Calibration of porous medium models for brush seals

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Abstract: One of the theoretical approaches to modelling brush seals is based on the porous medium models. In this approach, influence of the brush on the flow is defined by a set of resistance coefficients. Although these coefficients can be estimated, the brush seal model needs to be calibrated against the measurements. This work analyses calibration procedures with respect to extrapolation of the theoretical results on different brush seals and operating conditions. Two sealing configurations and two bristle packs are studied experimentally and theoretically. Computational fluid dynamics predictions and measurements of leakage, axial pressure, and brush clearance are presented. The efficiency of calibration procedures is also discussed.

Keywords: leakage, porosity, bristle pack, computational fluid dynamics

1 INTRODUCTION

Originally proposed for aircraft engine applications [**1**, **2**], brush seals are one of the innovative dynamic sealing concepts that have great potential as alternatives to the conventional labyrinth seals in steam turbines. Figure 1 shows a brush seal that consists of fine metallic or ceramic bristles closely packed between front and backing plates. Bristles are inclined to circumferential direction at a lay angle of 45°. Brush seal designs differ in bristle pack properties (material, diameter and length of bristles, packing density, and pack thickness) and geometry of front and backing plates. They can be designed as contact seals with zero or negative radial clearance and with a small cold clearance. Generally, brush seals provide significantly better leakage performance compared with labyrinths. Compliant bristle pack can compensate for radial clearance variation during transient, operating, and off-design conditions with controllable wear by eliminating immediate damage. Primary concerns when using brush seals can be costs of fabrication, uncontrollable wear, heat generation because of friction between a rotor and bristles, and rotordynamic performance. Moreover, other factors should be considered during the design process [**3**] due to complex aerodynamical and mechanical interaction of the bristle pack with stator and rotor.

Computational fluid dynamics (CFD) techniques have been used for brush seal modelling in many studies. Braun and Kudriavtsev [**4**] solved the two-dimensional Navier–Stokes equations for pin arrays representing an idealized brush seal in order to gain an understanding of the local characteristics of the flow. Later, more comprehensive models have been developed, in which the mechanical behaviour of bristles was taken into account [**5**]. Such an approach combines detailed CFD simulation resolving flow structure through the bristles with finite-element analysis to determine bristle deformations due to aerodynamic forces. The whole iteration procedure is computationally very expensive, which allows only a small number of bristles to be considered during simulations.

A simple and widely used approach to the brush seal flow calculation is based on the porous medium models. In this approach, a bristle pack is treated as an anisotropic continuous porous region with defined resistance to the flow. These models depend greatly on heuristic information and require adjustment (calibration) to improve correlation with the measurements quantitatively. More detailed description and a brief overview of the porous medium models are presented in the corresponding section.

In this article, experimental results on leakage, axial pressure, and radial clearance are presented for four combinations of brush and labyrinth seals. Theoretical

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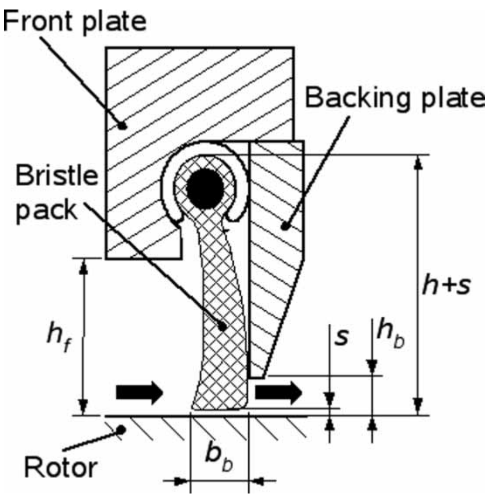

Fig. 1 Brush seal

results on sensitivity of calibration procedures based on variation of bristle pack thickness and brush clearance are discussed. The results can be used to develop a more general calibration procedure that requires less experimental data and is more accurate for diverse bristle packs.

2 EXPERIMENTAL INVESTIGATION

Experimental investigations on brush seals have been carried out on the static test rig at the Institute of Energy Systems, Technische Universität München, Germany (Fig. 2). The Jeffcott rotor has a diameter of 179.98 mm and its shaft is supported by two ball bearings at its ends. A variable-speed direct-current motor drives the test rotor up to 12 000 r/min. A compressor supplies air to the test rig at the maximum inflow pressure of 1.0 MPa. Compressed air is injected at the centre of the assembly into the swirl vane to generate an inlet preswirl nearly independent of the inflow pressure. The preswirl value can be set between 80 and 300 m/s. The air divided into two flows passes axially through the twin test sealing configurations. The detailed description of the test rig could be found in references [**6**] and [**7**].

The sealing configuration has a modular structure and is assembled from a series of interchangeable rings. Figure 3 presents a cross-section of the typical seal used in this study. A sealing ring refers to either brush seal or labyrinth seal. According to the notion used in this work, the seal shown in Fig. 3 is referred to as a BSS seal – a brush seal set upstream of two labyrinth teeth. Four sealing configurations are studied: two different seal designs with two different bristle packs. The two designs are brush seal at the upstream followed by two sealing teeth (Fig. 3) and brush seal placed downstream of two sealing teeth (SSB). Each sealing configuration is tested with two different bristle packs, B2 and B3, with metallic (cobalt-based alloy) bristles. The bristle packs differ in bristle diameter and packing density. All configurations tested are summarized in Table 1. The bristle pack B2 consists of a larger amount of finer bristles compared with B3. Another feature of the tested brush seals is a front plate design. Brush seals usually have a massive front plate that protects the

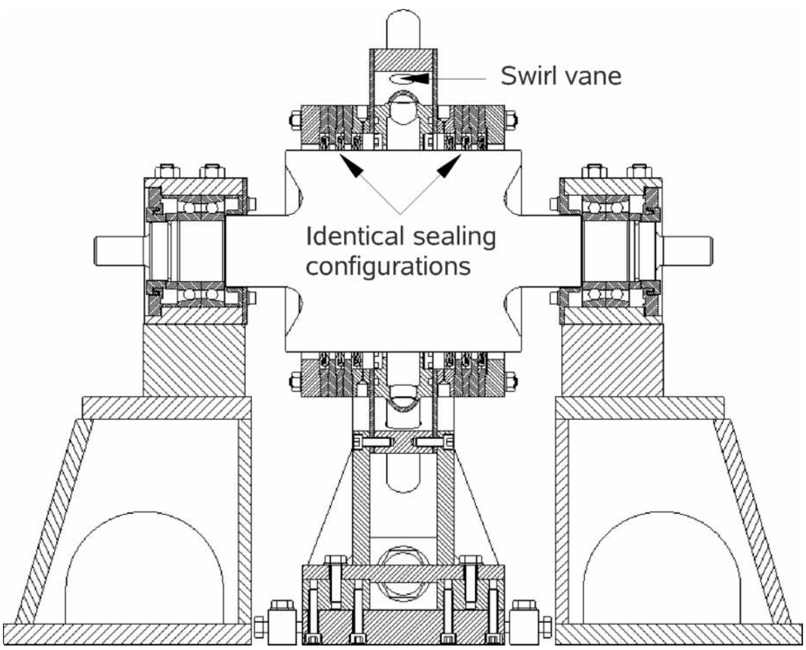

Fig. 2 Test rig

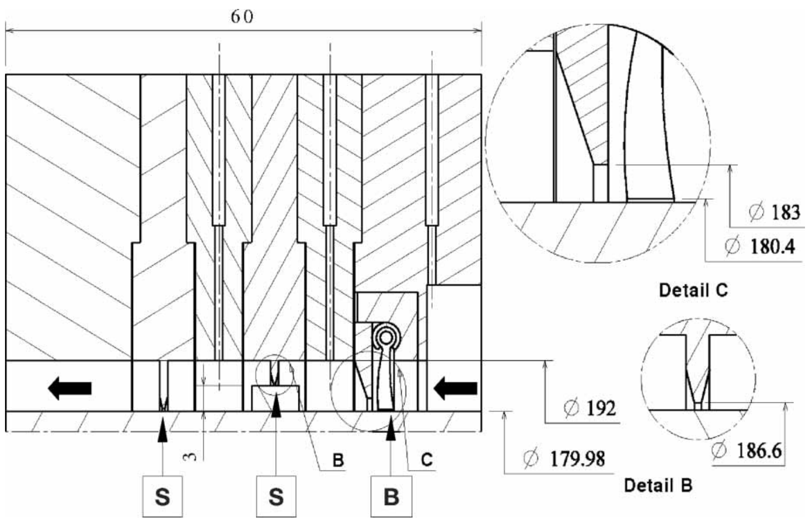

Fig. 3 BSS sealing configuration

Table 1 Tested sealing configurations

	BSS B2	SSB B2	BSS B3	SSB B3
N (bristles/mm)	200		50	
d (mm)	0.07		0.15	
b_{b} (mm)	1.98			

bristle pack from the upstream. Brush seals considered in this work have practically no front plate (Fig. 1).

A combination of labyrinth and brush seals provides some advantages. The brush seal offers better leakage performance and requires less space than the labyrinth seal. The leakage through brush seals is considerably less than that through conventional labyrinth seals. In real applications, brush seals are often built into existing labyrinth seals replacing one or several seal teeth, as in the case of the test seals presented in this work. The labyrinth seals in turn are low-cost sealing elements and could be used to control the magnitude of pressure drop across the brush.

Static air pressure is measured in all chambers of the sealing configuration. Pressure values in chambers were averaged over ten measurement positions across the circumference. The leakage through the left and right sealing configurations is calculated from the total leakage in the test rig. Inlet pressure takes values from 0.1 to 1.0 MPa. Separate measurements have been carried out to estimate the magnitudes of radial clearance in the brush seals at different pressure differentials. The brush radial clearance was determined from the optical measurements in the SSB configuration on a digital camera at the zero rotor speed. A simple image processing provides an estimation of radial clearance with the root mean square deviation of 10 per cent of cold clearance value of 0.21 mm. Tooth clearance is 0.31 mm. More detailed description of the optical measurements could be found in reference [**6**].

3 CFD MODELLING OF BRUSH SEALS

3.1 Porous medium model

A porous medium approach is considered in this work to model the bristle pack. This approach allows avoiding full resolving of individual bristles. It makes the whole CFD model of the seal simpler. The bristle pack of the brush seal is treated as a porous structure. The basic characteristic of the porous medium is porosity ε – the ratio of the volume of voids to the total volume (voids and solids). For the bundle of cylinders, porosity is represented as

$$\varepsilon = 1 - \frac{\pi d^2 N}{4 b_{\mathrm{b}} \cos\varphi} \tag{1}$$

In this formula, there is only one parameter that may greatly depend on operating mode. This parameter is the bristle pack thickness b_{b} and it depends on the pressure drop across the seal due to the compliant nature of the bristle pack. The porosity of the tested brush seals for the initial bristle pack thickness (manufacture's value) is 0.42 and 0.34 for brushes B2 and B3, respectively. The theoretical closest packing of bristles may be estimated from the geometrical considerations [**8**]

$$b_{\mathrm{b}}^{\min} = d + \frac{\sqrt{3}d}{2}\left(\frac{dN}{\cos\varphi} - 1\right) \tag{2}$$

Minimum values of b_{b} for B2 and B3 are equal to 1.21 and 1.40 mm with porosities of 0.1 and 0.11, respectively. However, as several theoretical studies have shown [**8**, **9**], the bristle pack thickness does not reach

Table 2 Minimal pack thickness and porosity of investigated bristle packs

	B2	B3
Minimal pack thickness (mm)	1.21	1.40
Porosity (–)	0.10–0.42	0.11–0.34

its theoretical minimum value even at high pressure differentials. Porosity ranges of the bristle packs are summarized in Table 2. The bristle pack B3 is less compliant than B2. For the same pack thickness, B3 is less porous compared with B2.

Porous medium models describe the relation between pressure gradient and velocity for the fluid flow through the porous structure. At low Reynolds numbers where viscous resistance is dominant, this pressure drop depends linearly on the flow velocity (Darcy's law). To eliminate deviations at high velocities, Darcy's law was extended taking into account a quadratic term that represents an inertial contribution to the momentum balance [**10**].

Bristle packs of brush seals have strong anisotropic structure. The flow resistance is obviously smaller in the direction along the bristle (streamwise direction s) than in the directions normal to the bristles (axial z and circumferential n directions). Thus, the porous medium equation in terms of linear and quadratic resistance for the three anisotropic directions (n, z, and s) in the bristle pack can be represented as

$$-\frac{\partial p}{\partial x_i} = a_i \mu v_i + b_i \rho |v_i| v_i \tag{3}$$

Considering the three directions in the bristle pack, the resistance equation is determined by three viscous or linear resistance coefficients a and three inertial or quadratic coefficients b. If an isotropic, one-dimensional porous medium model is considered, there are only two unknown resistance coefficients. In this case, one can directly calibrate these coefficients based on two operating points [**11**]. Otherwise, additional models for the resistance coefficients are required.

In the case of isotropic structure, the viscous resistance a may be obtained from the semi-empirical Carman–Kozeny theory for solid matrices [**10**]. Ergun [**12**] extended this theory and constructed an empirical correlation for the non-Darcy coefficient b for packed beds on the basis of large amount of experimental data.

The model by Ergun was adopted by several authors for the brush seal applications and modified to account for anisotropy and match experimental observations. Chew *et al.* [**13**, **14**] have modified viscous and inertial resistance in the streamwise direction; a_s is reduced by an empirical factor and b_s is set to zero. Recently, Pröstler [**8**] has proposed another factor for a_s by introducing a non-linear relation between viscous resistances in different directions

$$a_n = a_z = 80C, \quad a_s = 32\varepsilon C, \quad C = \frac{(1-\varepsilon)^2}{\varepsilon^3 d^2}$$
$$b_n = b_z = 1.16D, \quad b_s = 0, \quad D = \frac{1-\varepsilon}{\varepsilon^3 d} \tag{4}$$

The coefficients defined in equation (4) are used in this study. A comparison of the models of Ergun *et al.* applied to brush seals has shown that the leakage predictions with equation (4) lie between values obtained with the model by Ergun and modification by Chew [**15**]. The resistance coefficients are larger in the modification by Pröstler compared with Chew's expressions at the same bristle pack thickness, i.e. the medium is less porous.

3.2 Calibration procedure

As mentioned earlier, porous medium models are based on empirical information. Sources of uncertainty during operation are bristle pack thickness and radial clearance between bristle pack and rotor (the latter only in the case of non-zero cold clearance). Therefore, theoretical model for a particular brush seal needs to be calibrated. Calibration means that the seal operating characteristics (leakage and/or pressure drop) should be adjusted to experimental data for one or more operational points (inlet pressures), i.e. the greatest lack of available porous medium models. However, fortunately, the calibration only at one pressure drop could be sufficient to provide reasonable predictions of leakage performance.

The porous medium model in equation (4) for a particular bristle pack is fully determined by its bristle pack thickness; there is only one unknown variable during the operation. Variation of the lay angle can be neglected. Thus, the natural way to calibrate the model is to vary b_b between its initial cold value and theoretical closest packing from equation (2). In this case, one keeps the leakage through the clearance constant and affects the leakage through the bristle pack. Brush seals operating with non-zero radial clearance could also be calibrated by varying s. Brush radial clearance is constrained by the cold and zero clearance. One of the aims of this work is to compare these two possibilities and to show which procedure is preferable.

The calibration procedure could be also based on variation of both parameters (pack thickness and radial clearance). Further complications of calibration procedures are also possible, e.g. by dividing the bristle pack into a number of regions with different coefficients [**16**, **17**].

Generally, results of calibration are resistance coefficients of porous medium model and/or brush clearance. These results are used later to calculate brush seal performance for the whole operating range.

Bristle pack thickness variation is used as a primary calibration procedure in this work. Calibration of the theoretical model is carried out for four sealing configurations at a single pressure differential from the middle of the operating range. During calibration, the value of the bristle pack thickness is changed proportionally to the weighted value of leakage. A realistic value of brush radial clearance is estimated from the optical measurements (discussed subsequently).

3.3 CFD modelling

Numerical calculations are performed by using ANSYS CFX 11. A three-dimensional hexahedral grid with one cell in the circumferential direction that represents a 0.2° slice is generated in ANSYS ICEM CFD 11. Total pressure and temperature are set on the inlet boundary and static pressure on the outlet boundary. Periodic boundary conditions are applied on the slice faces. The rotor surface is modelled as a rotating wall and the porosity region as a subdomain with defined momentum losses. The dimensions of the porosity region are not defined strictly by geometry primitives during the mesh generation, but they are defined by algebraic expressions in the preprocessing of the CFD analysis. Two functions are introduced into the model: one for the brush radial clearance and the other for the bristle pack axial thickness. The function returns 1 for a particular node if the node lies within the porosity region, otherwise it returns 0. According to the value, the momentum loss model is either switched on or off. The nodes with the function value 1 represent the porous medium region. The algebraic definition of the bristle pack allows the automation of the calibration process and parametric studies (e.g. clearance and thickness variation in the brush seal), because the computational grid has to be generated only once. A disadvantage of such approach is that the grid in the bristle region must be extremely fine to capture possible changes in the dimensions of the porous medium, which in turn slows down convergence of calculations.

4 RESULTS AND DISCUSSION

To obtain better predictions with the theoretical model, the experimental data for brush radial clearance are used for calibration. The clearance values have been estimated from the optical measurements at different pressure drops in SSB sealing configuration. Figure 4 shows the optical measurement results at pressurizing and depressurizing conditions. The pressure drop shown on the horizontal axis corresponds to the whole sealing assembly. Both bristle packs observe similar behaviour with the distinction that the blow-down effect is not as strong for B3 as it is for B2. This is due to the higher stiffness and, therefore, smaller radial

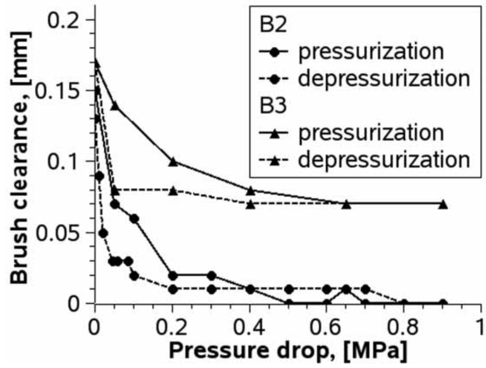

Fig. 4 Measured rotor brush clearance versus pressure drop for SSB

bending of bristles in B3. The bristle pack B2 reaches a zero clearance with increasing pressure, whereas the minimum clearance of B3 is ~40 per cent of its cold clearance. The near constant radial clearance is settled already by relatively moderate pressure differentials (0.2 MPa for B2 and 0.4 MPa for B3). It means that the thickness of the bristle pack could play an important role in leakage control.

Experimental results also show a hysteresis effect, which is a typical characteristic of brush seals and could have a great influence on seal leakage performance. A depressurization leads to smaller clearance values, i.e. smaller mass flowrates. The clearance values at pressurizing conditions are used for calibration.

Operating conditions at the calibration points and results of calibration are summarized in Table 3. It can be seen that the brush seal B3 possessing more stiffness undergoes compaction. The pack thickness of B3 tends to the theoretical minimal value. In contrast, the bristle pack B2 undergoes mainly a blow-down effect with only small changes in bristle pack thickness. The calibration results show that for the sealing configuration BSS B2, the bristle pack thickness remains unchangeable when compared with the initial thickness of 1.98 mm. Generally, SSB configuration shows smaller values for b_b and s, compared with BSS.

By using the calibration results from Table 3, leakage performance of four sealing configurations tested is calculated for the whole inlet pressure range. Figure 5 illustrates the experimental and theoretical results on mass flowrate as a function of inlet pressure. In Fig. 5,

Table 3 Calibration points and results

	SSB B2	SSB B3	BSS B2	BSS B3
Inlet pressure (MPa)	0.507	0.507	0.54	0.5
Mass flowrate (g/s)	86.20	55.64	100.64	67.19
Brush radial clearance (mm)	0.009	0.079	0.02	0.089
Bristle pack thickness (mm)	1.8	1.495	1.98	1.55

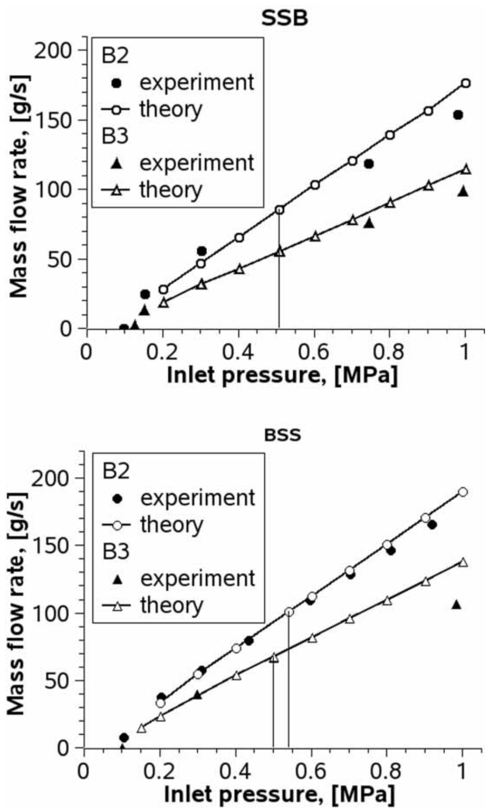

Fig. 5 Leakage versus inlet pressure

the stems represent the calibration points. A comparison between different brushes shows that brush B3 reduces leakage remarkably better than B2 in both seal designs, although B3 operates at higher clearances. This is one more significant difference between both brush seals. The leakage through a brush seal consists of two parts, of which one flows through the clearance and the other through the bristles. One could state that the leakage through the bristle is significantly smaller for B3. This decrease in bristle leakage is obviously higher than the increase in the clearance leakage caused by a larger clearance. This effect leads to a smaller leakage for B3. The lower bristle leakage is not surprising because the porosity of B3 is only 81 per cent of that of B2 under cold conditions. The results also show that the leakage performance of SSB configuration is slightly better than that of BSS. This means that the influence of the position of the brush seal (upstream or downstream) is insignificant for the leakage performance.

Theoretical predictions based on equation (4) follow the same tendency in leakage performance. Generally, the theory underestimates mass flowrates for pressures below the calibration point and overestimates for pressures above the calibration point. The difference increases at high pressures, although the accordance is fairly good with one exception. BSS B3 at high pressures demonstrates relatively large deviation between the measurements and predictions. Unfortunately, there is a lack of experimental data in the high-pressure range for B3. BSS B2 shows the smallest deviation at all pressure conditions.

The difference between CFD and experimental results could be explained by the pressure-dependent clearance in the brush seal. Although the value of s for calibration is taken from the optical measurements, it is kept constant over the whole pressure range. Introducing an approximate relation for a brush clearance (e.g. logarithmic function) into the theoretical model could increase the accuracy of predictions [**18**]. This has been confirmed for SSB sealing configuration. Other concern of deviation between theory and experiments is with applicability of the Ergun porous model and its modifications. The original Ergun's equation was derived for spherical particles with the porosity near 0.4. This could explain a larger deviation for B3, which has porosity <0.2 at operating conditions. In this regard, other models proposed in the theory of porous media (e.g. [**10**, **19**]) could be more accurate when applied to the brush seal applications.

From the experimental point of view, it should be mentioned that the error in leakage measurements was slightly higher at high pressure differentials due to the averaging procedure. A double-flow design of the test rig requires two identical test seal configurations. Experimental value of leakage across the seal is determined on the basis of the total leakage of the test rig. During measurements, unbalanced axial pressure distributions were observed at high inflow pressures for the brush seals being in operation for some time. This indicates that brush seals were no more identical at those points due to rub or other effects.

To investigate the sensitivity of mass flowrate on brush seal operating parameters (i.e. the sensitivity of different calibration procedures), parametric studies on variation b_b and s have been carried out. Figure 6 presents mass flowrates versus brush clearance at calibration point. The mass flowrate is shown relative to the maximal leakage of corresponding sealing configuration. The brush clearance is related to

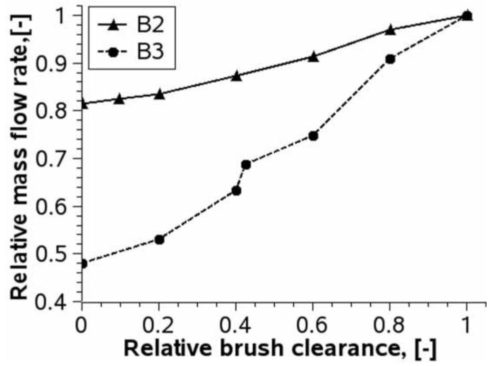

Fig. 6 Effect of brush clearance variation for BSS

the maximal value of 0.21 mm. It should be mentioned that the porosity is kept constant. Observing this plot from the right to the left, it is seen that the total leakage decreases due to the reduction of clearance mass flowrate. Decreasing brush clearance to zero results in leakage reduction of nearly 20 and 50 per cent for B2 and B3, respectively. According to this notable difference, one could state that the calibration procedure based on clearance variation may have different effectiveness when applied to different brush seals.

Figure 7 shows the effect of the bristle pack thickness variation on leakage. The pack thickness is related to the value of 2.4 mm, which is ~21 per cent more than the manufacture's value. The minimal thickness corresponds to the values near the theoretical closest packing. Here, a similar behaviour for B2 and B3 is observed. The leakage reduction comes to about 40 per cent. Generally, variation in b_b has a greater influence on leakage than the variation in s. All this makes the calibration procedure based on variation of b_b more preferable from the point of view of different bristle packs.

Figure 8 shows the axial pressure distribution for the brush seal B3 in SSB and BSS sealing configurations at calibration point. As expected, most of the pressure drop occurs in the brush seal, either in BSS or in SSB configuration. Slightly higher pressure drop is observed in the SSB configuration, which leads to a slightly smaller leakage (Fig. 5). The theory overestimates axial pressures for both configurations. The largest deviation occurs in the BSS configuration and is equal to 25 per cent. Figure 9 shows contour plots of pressure in the two bristle packs investigated. In B2, there is a strong radial pressure gradient. It confirms the fact that B2 operates under the blow-down conditions. In B3, the axial pressure gradient dominates over the radial one.

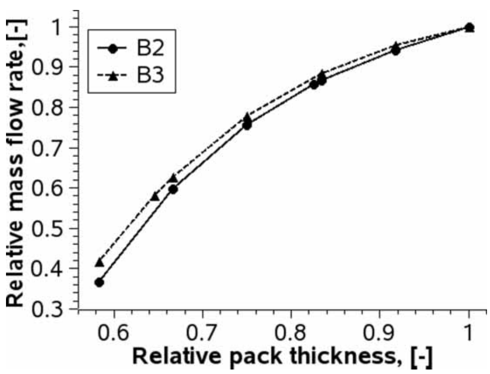

Fig. 7 Effect of bristle pack thickness variation for BSS

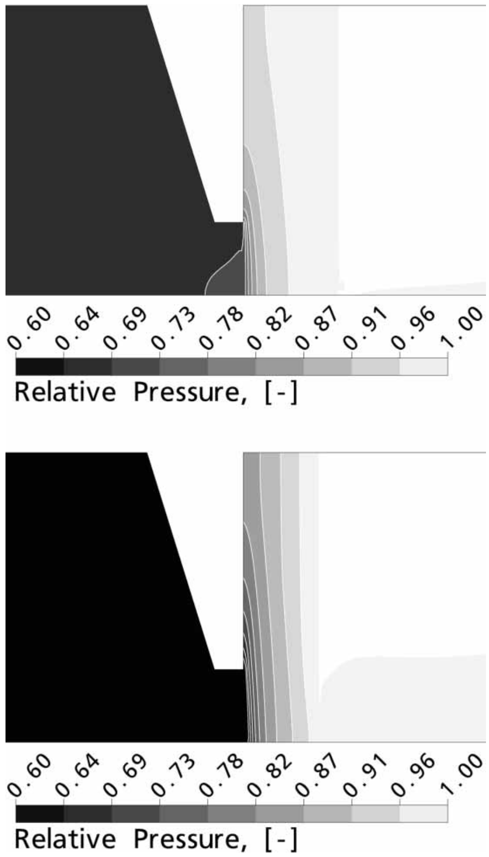

Fig. 9 Pressure contours in B2 (top) and B3 (bottom)

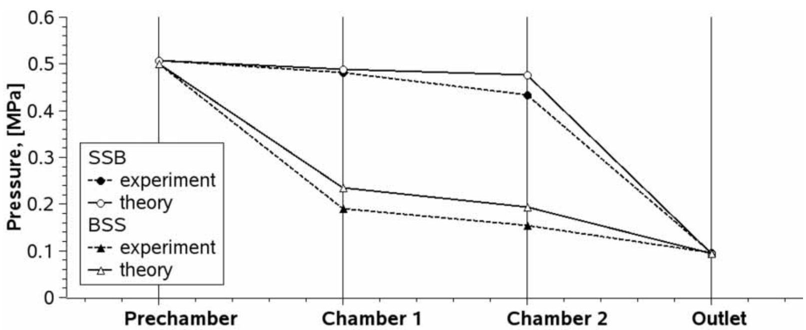

Fig. 8 Axial pressure distribution for the seals with the bristle pack B3

5 CONCLUSION

This work investigates the brush seal modelling based on a porous medium approach. A CFD modelling is applied to four different sealing configurations, including two types of brush seals with different bristle diameters and packing densities to predict their leakage performance. The calibration results indicate that varying bristle pack thickness is more effective even at high values of free radial clearance in the brush seal. The dependence of the mass flowrate on the thickness of the bristle pack can be approximated, which could simplify the calibration procedure for different brush seals. Theoretical predictions for mass flowrate show good correlation with experimental data. The estimation of the brush radial clearance from the optical measurements shows that the brush seal B2 operates under blow-down effect in most cases, whereas the brush seal B3 has a significant radial clearance. Despite this, the leakage is considerably smaller for the brush seal B3. This must be a consequence of smaller porosity of B3, which compensates for the higher clearance leakage by a smaller mass flowrate through the bristle pack.

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APPENDIX

Notation

a	viscous resistance ($1/m^2$)
b	inertial resistance ($1/m$)
b_b	bristle pack thickness (m)
d	bristle diameter (m)
h	bristle length (m)
h_b	backing plate clearance (m)
h_f	front plate clearance (m)
N	bristle packing density (bristles/m)

p	pressure (Pa)
s	radial clearance (m)
v	velocity (m/s)
x	spatial coordinate (m)
ε	porosity (–)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
ϕ	lay angle (°)

Subscripts

n, z	directions normal to bristles
s	bristle lengthwise direction