the inside of the bearing, preventing dust and impurities from entering the bearing and protecting the bearing. The main function of the end cover of the bearing seat is to ensure the safety of the bearing: the end cover of the bearing seat is generally produced of aluminum alloy material, with high strength and rigidity, which can effectively bear the load of the bearing during use and ensure the safety of the bearing. The end cover of the bearing seat can achieve good sealing effect through seals such as seal rings. In the environment of high speed, high temperature and high humidity, the loss of lubricating oil inside the bearing can be reduced and the normal operation of the bearing can be maintained. Therefore, the focus of our test piece design is on the end cover design.

The original end cover of the bearing seat was mechanically sealed, and the experiment was changed to a contact brush seal. To control the variables better and ensure the accurate test of the leakage of the brush seal, the static seal of the O-ring is designed on the contact surface between the end cover and the bearing seat. In the center of the end cover, a hole that meets the size of the brush seal is designed. The brush seal is matched with a small gap. The adjustment ring can be used to adjust the position of the brush seal.

4.2 Selection of expansion sleeve model

When designing the brush seal, we designed it according to the actual diameter of the engine shaft of 80 mm, but the diameter of the shaft is 50mm on our brush seal test bench. In addition, the shaft material of the bearing seat test bench is 40Cr, which is a reverse magnetic material and cannot form a loop with the magnetic brush seal. After considering the processing cost, processing time, installation difficulty and other comprehensive factors, we decided to expand the shaft diameter by expanding the sleeve. At the same time, the expansion sleeve can use paramagnetic material to close the magnetic induction line sealed by magnetic brush.

The expansion sleeve is a kind of mechanical fastener, which is usually used to connect the shaft and the machine parts. The expansion sleeve has the characteristics of simple structure, convenient installation, large fastening force, stable and reliable operation, and has high bearing capacity and self-locking. It is usually used to connect the rotating parts on the shaft, such as hubs, flywheels, gears, etc., can also be used to connect two or more mechanical parts or widely used in the transmission system of automobiles, aviation, power, etc. It should be noted that the appropriate size and model must be selected when the expansion sleeve is used to ensure the correct expansion force and installation quality.

4.3 Experimental design

The test scheme we designed: The lubricating oil is ejected from the injection device on the left side, some of the lubricating oil flows back from the left oil return channel, and some passes through the bearing, which can not only lubricate the bearing, but also play a role in cooling. The lubricating oil comes to the right part. Most of the lubricating oil is blocked by the brush seal and returns to the right oil return channel. A small part enters the external part of the bearing seat through the brush seal into the leakage oil collection device. There is a small hole below and above the device. When the liquid leakage is measured, the above small hole is blocked, and the measuring cup is placed below to measure the leakage volume. When the gas leakage is measured, the lower hole is blocked, and the gas rotor flowmeter is connected at the upper hole to measure the gas leakage volume.

4.4 Construction of brush seal test bench

After designing the test plan and making the brush seal finished product, we are ready to build a brush seal test bench for experiments. We disassembled the original test bench and rebuilt the brush seal test bench according to the needs of our experiment.

Figure 14 End cover equipped with brush seal

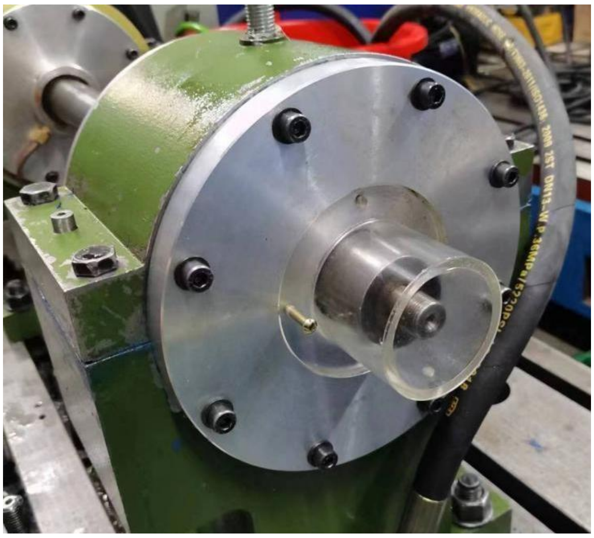

Figure 15 Right sealing end cover

After installing the upper and lower cover of the bearing, the brush seal test bench is built.

4.5 Leakage Test

We carried out a test using a test bench that has been built. The leakage test was performed on an 80.5 mm shaft, and a front baffle was set up for the brush seal in the test structure to enhance its sealing performance.

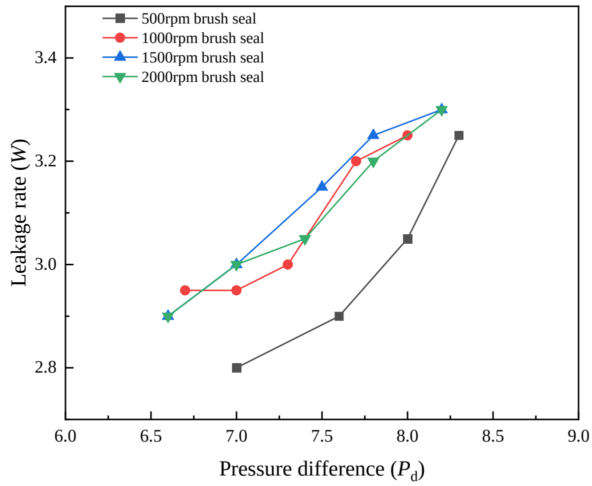

Figure 16 Diameter 80.5mm shaft brush seal with 84mm front baffle leakage test

In this test, the performance of the brush seal (with 84mm front baffle) mounted on a shaft with a diameter of 80.5mm at four rotational speeds was tested (500rpm, 1000rpm, 1500rpm. 2000rpm). and it can be clearly seen that as the pressure difference increases, the leakage amount also increases. However, with the increase of rotational speed, the increase of leakage is not obvious.

5 Conclusion

In this paper, we focus on the design of magnetic composite brush seal. The influence of front and rear plates and brush wires of different materials on the design is obtained by Maxwell simulation, which provides theoretical support for the subsequent design of magnetic composite brush seal. We try to use a new process for brush seal processing and manufacturing and strive to reduce manufacturing costs and manufacturing time. The brush seal manufacturing process of the wire suitable for magnetic composite brush seal was studied, and some results were obtained. In addition, we also designed and modified the original sealing test bench for this kind of brush seal. And the brush seal was tested on the test bench. In the future work, we will continue test the brush seal and compare it with the existing labyrinth seal.

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Conflict of interest statement

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work. There is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of the current manuscript.

References:

[1] C. Wolfe; R. Chiu; R. Cromer; G. Crum; P. Marks; A. Stuck; N. Turnquist; G. Reluzco; O. Dinc. Brush seals in industrial gas turbines.33rd Joint Propulsion Conference and Exhibit,1997

[2] QIN ZZ, Zhou P, Zhang B, et al. Simulation and experimental study on sealing performance of PEEK rotary seal ring. *Tribology* 2020; 40: 330-338.

[3] Andriy Zahorulko; Oleksandr Pozovnyi; Grzegorz Peczkis. Experimental and CFD analysis of static and dynamic rotor stabilities in three-annular seals[J].Tribology International,2023,Vol.185: 108566

[4] G. HOLLE;M. KRISHNAN. Gas turbine engine brush seal applications[J].26th Joint Propulsion Conference,1990,

[5] Baotong Chai. Study on dynamic characteristics of rotor-brush seal system of large steam turbine[D]. Southeast University,2015.

[6] Ilieva, G;Pirovsky, C.Labyrinth seals with application to turbomachinery.[J].Materialwissenschaft und Werkstoffechnik,2019, Vol.50(5): 479-491

[7] Lidong He. Xin Yuan. Xin Yin. Research progress of brush seal(in Chinese)[J]. Proceedings of the CSEE, 2001(12): 29-33+54.

[8] Harinadh Vemanaboina; Edison Gundabattini; Kaushik Kumar; Paolo Ferro and B Sridhar Babu. Thermal and Residual Stress Distributions in Inconel 625 Butt-Welded Plates: Simulation and Experimental Validation[J].Advances in Materials Science and Engineering,2021,Vol.2021(1): 1-12

[9] Alfons Gail; Stefan Beichl. MTU brush seal - Main features of an alternative design[A].35th Intersociety Energy Conversion Engineering Conference and Exhibit[C],2000

[10] Decai LI,Yanwen LI,Zixian LI,Yuming WANG.Theory analyses and applications of magnetic fluids in sealing[J]. Friction (Eng),2023,Vol11(10): 1771-1793

[11] Li, WY (Li, Wenyi); Zhang, ZL (Zhang, Zhili); Li, DC (Li, Decai). Rheological properties of silicon oil-based magnetic fluid with magnetic nanoparticles (MNPs)-multiwalled carbon nanotube (MWNT)[J].SMART MATERIALS AND STRUCTURES,2019,Vol.28(6): 065023

[12] Afifah, A.N.; Syahrullail, S.; Sidik, N.. Magnetoviscous effect and thermomagnetic convection of magnetic fluid: a review[J].Renewable & Sustainable Energy Reviews,2016,Vol.55: 1030-1040

[13] Yu, Wenjuan; Li, Decai; Zhang, Zhili. Magnetic Fluid Sealing Structure of Integrated Pole Shoe[J].Xinan Jiaotong Daxue Xuebao/Journal of Southwest Jiaotong University,2023,Vol.58(4): 940-946

[14] Jiawei Liu; Decai Li; Jingcheng Cai; Zhibin Wang; Sijia Liu. Advanced applications of magnet in magnetic fluid seal: a developers' perspective[J].Journal of Magnetism and Magnetic Materials,2023,Vol.579: 170814

[15] Li, Shicong; Li, Decai;Li, Shuangxi. The Influence of Shaft Eccentricity on the Magnetic Fluid Sealing Performance[J]. JOURNAL OF MAGNETICS,2023,Vol.28(2): 135-150

[16] Ha, Yunseok; Ha, Taewoong; Byun, Jaeseung; Lee, Yongbok .Leakage effects due to bristle deflection and wear in hybrid brush seal of high-pressure steam turbine[J].Tribology International,2020,Vol.150: 106325

[17] Yuan Wei; Xuhe Ran; Bin Xiong; Shulin Liu. Influence of brush seal hysteresis effect on the nonlinear characteristics of rotor system[J].Communications in Nonlinear Science and Numerical Simulation,2023,Vol.121: 107239

[18] Basu, P. Datta, A. Loewenthal, R. Short, J. Crand.Hysteresis and bristle stiffening effects in brush seals[J].Journal of Propulsion and Power,1994,Vol.10(4): 569-575

[19] Yiren Xu; Ting Ma; Lingcheng Kong; Juying Zhao; Yongjian Li. Wear and Leakage Behaviors of Brush Seal Considering Eccentricity and Radial Deformation[J].Energies,2023,Vol.16(3394): 3394

[20] ANSYS Simulation Innovation Engineer Certification Low Frequency (Elementary) Tutorial[M]. Xi 'an : Northwestern Polytechnical University Press,2019

[21] The Investigation of Nonuniform Demagnetizing Field in Magnetic Rectangular Element by Megnetostatic Theory[A].Ⅻ International Symposium on Small Particles and Inorganic Clusters[C],2004-09