

Leakage Calculation Method of Carbon Fiber Brush Seal Based on Porous Medium

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Title page

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ORIGINAL ARTICLE

Leakage calculation method of carbon fiber brush seal based on porous mediumYan-Chao Zhang¹ • Chun-Hua Du¹ • Rui Zhao¹ • Ya-Hui Cui¹

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Abstract: As a kind of flexible high-speed dynamic sealing device, brush seal has a good application prospect in high-speed dynamic sealing parts of major equipment, such as gas path of aircraft engines, rocket motors and gas turbines. However, the theoretical research and practical engineering application of brush seal are limited because there are some problems in the practical application. For example, the tip of bristle burned by friction heat under high speed, increased wear and the difficult calculation of leakage. To this end, the structure of the brush seal use the carbon fiber instead of the high-temperature alloy metal bristle. Then the carbon fiber brush volume equivalent diameter is used to establish the carbon fiber brush resistance calculation model based on the porous medium method, which construct the leakage calculation model of the carbon fiber brush seal. Finally, they are obtained by solution of the model in Fluent software that the leakage flow characteristics of the carbon fiber brush seal at work and the influence of different working conditions and structural parameters on the leakage performance. The results show that the carbon fiber calculation model has better adaptability, and the calculation results also show that the carbon

fiber brush seal has a lower leakage than the metal bristle under the same working condition. Moreover, the linear factors affecting the leakage of the carbon fiber brush seal are the height of the back plate and the diameter of the bristle, and the height of the front baffles has little effect, while the nonlinear factors are the thickness of brush and the angle of the bristle arrangement. The study provide an significant reference for high performance design of brush seal and its engineering applications.

Keywords: Carbon fiber • Brush seal • Porous medium • Leakage • Abrasion

1 Introduction

The labyrinth seal, which used to be the "standard" dynamic seal, has been widely used in various dynamic sealing applications due to its stable working performance, but because of its rely on the gap between the seal and the rotor flow resistance sealing effect, there are many disadvantages such as large axial dimension, high leakage, and rigid wear of the sealing pair when the rotor is jumping. In order to solve the problem of dynamic seal wear caused by rotor run out during high-speed operation, the researchers proposed a brush seal structure that relies on the flexible contact between the seal and the rotor to simultaneously reduce the leakage level and wear of the high-speed dynamic seal. Compared with the labyrinth seal, the leakage can be reduced by 20%-70% [1], so as to make up for the large leakage and rigid wear of the

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traditional labyrinth seal. Therefore, as early as 1955, GE proposed the idea of applying brush seals to aero-engines. In recent years, brush-type sealing technology has received extensive attention from scholars in the industry and has been rapidly developed and widely used in various types of turbine machinery. Brush seal has been widely used in aerospace engine, modern industrial gas turbine, water turbine generator and other fields as the ideal replacement of the traditional labyrinth seal. It has become one of the key technologies for the development of modern advanced turbine machinery and has a good application prospect [2-3].

But the traditional brush seal application in high speed and high temperature environment, usually using nickel base high temperature alloy or cobalt base high temperature alloy wire manufacturing, rely on the brush wire bundle of cross arrangement to achieve sealing, usually per square millimeter about 120 brush wire, brush wire diameter only 0.07mm or so. When the extremely fine brush wire is used in high-speed occasions, the temperature rise is too high under the action of local frictional heat, and the end of the brush wire is likely to overheat and burn off when the temperature fluctuates rapidly. On the one hand, the broken brush wire may become a hard abrasive particle between the matching pair, which may aggravate the wear of the matching pair. On the other hand, it may enter the lubrication system and cause wear failure of bearing and other transmission parts, resulting in limited application conditions and fields. In addition, the calculation of the leakage amount of the brush seal becomes complicated due to the presence of leakage between the bundles of the brush [4-5]. To this end, industry scholars have carried out a lot of research work around their structural design, performance simulation analysis, performance test, etc [6-8].

In order to study the brush seal performance, the theoretical models proposed mainly include the uniform staggered pipe model proposed by Kundsen, the semi-empirical effective thickness model proposed by Chupp [9] combined with experimental data, and the improved darcy porous medium model considering viscous resistance and inertial resistance proposed by Chew [10] In addition, Huang SQ et al [11] established a three-dimensional slicing model of brush seal and calculated the flow field and temperature field of brush seal, and studied the influence of brush wire number on the leakage amount. Sun Dan et al [12] applied two-way fluid-solid coupling and dynamic mesh technology to establish a two-dimensional fluid-solid coupling transient three-dimensional solution model of brush-type seal flow

field and mechanical properties considering brush filament deformation. At present, the porous media model is the most widely used in the study of brush seal leakage.

In China, Ding ST and Tao Z [13] were the first to treat the brush bundle as porous media, and Darcy's law was used to replace the momentum equation and conduct numerical simulation on the flow and heat transfer of brush seal. Cao GZ et al. [14] treated the brush bundle as porous media, and added the fluid resistance of the brush bundle as the source term to the governing equation. The flow resistance model of porous media for fluid leakage flow in the brush bundle area was established. The leakage flow characteristics of brush seals were numerically studied by calculating the resistance coefficient in the source term through the Ergun equation. The experimental data are used to modify the brush bundle thickness, and the modified model is consistent with the experimental results, which proves the rationality of the model. Bai HL, Wang W et al. [15] studied the leakage characteristics of the brush seal structure by taking the derivative of pressure versus space coordinates as the source term and fitting the experimental data to obtain the relationship between pressure change and drag coefficient. Dai W et al. [16] processed the brush wire bundle into a compact forked tube bundle, and used the resistance force to indicate the blocking effect of the brush filament on the fluid. The pressure, velocity and temperature field distribution of the brush seal area were obtained by numerical calculation.

A comprehensive analysis of the current research status of brush seal shows that the brush seal has a good application prospect, but the burn-point fracture and performance calculation of the brush wire are the hot spots of researchers. For this purpose, the research combined with excellent high temperature resistance and wear resistance properties of the carbon fiber, replaces the high temperature alloy metal brush wire with carbon fiber brush wire, designs the brush seal structure, and builds the calculation model of the leakage amount of carbon fiber brush wire based on the characteristics of porous media. Exploring the influence of structural parameters and working conditions on sealing performance mechanism, and providing reference for the structure and performance design of carbon fiber brush seals.

2 Carbon fiber brush seal structure features

The brush seal is composed of a brush ring and a rotor track paired there with [17]. The brush ring is composed of a front and rear baffle and a flexible brush body

sandwiched between the two, and the structure thereof is as shown in FIG. 1. The front baffle is located on the high pressure side of the airflow to prevent the brush wire from being directly disturbed by the incoming flow. The back baffle is located on the low pressure side of the airflow to support the brush bundle body, and the brush sealed brush bundle body is closely arranged by the filaments. The front and rear baffles and the brush body are integrally connected by welding or other processes, and are assembled on the rotor during assembly.

The brush bundle body of carbon fiber brush seal is made of carbon fiber filaments. Carbon fiber filaments is wrapped around core wire using clamping tube, and is fastened by upper casing and lower casing. The structure is shown in FIG. 2.

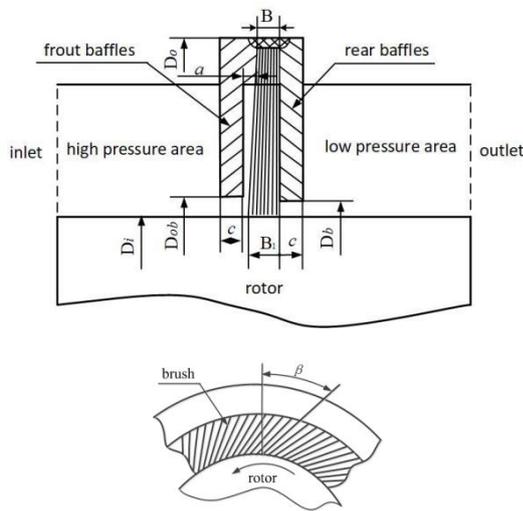


Figure 1 Brush seal structure

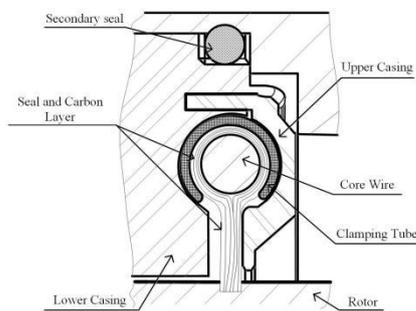


Figure 2 Carbon fiber brush seal structure

During the brush seal operation, the sealing medium leaks through the front baffle body to the downstream sealing cavity via the upstream high pressure side, and the leakage channel is mainly composed of two parts [11]. Part of the leakage is caused by the contact gap between

the brush tow and the rotor, which is further aggravated by the hysteresis caused by the friction block between the brush tow and the front and rear baffles. The other part is the leakage through the gap between the filament bundles. The leakage flow in this part is very complicated, including the flow of the sealing medium to the low pressure side through the gap between the filaments, the flow of the sealing medium to the low pressure side through the gaps between the wire and the rear baffle after the sealing medium passes through the brush bundle area, and the circumferential flow of the sealing medium caused by the gap turbulence. Brush seal is to use the complex flow principle of leakage to achieve the sealing, when the sealing medium flows through the area of the brush bundle, the uneven gap generated by the arrangement between the filaments can cause a flow retardation effect on the leaking fluid. As the fluid flows through the brushing region, it encounters tightly arranged brush filaments and turns the original flow into transverse flow, a portion of which bypasses the filament flow to the next filament bundle and a portion that flows circumferentially. It is also because the tightly arranged brush tows disrupt the original flow of the fluid, causing the pore flow to create a self-sealing effect, thereby reducing leakage and ensuring a sealing effect.

Studies have shown that the brush wire diameter of the brush seal has a great influence on the leakage performance, and the smaller the wire diameter, the lower the leakage amount [14]. However, due to the influence of the burning tip and the broken hair defect, the metal brush wire is difficult to be made too fine in practical engineering applications, and after using carbon fiber brush wire instead of metal wire, wire brush for 5 ~ 10 microns in diameter, which is relative to the diameter of the metal wire reduced the one order of magnitude, and because the carbon fiber brush wire diameter is very small, the number of rows of the carbon fiber brush wire will increase and the density of the brush wire will increase when the same thickness of the brush bundle is used, thereby effectively reducing the gap between the filaments. Therefore, in theory, the leakage amount of the carbon fiber brush seal is greatly reduced with respect to the metal brush seal.

3 Numerical calculation model of carbon fiber brush seal

The numerical calculation method of brush seal includes selecting calculation domain, mesh division, brushing zone processing, boundary condition setting, etc.

In this paper, Gambit software is used to build the model and divide the grid. The treatment of the brushing zone is based on the method of porous media, and the control equation of the leakage flow of the carbon fiber brush seal is established by adding the resistance of the filament to the fluid as a source term in the momentum equation. The resistance in the momentum equation was calculated by the Ergun equation, and the obtained resistance coefficient was used as the condition of the brush bundle area [18]. When fluent was used to set the porous media area, the resistance in the brush bundle area was set.

3.1 Physical models and computational domains

Figure 1 shows the physical model of carbon fiber brush sealing structure established in this paper according to relevant experimental device parameters. The structural parameters are as table 1. There is a zero clearance fit between the rotor and the brush seal.

Table 1 Dimensions of the brush seal

Dimensions and symbol	metal brush seal	Carbon fiber brush seal
Inner diameter of brush ring D_{ib} (mm)	104	104
height diameter of brush wire D_o (mm)	122	122
Front baffle inner diameter D_{ob} (mm)	106.5	106.5
Backsplash inner diameter D_b (mm)	106	106
Brush bundle thickness B (mm)	1.2	1.2
Brush bundle thickness B_1 (mm)	1.8	1.8
Front and rear baffle thickness c (mm)	1.27	1.27
Gap between front baffle and brush bundle a (mm)	0.76	0.76
brush wire arrangement Angle β	50	50
Diameter of carbon fiber d (mm)	0.07	0.007

In this paper, a two-dimensional axisymmetric model is used to calculate the leakage of the brush seal. The calculation domain is composed of the upstream high pressure area, the area between the front baffle and the brush bundle, the porous media area composed of the brush bundle and the protection height area of the front and rear baffle, etc., as shown in the blue wire frame area

in figure 1.

3.2 Porous media model

(1) Control equation

In the numerical calculation process, the brush bundle region of the brush seal is composed of a large number of fine brush filaments, and its flow is similar to that in the porous medium, so the calculation is performed using a porous medium model. Areas other than the brush bundle are treated using traditional CFD techniques. Among them, the flow calculation in the brush bundle region uses the steady-state continuous equation and the momentum conservation equation, as follows:

Equation of state

$$p = \rho RT \quad (1)$$

Continuous equation

$$\nabla \cdot (\rho \varepsilon \dot{V}) = 0 \quad (2)$$

Momentum conservation equation

$$\rho (\dot{V} \cdot \nabla) \dot{V} = -\nabla p + \mu \nabla^2 \dot{V} + S_v + S_i \quad (3)$$

where: ρ is the fluid density; p is the pressure; R is the ideal gas constant; T is the thermodynamic temperature constant; ε_a is the surface porosity; μ is the viscosity coefficient of the fluid; S_v is the sum of the other terms except the viscosity term; S_i is the momentum source term.

(2) Viscous drag coefficient and inertial drag coefficient

In the momentum conservation governing equation, the momentum source term S_i includes the viscous resistance term and the inertia resistance term caused by the porous medium, as shown in equation (4), where $1/\alpha$ is the viscous drag coefficient and C_2 is the inertia drag coefficient. According to literature14, the calculation formula of the two coefficients is shown in equation (5), where D_p is the equivalent diameter.

$$S_i = - \left(\frac{\mu}{\alpha} \cdot \dot{V} + \frac{1}{2} C_2 \rho |\dot{V}| \dot{V} \right) \quad (4)$$

$$\begin{cases} C_2 = \frac{3.5(1-\varepsilon_a)}{D_p \cdot \varepsilon_a^3} \\ \frac{1}{\alpha} = \frac{150(1-\varepsilon_a)^2}{D_p^2 \cdot \varepsilon_a^3} \end{cases} \quad (5)$$

where $1/\alpha$ is the viscosity loss coefficient, C_2 is the internal loss coefficient, ε_a is the surface porosity; D_p is the equivalent diameter.

(3) Determination of parameters

To calculate the viscous and inertial resistance in a porous media model, the porosity and equivalent diameter of the porous media need to be determined first. The surface porosity in the axial, radial and circumferential planes of the porous medium in the brush bundle region is calculated by the formulas (6) to (8). In formulas (6) to (8), the surface porosity of the porous medium considers radial displacement of rotor surface caused by change of rotor speed. The thickness B of the brush bundle is determined by the method in literature 14. In the calculation of porosity of porous media, the change of porosity with radial position is considered. The angle β_r varies with the radial position. The larger the diameter of the brush wire in the bundle area is, the greater the angle β_r is, and the greater the porosity is. β_r and β_0 satisfy the relationship of the formula (9).

$$\varepsilon_{ax} = 1 - \frac{nd^2 \cdot (r_{ob} - r_{ib})}{4[r_{ob}^2 - (r_{ib} + \delta)^2]B \cos \beta} \quad (6)$$

$$\varepsilon_{ar} = 1 - \frac{d^2 n}{8rB \cos \beta_r} \quad (7)$$

$$\varepsilon_{a\theta} = 1 - \frac{nd^2 \cdot (r_{ob} - r_{ib})}{4[r_{ob}^2 - (r_{ib} + \delta)^2]B \cos \beta} \quad (8)$$

Where ε_{ax} is axial surface porosity, ε_{ar} is radial surface porosity, $\varepsilon_{a\theta}$ is circumferential surface porosity, d is brush wire diameter, n is number of brush wire, r_{ob} is radius of brush seal outer diameter, r_{ib} is radius of brush seal inner diameter, δ is radial displacement of the rotor surface, B is thickness of brush bundle, β_r is brush wire arrangement angle at radius, D is any other brush seal diameter, D_i is brush seal inner diameter, β_0 is brush wire arrangement angle at brush seal inner diameter.

The diameter of the carbon fiber is 0.007mm, and its length is much larger than the diameter. Therefore, the volume equivalent diameter of the carbon fiber is used to

calculate the resistance coefficient in this paper by using the Ergun equation [19]. The calculation formula is shown in equation (9) :

$$d_p = \left(\frac{6V_p}{\pi} \right)^{1/3} \quad (9)$$

where V_p is the equivalent volume.

3.3 Meshing and boundary conditions

Figure 3 is a grid diagram of the numerical calculation model in this paper. The density of computational model grid varies with different positions. In the axial position, the density of brush bundle area and back splash protection height area is the largest, followed by the density of upstream and downstream area. In the radial position, the grid near the rotor wall is encrypted. After the independence verification, the total amount of grid is about 60,000.

The boundary condition of the exit is the pressure outlet, the pressure is one atmosphere; the inlet boundary condition is the pressure inlet, and the pressure is determined according to the pressure difference and the outlet pressure. The pressure difference studied in this paper is 0.1MPa, 0.2MPa, 0.3MPa, 0.4MPa, 0.5MPa, 0.6MPa. The rotor surface is arranged as a non-slip rotating wall surface relative to the adjacent grid region. The solid wall boundary is set to adiabatic and non-slip solid wall.

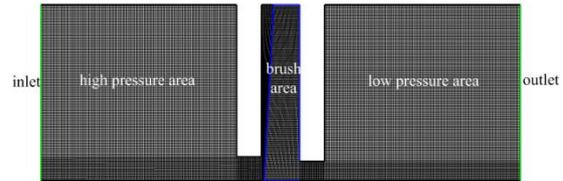


Figure 3 Grid diagram of brush seal calculation model

3.4 Experimental verification of porous media model

(1) Test rig and experimental procedure

To obtain the leakage characteristics of brush seal in this article, a self-developed dynamic sealing test rig was used to carry out the leakage characteristics tests of brush seal. The construction of the test rig and test unit is shown in Fig. 4.

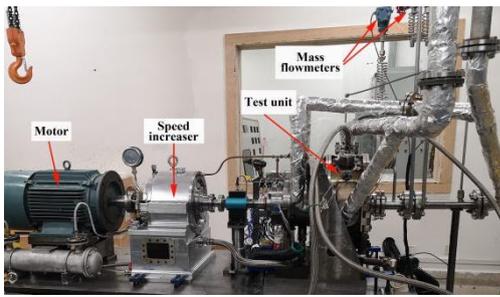


Figure 4 Test rig for brush seal

The test rig is driven by a three-phase asynchronous motor with a rated speed of 5,000rpm. The motor is connected with the rotor of the test unit with couplings and a speed increaser, which allows a highest rotation speed of the brush seal test unit of 40,000rpm. A vortex gas compressor supplies high-pressure gas for the experiments, and the pressure of the gas can be adjusted through a pressure regulating valve. In order to eliminate the influence of the oil mist in the shaft bearing cavity, which may leak the lubricant in the leaking gas, on the leakage measurement results, the tester adopts a double-layer design. The low-pressure cavity air hole is opened at the bottom of the inner layer of the tester and, at the same time, a vent hole is set in the middle of the outer shell of the tester and the external flow meter is measured. In the experiments, the high-pressure gas flows into the high-pressure chamber of the test unit, leaks into two adjacent low-pressure chambers through two brush seals, and exhausts through two vents at the bottom. The vents are connected to two mass flow meters, which measure the leakage rates of the two brush seals.

As mentioned above, the leakage rates of the two test brush seals are measured by two mass flow meters connected with the two vents at the bottom of the test unit. To minimize the measurement error caused by manufacture and assembly, the average of the two measuring results are defined as the final result of each test. In the experiments, leakage tests were carried out at three pressure differentials (0.1, 0.2 and 0.3MPa). First, static leakage tests (the rotor is not rotating) were carried out at each pressure differential. Dynamic tests (the rotor is rotating at various speeds) were performed after the static leakage tests. In the dynamic tests, the rotation speed was increased as follows: 0, 10,000, 20,000, 30,000, and 38,000 rpm and then was decreased to zero.

(2) Experimental verification

The experimental data obtained by the experiment above were used to modify the parameters of the porous media model established for calculating leakage of metal brush seal in this paper. And The experimental data also

were used to verify the rationality and calculation accuracy of the porous media model. Figure 5 is comparison of numerical calculation results and experimental data of leakage of metal brush seal varying with rotor speed under different pressure differences. The numerical results are in good agreement with the experimental results in the figure 5. The maximum error between numerical calculation results and experimental data is 10.6%. Therefore, the porous media model used for the calculating leakage of metal brush seal in this paper is reasonable and reliable. It is also feasible to use the porous media model to calculate leakage of carbon fiber brush seal.

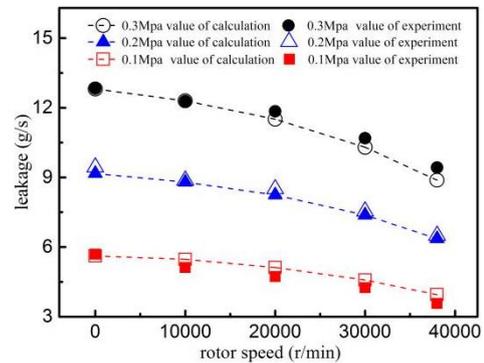


Figure 5 Leakage of metal brush seal along with speed change under different pressure difference.

(3) Verification of porous media model using in calculating leakage of carbon fiber brush seal

There are generally four arrangement mode of the brush wires in the brush bundle. They are loose arrangement, tightly aligned arrangement, tightly crossed arrangement and transitional arrangement respectively. The pressure difference changes thickness of brush bundle and clearance between brush wires by changing the arrangement of brush wires, and then changes the leakage characteristics of brush seal. In the leakage calculation of brush seal, the influence of pressure difference on brush bundle thickness and porosity of porous media model should be considered. As diameter of carbon fiber brush wire is very small, the clearance between the brush wires is also small. Thus, the influence of pressure difference on thickness of brush bundle and clearance between brush wires is also very small.

Figure 6 is the variation of brush seal leakage with pressure difference under different arrangement modes. In Figure 6, the variation trend of leakage with pressure difference is the same in different arrangement of brush wires. But under the same pressure difference, the leakage of brush seal is different with different arrangement of brush wires. The leakage is the minimum when brush seal

wires are tightly crossed arrangement. The leakage is the maximum when brush seal wires are tightly aligned arrangement. The calculation results using the brush bundle thickness determined by the method of determining thickness of metal brush seal are located between them. Table 2 is the error of calculation results under the three arrangement mode. In the table, δ_0 is the error between calculation result based on the tightly crossed arrangement and tightly aligned arrangement, and its maximum value is 27.73%. δ_1 is the error between calculation result based on the tightly crossed arrangement and corrected thickness of brush bundle, and its maximum value is 15.01%. δ_2 is the error between calculation result based on corrected thickness of brush bundle and tightly aligned arrangement, and its maximum value is 14.96%.

Under the action of pressure difference, arrangement of brush wires is generally a transitional arrangement. The leakage of brush seal with transitional arrangement is between the leakage of brush seal with tightly crossed arrangement and tightly aligned arrangement. Therefore, the error between actual leakage and calculation result based on corrected thickness of brush bundle doesn't beyond δ_1 and δ_2 . Thus, the error between actual leakage and the calculated results of carbon fiber brush seal base on corrected thickness of brush bundle is 15.01% at most. Although the maximum error between the numerical calculation results and actual results is 15.01%, the calculation results do not affect qualitative analysis results of leakage characteristics of carbon fiber brush seal in the following part, and have no influence on the conclusion of this paper. The calculation method of leakage of carbon fiber brush seal in this paper can greatly improve calculation accuracy after being modified by the test of carbon fiber brush seal. The calculated results can predict leakage characteristics of carbon fiber brush seal more accurately.

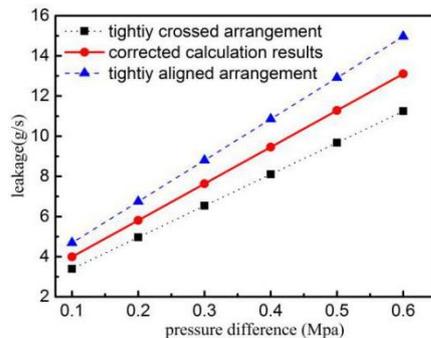


Figure 6 Variation of brush seal leakage with pressure difference under different arrangement modes

Table 2 Error of calculation results under the three

Pressure difference (MPa)	arrangement mode					
	0.1	0.2	0.3	0.4	0.5	0.6
δ_0 (%)	27.73	26.46	25.79	25.37	25.08	24.88
δ_1 (%)	15.01	13.87	13.26	12.88	12.63	12.44
δ_2 (%)	14.96	14.62	14.44	14.33	14.26	14.21

4 Result analysis

In this paper, a porous media model for numerical calculation of carbon fiber brush seal leakage characteristics is constructed, and experiments show that the model has good adaptability in numerical calculation of carbon fiber brush seal leakage characteristics. Finally, the effects of structural parameters and working conditions on leakage characteristics are studied.

4.1 Leakage flow characteristics of carbon fiber brush seals

(1) Leakage flow characteristics under different pressure differences

Figure 7 is the velocity field obtained by numerical calculation of the carbon fiber brush seal with the upstream and downstream pressure difference of 0.1MPa, 0.2MPa and 0.3MPa. The figure shows that the inlet flow is uniform and the flow gradually goes to the lower half of the brush bundle. After reaching the protection height of the front baffle, the fluid velocity increases due to the inflow flow channel shrinkage; However, the flow rate of the fluid is sharply reduced due to the existence of brush wire resistance when passing through the brush and continues to deflect in the backward-baffle protection height. Table 3 shows the maximum flow velocity and the average flow velocity at the outlet of the carbon fiber brush seal velocity field under different pressure differences. By comparing the results in figure 7 and table 3, it can be seen that the flow velocity increases with the increase of the pressure difference. Analyze the main reason is that with the increase of upstream and downstream pressure difference, the pressure gradient in the porous medium region increases, so that the fluid flow rate increases.

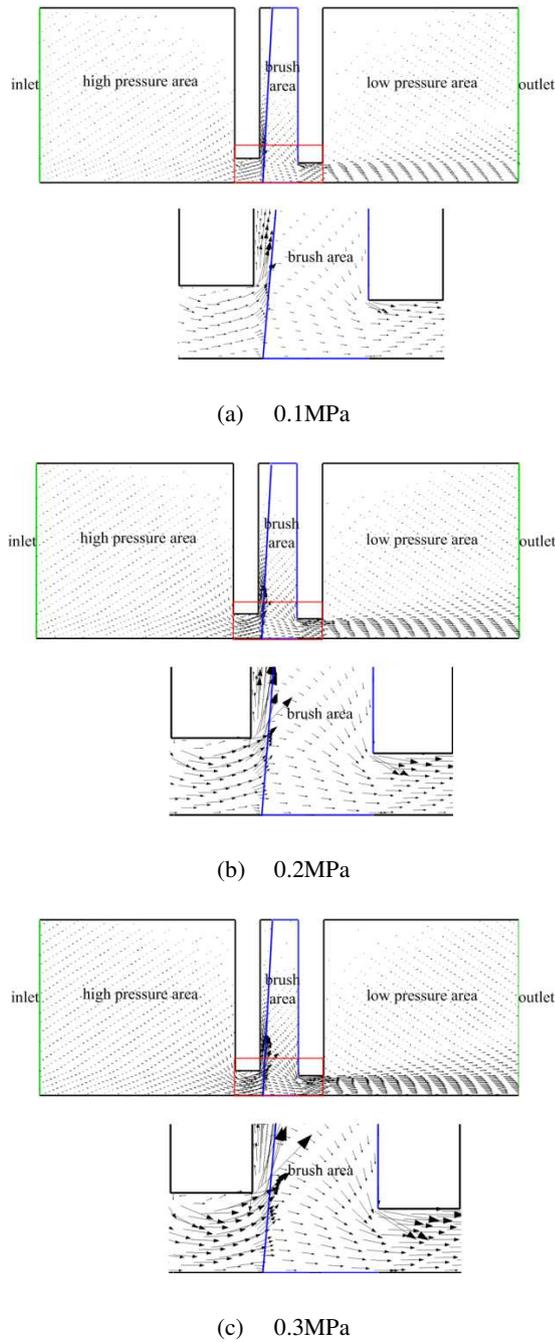


Figure 7 Carbon fiber brush seal speed field under different pressure difference.

Table 3 Reflow speed and maximum flow rate of carbon fiber brush seal speed field under different pressure difference.

Pressure difference (MPa)	0.1	0.2	0.3
Maximum flow rate (m/s)	24.32	43.32	60.78
Average outlet velocity (m/s)	1.07	1.92	2.72

Figure 8 is the pressure field obtained by numerical

calculation of the carbon fiber brush seal with the upstream and downstream pressure difference of 0.1MPa, 0.2MPa and 0.3MPa.

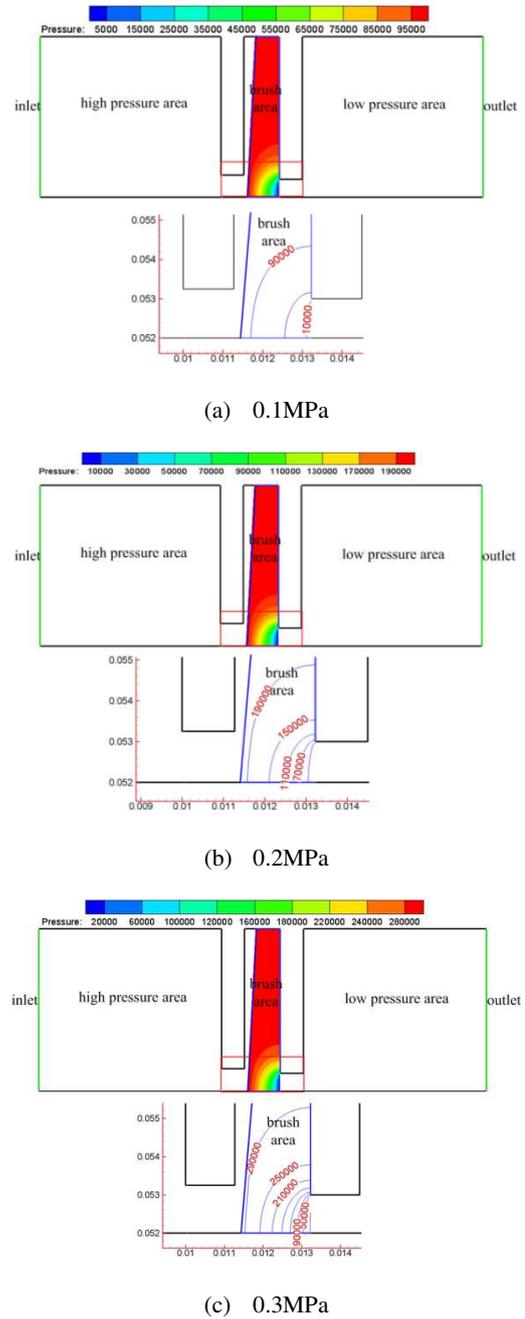


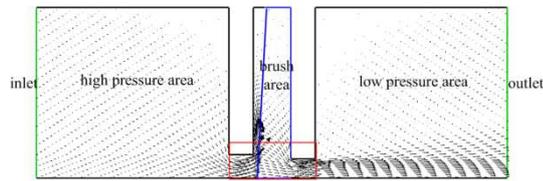
Figure 8 Pressure distribution of carbon fiber brush seal under different pressure difference.

The figure 8 shows that the pressure drop of the carbon fiber brush seal structure leakage flow mainly occurs in the area where the brush bundle is close to the rotor surface, which is the area where the fluid leaks. The pressure gradient in the first half of the axial brush bundle is small, while that in the second half is large. In the radial

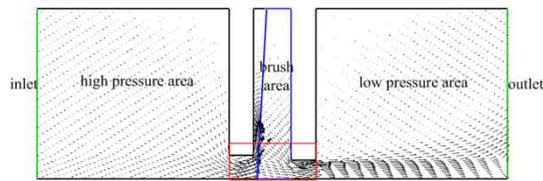
direction, the pressure in the brush bundle area increases along the radial direction. By comparing the pressure distribution of carbon fiber brush seals under different pressure differences, it can be concluded that the pressure gradient in the porous media region increases with the increase of the pressure difference in both axial and radial directions.

(2) Leakage flow characteristics at different speeds

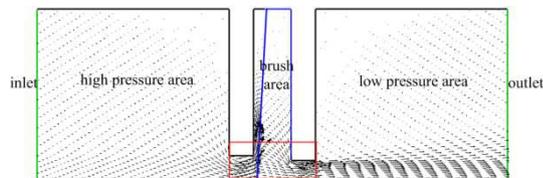
Figure 9 and Table 4 show the velocity field, the maximum flow velocity and the average flow velocity of the fluid obtained by numerical calculation of the carbon fiber brush seal when the rotor speed is 10000r/min, 20000r/min, and 30000r/min.



(a) 10000r/min



(b) 20000r/min



(c) 30000r/min

Figure 9 Carbon fiber brush seal speed field at different rotational speeds.

The results in figure 9 and table 4 show that the flow velocity of the fluid in the porous media region hardly changes with the increase of rotor speed. However, as the rotational speed increases, the average flow velocity of the fluid at the outlet decreases. The main reason is that: the rotor speed increases, the porosity of the porous medium model is changeless, and the flow of the porous medium area mainly influenced by porosity, therefore the rotor speed increases, the fluid flow in porous media area with little change; When the rotation speed increases, under the action of viscous force, the rotor will drive the fluid in the downstream low-pressure area to move with the rotor, increase the disturbance of the fluid in the low-pressure area, and make its backflow more obvious, and the backflow speed increases, so that the average velocity at the outlet decreases. Although the increase of rotation speed causes the change of the fluid in the brush bundle area in the circumferential motion, the change is very small under the action of the brush bundle resistance and does not cause the change of the flow field distribution in the brush bundle area.

Table 4 Reflow speed and maximum flow rate of carbon fiber brush seal speed field at different rotating speeds

rotating speeds (r/min)	10000	20000	30000
Maximum flow velocity (m/s)	60.78	60.96	61.36
Average flow rate of exit (m/s)	2.72	2.71	2.33

Figure 10 shows the pressure field obtained by numerical calculation of carbon fiber brush seal when the rotor speed is set at 10000r/min, 20000r/min and 30000r/min. The results in the figure show that as the rotor speed increases, the pressure gradient of the fluid in the brushing zone does not change significantly. The reasons are as follows: the increase of rotor speed does not change the porosity of the porous media model in the brush bundle area, and the resistance of the brush bundle to the axial flow of the fluid remains unchanged. Therefore, the pressure gradient of the fluid in the brush bundle will not change under the same pressure difference.

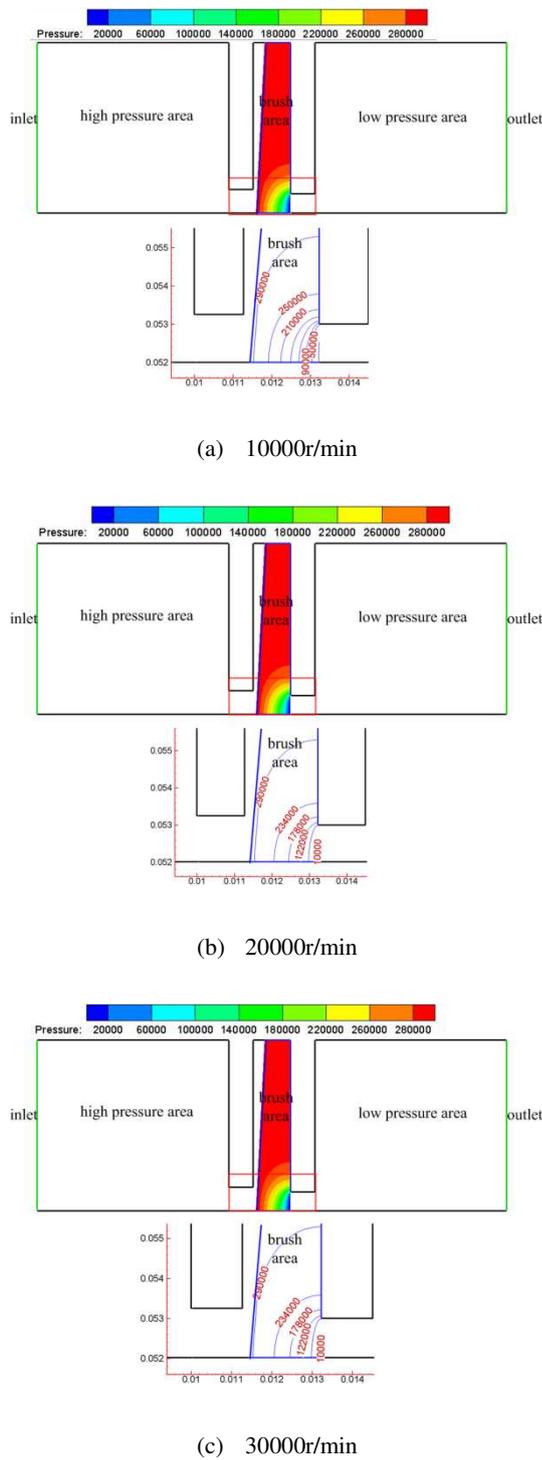


Figure 10 Pressure distribution of carbon fiber brush seals at different speeds

4.2 Comparison of leakage characteristics between carbon fiber and metal brush wire brush type seal

In this paper, the numerical calculation is carried out with a metal brush seal with the same carbon fiber brush

seal structure parameters (except for the wire diameter) and the working condition parameters, and compared with the carbon fiber brush seal leakage characteristics. Figure 11 compares the numerical calculation results of the leakage characteristics of carbon fiber and metal brush seal: under the same working condition, the leakage amount of carbon fiber brush seal is smaller than that of metal brush seal, with better sealing performance. The main reasons are as follows: compared with the diameter of carbon fiber brush type sealing brush wire, the metal brush type sealing brush wire is larger. According to the contact characteristics of the brush filament, the gap between the brush wire is also larger, so that the resistance of the fluid flowing through the brush bundle is smaller. Therefore, the maximum velocity and reflux velocity of the fluid in the metal brush wire sealing velocity field are larger, the leakage amount is larger, and the sealing effect is poor. Table 5 shows the maximum flow velocity and the average exit velocity of the metal brush seal speed field under different pressure differences, compared with the carbon fiber brush seal in table 3, the maximum flow velocity and the export average flow velocity of the metal brush seal velocity field are higher than those of the carbon fiber brush, also further validates the carbon fiber brush seal is better than metal brush seal sealing effect.

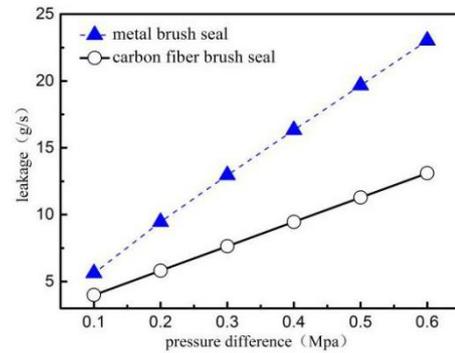


Figure 11 Comparison of numerical calculation results between carbon fiber and metal brush seal

Table 5 reflux velocity and maximum velocity of metal brush seal velocity field under different pressure differences

Pressure difference (MPa)	0.1	0.2	0.3
Maximum flow rate (m/s)	35.65	59.24	80.04
Average outlet velocity (m/s)	1.60	2.69	3.68

4.3 Effect of working conditions and structural parameters on leakage characteristics

In this paper, the porous media model is used to calculate the leakage characteristics of carbon fiber brush seals, and the influence of structural parameters such as the length of brush wire, the arrangement angle of brush wire, the inner diameter of brush ring, the protection height of front baffle and the protection height of rear baffle on the leakage characteristics was studied [20]. The influence of operating parameters such as differential pressure and rotor speed on leakage characteristics is also studied. In order to study the influence rule and sensitivity of working condition and structural parameters on the leakage characteristics of brush seal more conveniently, this paper first dimensionless each parameter. Formula (10) is the calculation formula of dimensionless parameter C , where V_{\max} , V_{\min} and V respectively represent the maximum value, minimum value and calculated value of each parameter.

$$C = \frac{V - V_{\min}}{V_{\max} - V_{\min}} \quad (10)$$

Figure 12 shows the influence of dimensionless structural parameters on the leakage characteristics of carbon fiber brush seals after. The figure shows that the leakage amount of the brush seal increases linearly with the increase of the inner diameter of the brush ring and the protection height of the rear baffle. The slope in the figure shows the influence of structural parameters on the leakage, and the increase of leakage caused by the increase of the inner diameter of the brush ring is the most obvious, followed by the height of the rear baffle protection. In the range of structural parameters studied, the protection height of front baffle has no effect on the leakage of the brush seal. The influence of the length of the brush wire on the leakage is nonlinear, and the increase rate of leakage will be flat with the increase of the length of the brush wire. In addition, the trend shown in Figure 9 that the leakage increases with the increase of the brush wire arrangement angle is also non-linear. At the brush wire arrangement angle of 10° to 20° , the leakage of the carbon fiber brush seal changes very little. With the increase of brush wire arrangement angle, The increasing trend of leakage has increased dramatically. To sum up, the influence of structural parameters on carbon fiber brush seal is in order: the height of the front baffle, the length of the brush wire, the height of the rear baffle, and the inner diameter of the brush ring. Therefore, the structure parameters of carbon fiber brush seal can be optimized to improve its sealing performance.

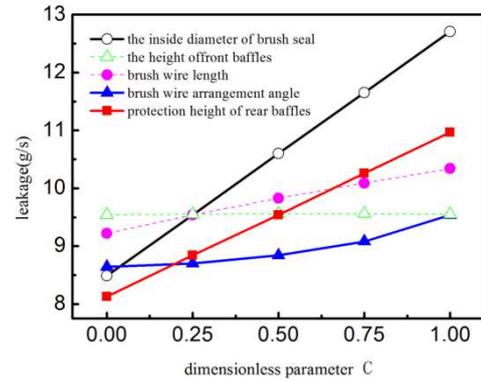


Figure 12 Effect of structural parameters on the leakage characteristics of brush seals.

Figure 13 shows the variation of leakage rate with rotational speed when carbon fiber brush seal only considers the conditions of rotor deformation. The picture shows that with the increase in speed, the leakage volume has decreased. The reason is that when the speed increases, the rotor expands and deforms, causing the porosity of the brush beam area and the fluid flow at the end of the brush wire to be affected, thus reducing the leakage.

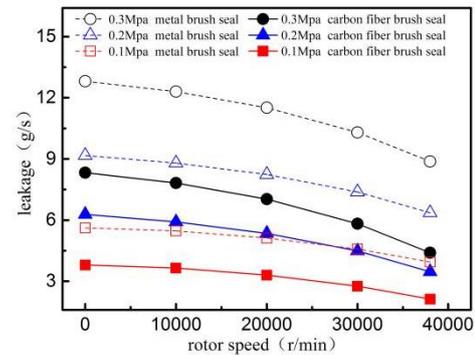


Figure 13 The variation of leakage amount with rotation speed under different pressure difference of carbon fiber brush seal.

5 Conclusion

(1) The leakage of carbon fiber brush seal mainly occurs in the lower part of the brush beam, and its pressure drop mainly occurs in the brush beam near the rotor portion. Within the front and back baffle protection heights, the flow rate of the fluid increases dramatically due to the narrowing of the channel. In addition, in the brush beam area, the flow rate of the fluid decreases dramatically due to the resistance of the brush beam..

(2) Under the same working conditions, the leakage of carbon fiber brush seal is greatly reduced compared with

that of metal wire brush seal, and the smaller the pressure difference, the more significant the improvement of sealing performance.

(3) Under certain pressure difference in the upstream and downstream, the leakage increased linearly with the increase of the protection height of the inner diameter and rear baffle of the brush ring, and showed nonlinear characteristics with the increase of the length of the brush wire and the arrangement angle of the brush wire.

6 Declaration

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Availability of data and materials

The datasets supporting the conclusions of this article are included within the article.

Competing interests

The authors declare no competing financial interests.

Consent for publication

Not applicable

Ethics approval and consent to participate

Not applicable

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Figure 2

Carbon fiber brush seal structure

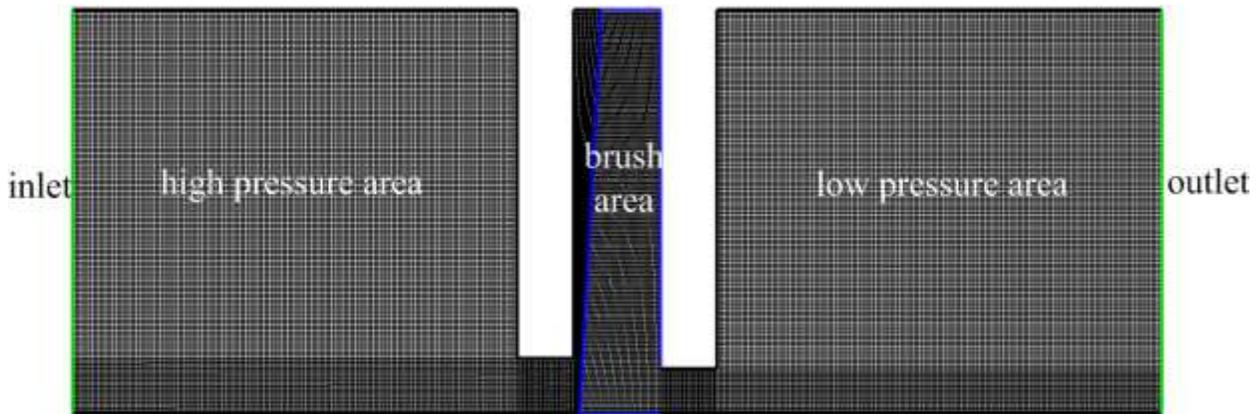


Figure 3

Grid diagram of brush seal calculation model

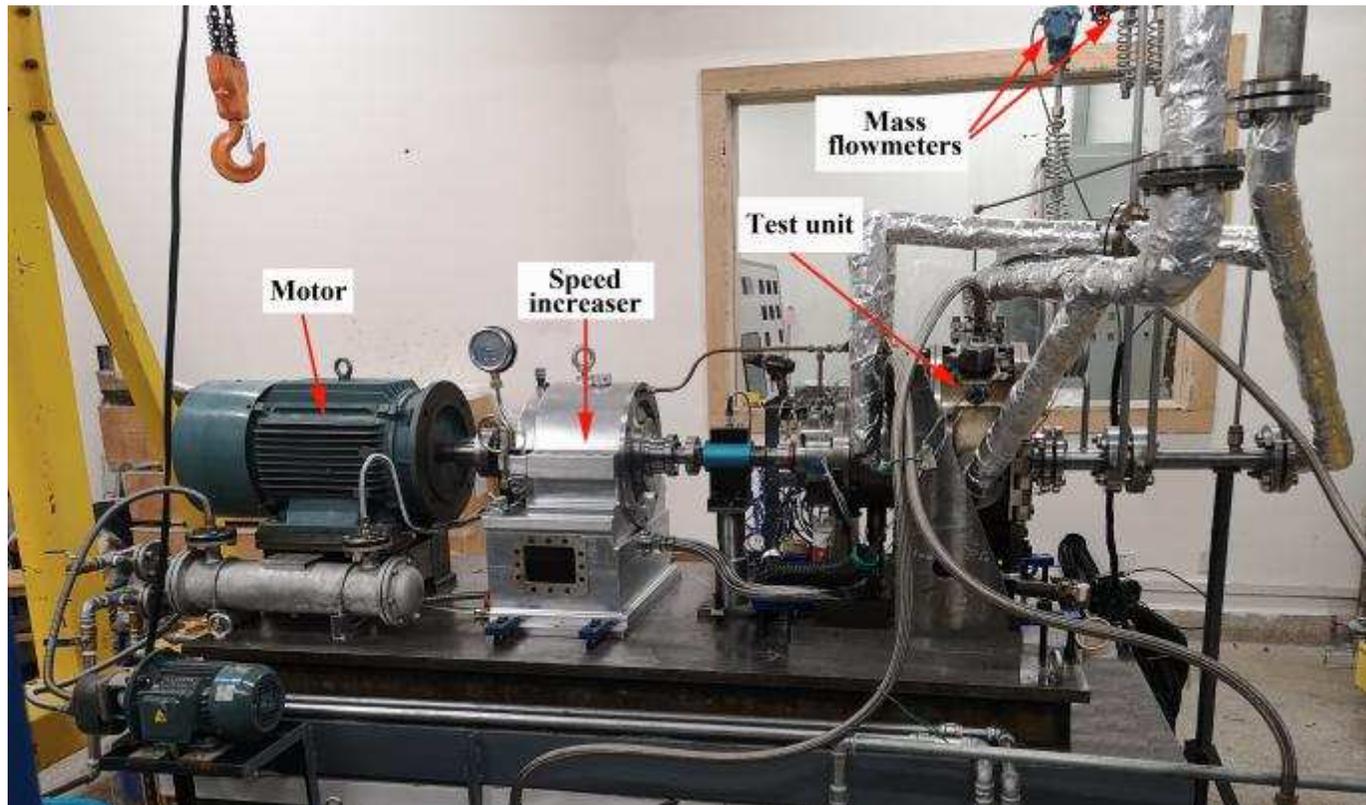


Figure 4

Test rig for brush seal

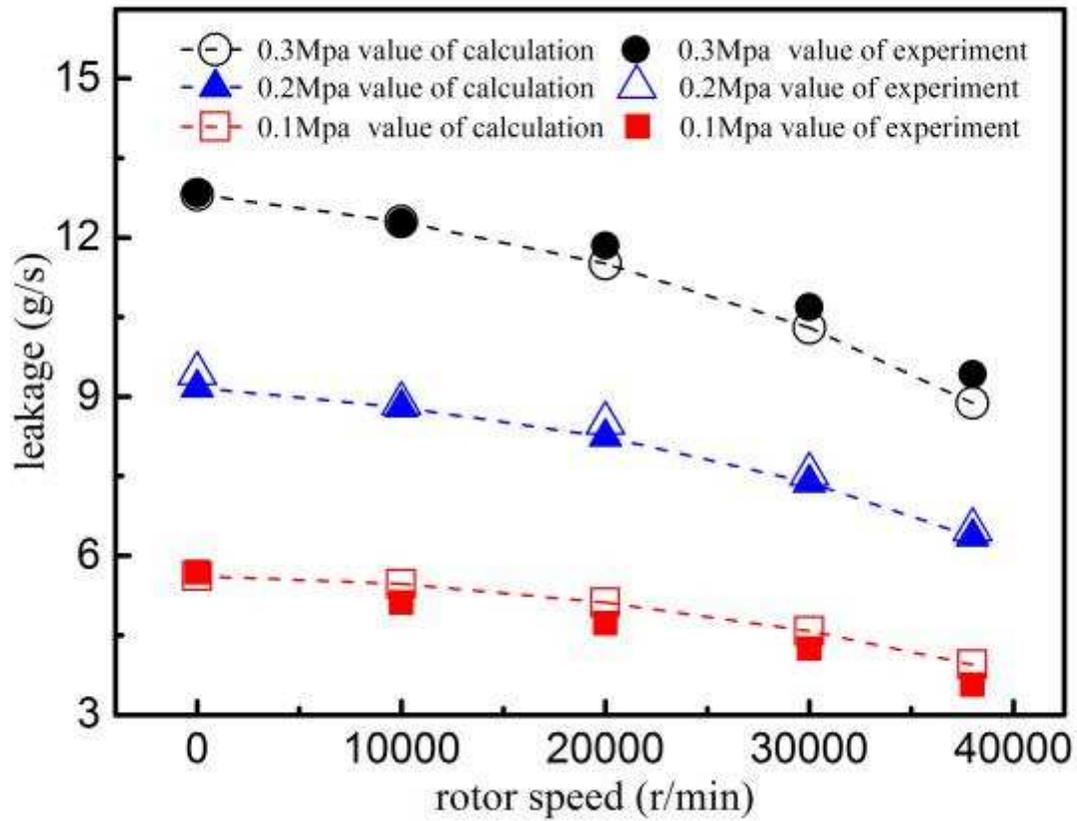


Figure 5

Leakage of metal brush seal along with speed change under different pressure difference.

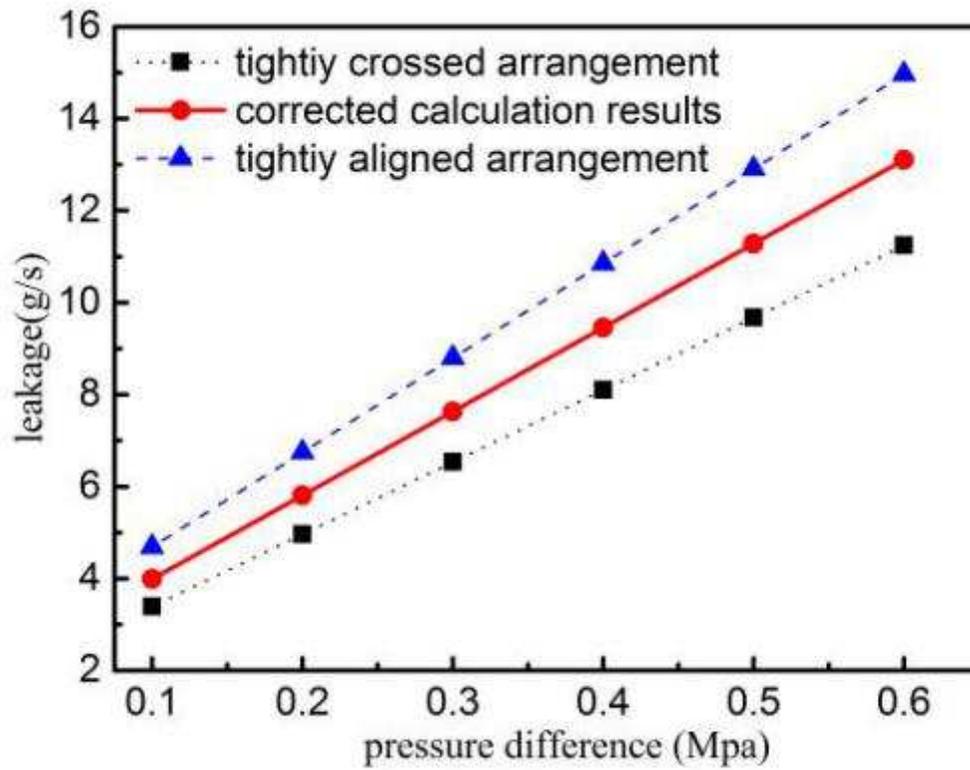
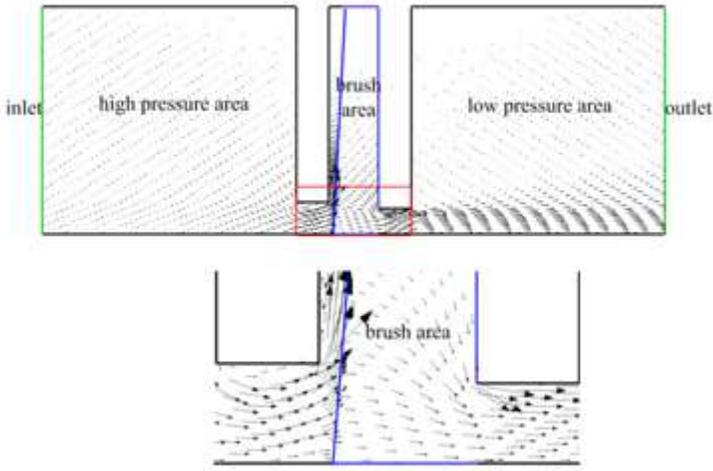


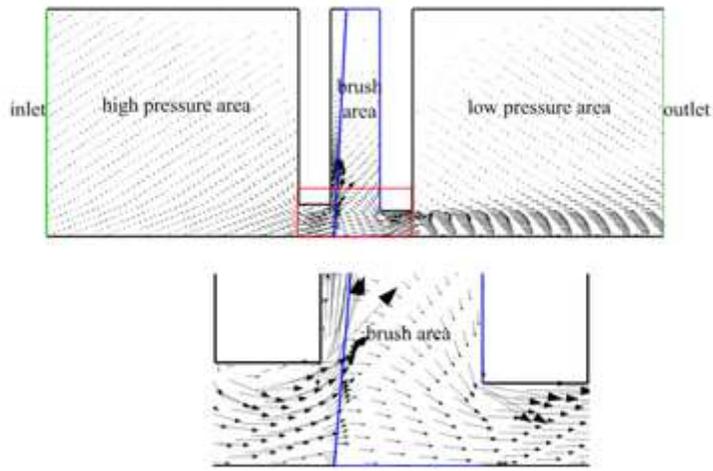
Figure 6

Variation of brush seal leakage with pressure difference under different arrangement modes

(a) 0.1MPa



(b) 0.2MPa



(c) 0.3MPa

Figure 7

Carbon fiber brush seal speed field under different pressure difference.

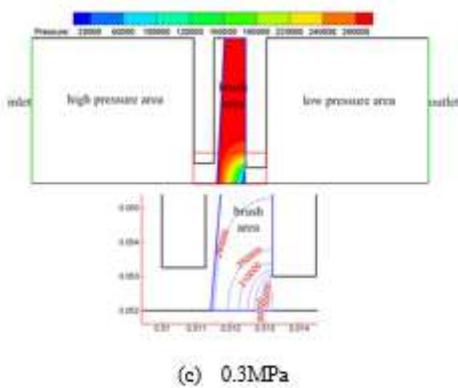
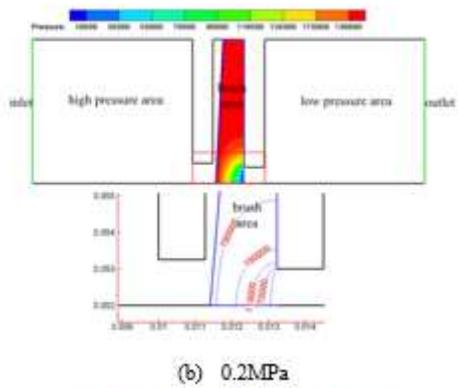
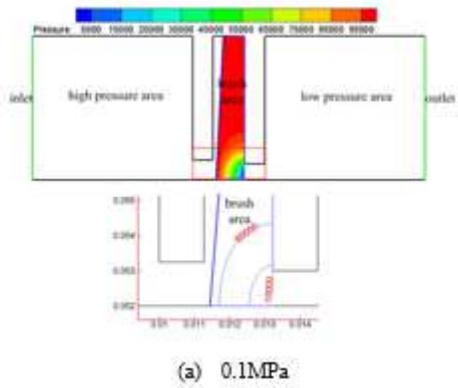
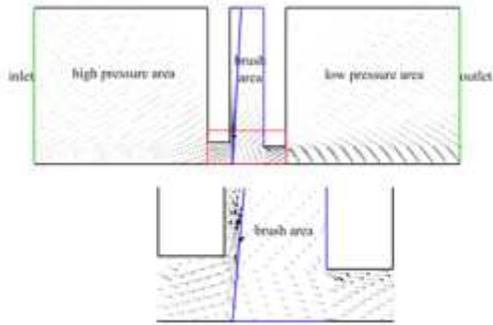
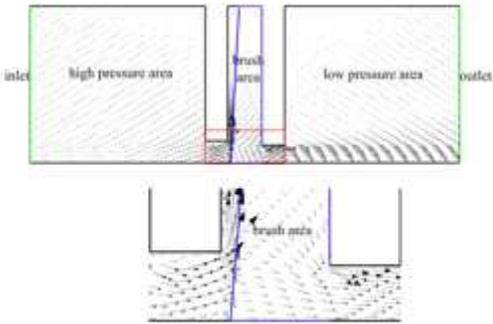


Figure 8

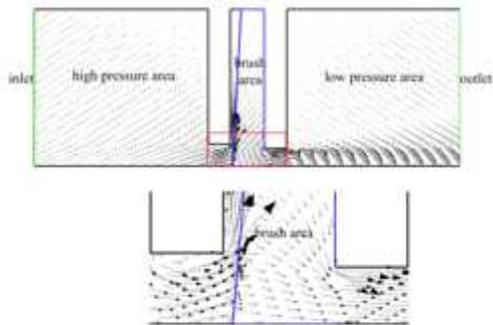
Pressure distribution of carbon fiber brush seal under different pressure difference.



(a) 0.1MPa



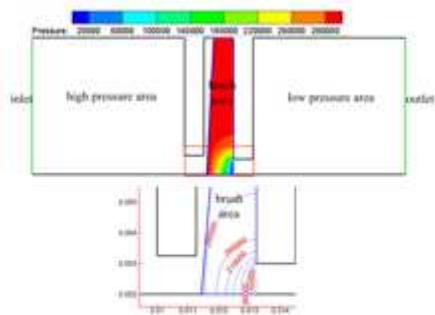
(b) 0.2MPa



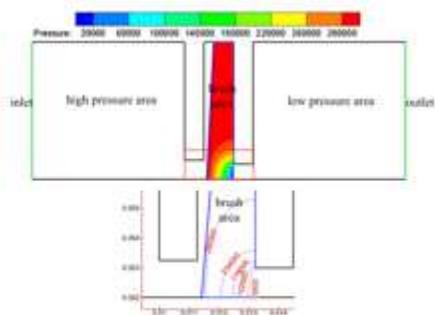
(c) 0.3MPa

Figure 9

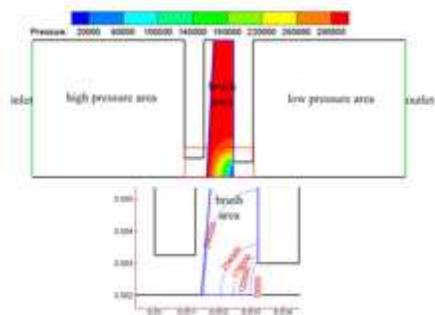
Carbon fiber brush seal speed field at different rotational speeds.



(a) 10000r/min



(b) 20000r/min



(c) 30000r/min

Figure 10

Pressure distribution of carbon fiber brush seals at different speeds

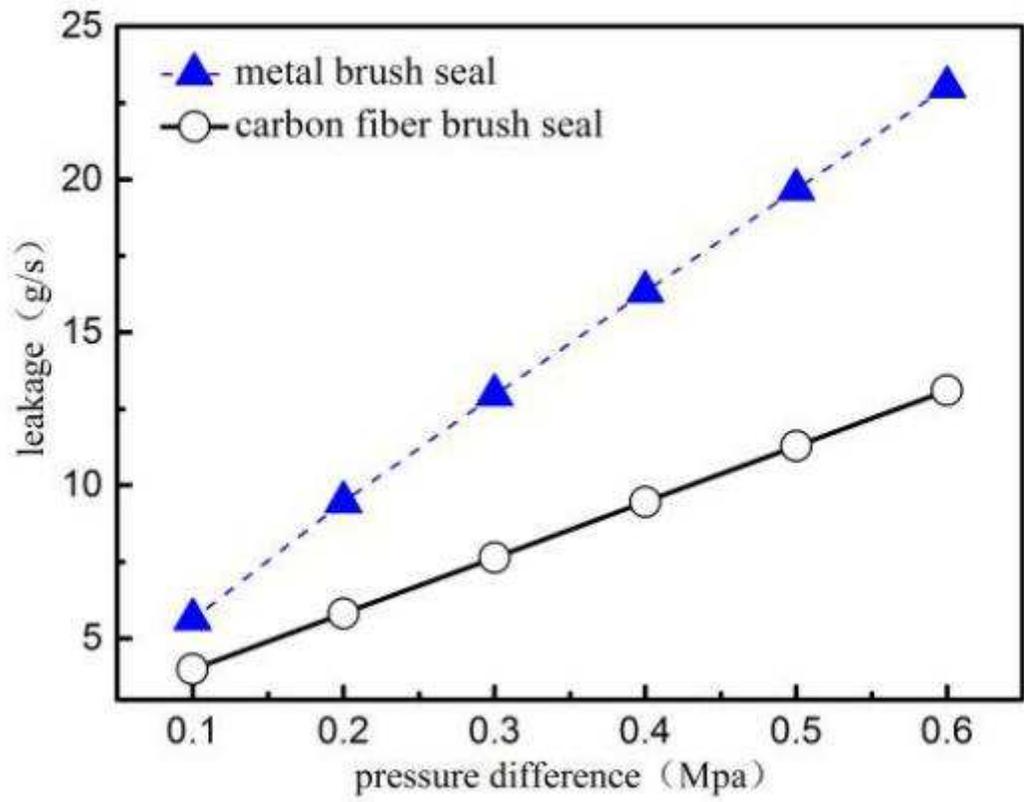


Figure 11

Comparison of numerical calculation results between carbon fiber and metal brush seal

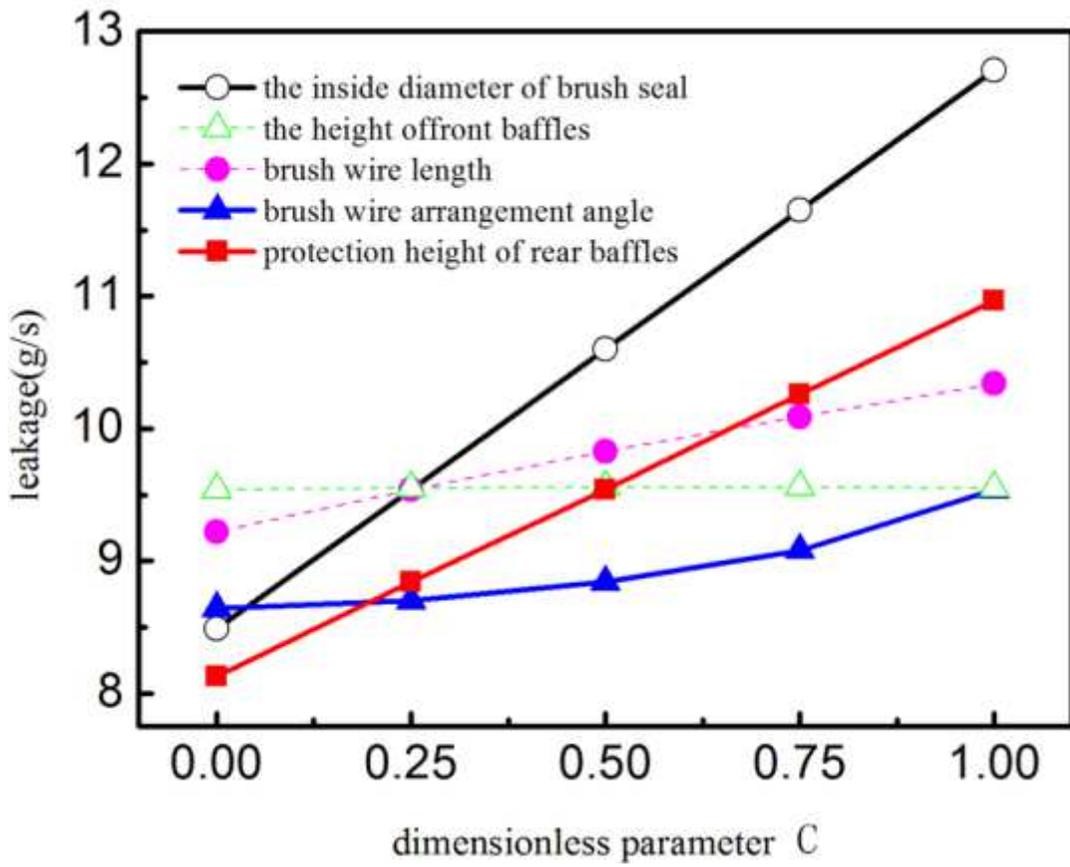


Figure 12

Effect of structural parameters on the leakage characteristics of brush seals.

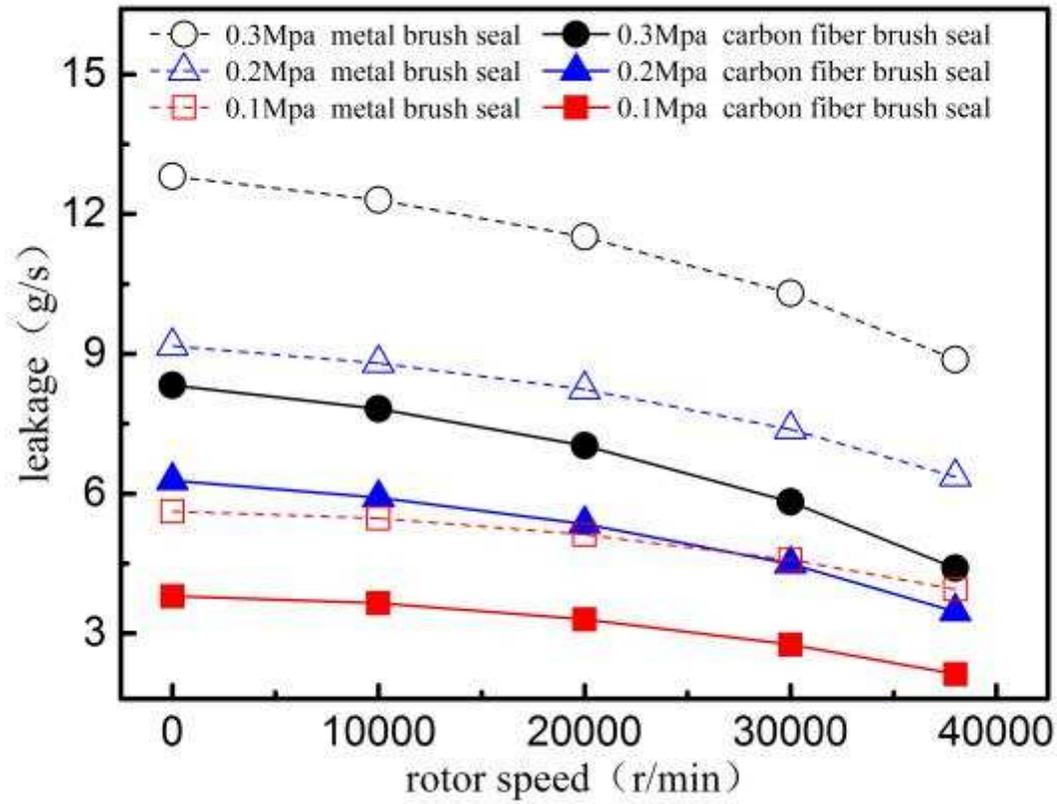


Figure 13

The variation of leakage amount with rotation speed under different pressure difference of carbon fiber brush seal.