

# PREDICTED PERFORMANCE OF BRUSH SEALS: POROUS MEDIUM VERSUS RESOLVED BRISTLE MATRIX AND COMPARISON WITH EXPERIMENTAL DATA

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## ABSTRACT

The paper compares two theoretical approaches for modeling gas flow through brush seals. In the first approach, the bristle pack is represented as a porous medium. The resistance to the flow through the bristle pack is described by viscous and inertial resistance coefficients defined in a bristle streamwise direction and directions normal to bristles. In the second approach, several tens of individual bristles representing the bristle matrix segment are modeled directly. In contrast to the model based on the porous medium approach, the model with the resolved bristle matrix provides more accurate local flow characteristics but at the expense of complexity and high computational costs. Two brush seals are studied numerically to compare two theoretical approaches in terms of leakage, pressure and velocity distributions. In addition, the predicted results are compared with available experimental data on leakage and the axial pressure drops for various operating conditions. The capability of both approaches to predict brush seal performance is discussed in detail.

## NOMENCLATURE

$a$  viscous resistance  
 $b$  inertial resistance  
 $b_b$  bristle pack thickness  
 $d$  wire diameter  
 $D_r$  shaft diameter  
 $h^{\text{eff}}$  effective clearance  
 $\dot{m}$  leakage  
 $N$  bristle packing density  
 $p$  pressure  
 $T$  gas temperature  
 $v$  gas velocity  
 $x$  spatial coordinate  
 $\varepsilon$  bristle pack porosity  
 $\mu$  gas dynamic viscosity

$\rho$  gas density  
 $\varphi$  bristle lay angle

### Subscripts:

0 inlet  
3 outlet  
 $n, z$  bristle normal directions  
 $s$  bristle streamwise direction

### Abbreviations:

B1 line-on-line brush seal  
B2 clearance brush seal  
SSS three-tooth-on-stator labyrinth seal  
SSB two-tooth-on-stator labyrinth seal with a brush seal placed downstream of fins

## INTRODUCTION

In dynamic sealing of gas and steam turbines, the brush seal technology gains an ever-broader application. Using brush seals with their advantageous leakage characteristics in place of conventional labyrinth seals is one of the cost-effective ways of meeting the current demands for higher efficiency and lower environmental impact of new and retrofitted turbomachinery units.

Although the brush seal technology became well-known since the 1980s, design and manufacturing of brush seals are still coupled with many challenges. A large number of fine bristles packed between front and backing plates predisposes a complex aerodynamic and mechanical behavior of brush seals. Many studies were performed to understand flow patterns in the bristle pack. Several

works (Braun et al., 1990, Hendricks et al., 1990) discussed results of water and oil tunnel experimental visualization tests for the model linear brush seals obtained using a laser illumination technique. Typical flow formations were identified. Theoretical modeling of inter-bristle flows was also utilized for a better understanding of local flow characteristics. Braun and Kudriavtsev (1995) solved the two-dimensional Navier-Stokes equations for pin arrays representing an idealized brush seal. The numerical results revealed several mechanisms similar to those observed in the water tunnel visualization tests.

Pekris et al. (2011) presented a methodology of modeling an idealized contacting brush seal using computational fluid dynamics (CFD). Design of Experiments approach was used to analyze the sensitivity of the performance parameters (forces, bristle tip temperature, mass flow rate) to the brush seal geometry parameters (bristle length, spacing, number of rows, lay angle, bristle diameter, backing ring clearance). The significance tables for the main effects and their interactions were calculated from the numerical gradients of the corresponding curves.

Many theoretical and experimental studies were devoted to the mechanical characteristics of bristles. Stango et al. (2003) studied bristle tip contact forces for different brush seal design parameters (lay angle, radial interference, etc.) in the absence of aerodynamic loading. One of the conclusions was drawn on a crucial role of lay angle in regulating the magnitude of bristle contact force and bending stress. The work was continued in (Zhao and Stango, 2004) taking into account the blow-down effect, i.e. aerodynamic forces in radial direction. Guardino and Chew (2005) presented a method for predicting three-dimensional bending behavior of bristles in brush seals. The method was based on the linear beam-bending theory and allowed relatively large number of bristles and arbitrary initial bristle packs to be considered. Arbitrary imposed aerodynamic forces, bristle-to-bristle and shaft-to-backing-ring contacts, and deflections were considered.

Lelli et al. (2006) reported on a comprehensive brush seal model for fluid-structure interaction simulation. The approach combines a 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 was computationally very expensive and allowed to consider only a small number of bristles during simulations. The theoretical results showed that the bristle deflections tended to lead to asymmetric packing. Taking into account the inlet swirl of the flow resulted in relatively small additional forces on the upstream bristle row with little effect on other rows.

Turner et al. (1998) studied the effect of the free radial clearance in the brush seals using a porous medium approach and a mechanical model showing a great influence of the bristle blow down behavior on the brush seal performance.

The porous-medium-based CFD models neglect the discrete nature of the bristle pack. Thus, the numerical analysis of the brush seal is considerably simplified. These models are sufficiently reliable for leakage prediction. However, some knowledge about the behavior of the particular brush seal is still needed to calibrate the porous medium model. Prediction of forces acting in the brush seal and sealing cavities using the porous medium approach is a more challenging task, particularly if a non-homogenous packing must be considered (e.g. due to the eccentric shaft position). Here, experimental data is required to obtain acceptable predictions with the porous medium approach.

This paper addresses the modeling of two brush-labyrinth sealing configurations with line-on-line and clearance brush seals of different designs. The aim of this paper is to provide a comparative analysis of two approaches for modeling brush seals. Three-dimensional CFD modeling of inter-bristle flow is considered for a large number of bristles. A full 3D porous-medium-based CFD model with various sets of resistance coefficients is used as a standard approach to model the global behavior of brush seals. Interaction of the brush seal element with upstream cavities and fins of the brush-labyrinth sealing configuration is considered and analyzed. Considerably higher costs (costs for structural grid generation in particular) in comparison with the porous-medium-based CFD models limits the use of the inter-bristle flow modeling. However, the inter-bristle flow model may be successfully applied for studying local effects in the bristle packs and for the purpose of calibration of porous medium models when experimental data is limited or not available.

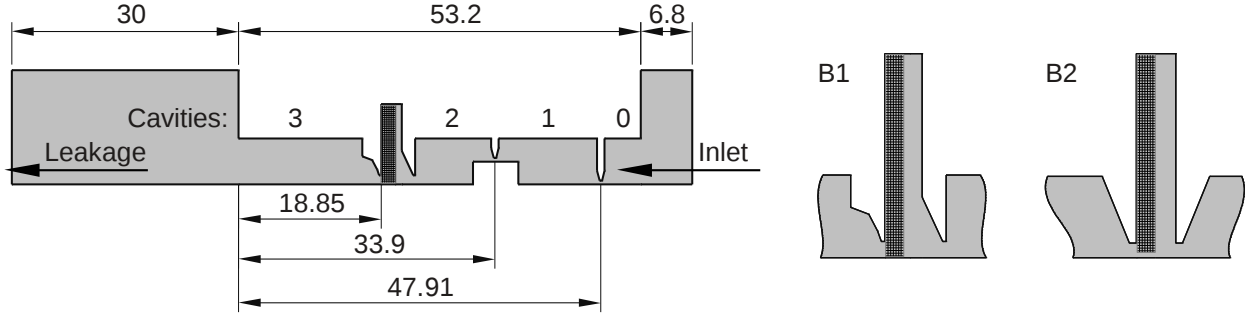


Figure 1: Configuration of the brush-labyrinth seal SSB (all dimensions are in mm)

Table 1: Bristle pack parameters

	B1	B2
Wire diameter [ $\mu\text{m}$ ]	167.64	70.0
Bristle length [m]	15.0	15.0
Bristle packing density [bristle/mm]	47.64	200.00
Bristle lay angle ( $^\circ$ )	45	45
Bristle tip cold radial clearance [mm]	0.0	0.31
Shaft diameter [mm]	179.86	180.05

## SEALING CONFIGURATIONS WITH BRUSH SEALS

Figure 1 shows a sealing configuration studied in this work. It consists of two labyrinth fins and a brush seal placed in the downstream cavity. The configuration is called SSB. Such short three stage sealing configurations are typically used as shrouded-rotor seals. Replacing one or several labyrinth fins with a brush seal improves leakage characteristic significantly and can be applied for both new sealing designs and as a retrofit to existing labyrinth seals. Labyrinth fins act in the brush-labyrinth configurations mainly as a backup measure in case of a bristle pack failure.

### Brush Seal Parameters

Dimensions of the sealing configuration SSB are shown in Figure 1. The seal cavity diameter is 192 mm. Diameter of the upstream and downstream regions is 210 mm. The labyrinth tooth radial clearance is either 0.27 mm (shaft diameter 180.05 mm) or 0.5 mm (shaft diameter 179.86 mm). The rotor band is 3 mm high and 6 mm long. The geometry of two brush seals considered in this work is shown in Figure 1 and listed in Appendix (Table 4). Parameters of the bristle packs are summarized in Table 1. The bristle pack B1 is a welded brush seal and used in a line-on-line (zero clearance) configuration. The bristle pack B2 is a clamped brush seal fabricated from a finer wire and is assembled with a cold clearance. Bristles in both cases are made of a superalloy Haynes 25.

## MODELING OF THE BRUSH SEALS USING POROUS MEDIUM APPROACH

The porous medium approach is a popular method to predict brush seal global performance characteristics (e.g. leakage). In this approach, the bristle pack is treated as a porous medium. The resistance of the porous medium to the flow is described by the following equation defined in the bristle streamwise direction  $s$  and bristle normal directions  $n$  and  $z$ :

$$-\frac{\partial p}{\partial x_i} = a_i \mu v_i + b_i \rho |v_i| v_i, \quad \begin{aligned} a_n = a_z = 80 C, & \quad b_n = b_z = 1.16 D, & C = (1 - \varepsilon)^2 \varepsilon^{-3} d^{-2} \\ a_s = 32 \varepsilon, & \quad b_s = 0, & D = (1 - \varepsilon) \varepsilon^{-3} d^{-1} \end{aligned} \quad (1)$$

The behavior of the porous medium is determined by the viscous resistance coefficient  $a$  (inverse of the permeability) and the inertial resistance coefficient  $b$ . The expressions for the resistance coefficients in Eq. (1) are taken from the work by Pröstler (2005). This model is referred below as M1. Another, very popular set of expressions proposed by Chew et al. are used for comparison and are referred below as M2. The single difference between M1 and M2 is in the viscous resistance coefficient for the streamwise direction (Neef et al., 2007).

For the bristle pack of thickness  $b_b$  composed of bristles with diameter  $d$  packed with density  $N$  and aligned with the lay angle  $\varphi$ , the expression for the porosity is:

$$\varepsilon = 1 - \frac{\pi d^2 N}{4 b_b \cos \varphi} \quad (2)$$

A theoretical value of the minimal bristle pack thickness can be estimated as (Pröstler, 2005):

$$b_b^{\min} = d + \frac{\sqrt{3}d}{2} \left( \frac{dN}{\cos \varphi} - 1 \right) \quad (3)$$

The expressions for the resistance coefficients are derived from empirical data. Therefore, the CFD model based on the porous medium approach must be calibrated for the particular brush seal for at least one operating point (e.g. pressure drop). Calibration means an adjustment of one or more model parameters (usually, either  $b_b$  or free radial clearance or both) to get a correct output value (leakage, local pressure drop, force). Alternatively, one can adjust the resistance coefficients  $a$  and  $b$  directly, for instance, by scaling the values of these coefficients in the fence height region (Chen et al., 2000; Dogu, 2005).

The bristle pack thickness  $b_b$  is the main uncertain parameter in the porous medium model. In clearance brush seals, a free radial clearance between bristle tips and rotor surface is the second uncertain parameter. Values of both parameters can be estimated by performing optical measurements (Pugachev and Helm, 2009; Schwarz et al., 2010, 2012). The brush seal radial clearance can also be estimated by using mechanical models of bristle bending. Depending on the blow-down behavior of the brush seal, the information on the free radial clearance might be also important for the line-on-line arrangement when considering eccentric operation.

### **Porous-Medium-Based CFD Model**

CFD modeling of the brush-labyrinth seals is performed in a commercial software ANSYS CFX 14.0 using the compressible Reynolds-Averaged-Navier-Stokes approach with the Total Energy model and Shear Stress Transport turbulence model with automatic wall functions (ANSYS, Inc., 2011). Sealing medium is air as an ideal gas at ambient temperature. Pressure boundary conditions are used at the inlet and outlet. Inclination of the bristle pack is taken into account in the model by specifying resistance directions (bristle lengthwise and bristle normal directions) of the porous region. The calculations are performed using the advection scheme with specified blend factor of 0.8. Convergence rate is checked by setting targets for the root mean square equation residuals and global balances, as well as by observing the convergence history of leakage.

Three-dimensional structured hexahedral O-grids for the concentric shaft position are generated using ANSYS ICEM CFD. The results of grid independence studies performed in the previous works for similar sealing configurations are taken into account. The total number of nodes in the full, 3D model is about 6 million for the B1 design and 8 million for the B2 design.

### **RESOLVED BRISTLE MATRIX**

An alternative approach to model the bristle pack is to resolve all bristles individually. Due to high pre-processing and computational costs, only a small segment of the brush-labyrinth seal is considered in this work.

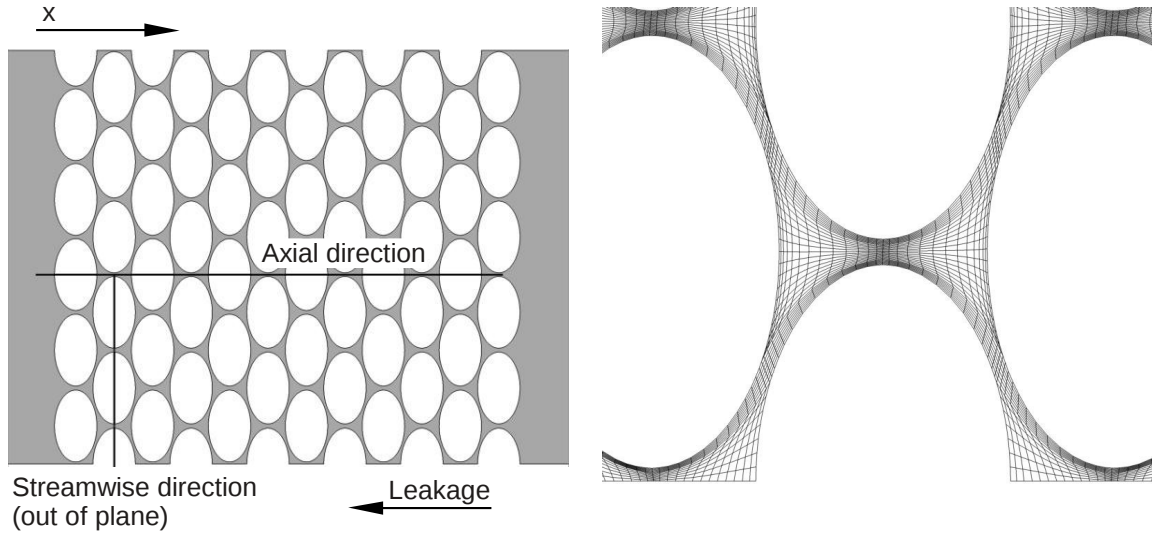


Figure 2: Part of geometry and computational mesh for the resolved bristle matrix B1

Table 2: Parameters of the inter-bristle flow models

	B1	B2
Total number of modeled individual bristles	72 (12 rows)	144 (24 rows)
Bristle pack thickness in the resolved model [mm]	1.85	1.53
The tightest bristle gap in the resolved model [mm]	0.01	0.004

The B1 model with the resolved bristle matrix includes 72 homogeneous non-moving bristles with round cross-section. Figure 2 shows a geometry and a fragment of the computational mesh in the bristle tip region for the hexagonal packing arrangement. The idealized bristle pack consists of 12 rows with 6 bristles in each row. The tightest gap between individual bristles is 0.01 mm. The model represents an idealized symmetric bristle pack. A photograph of bristle tips of the real brush seal B1 shown in Figure 3 reveals partial bristle distortions and irregular voidage of the bristle pack. The bold lines shown in Figure 2 are used in the analysis of the results (see below Figure 7 and Figure 8). The parameters of the resolved models B1 and B2 are summarized in Table 2.

The CFD analysis is similar to one described for the 3D porous-medium model. The difference is only in turbulence modeling. A transition model (Menter et al., 2006) is used to take into account the effect of laminar flow in the bristle pack. The comparison with the SST turbulence model without transition done for the brush seal B1 showed, however, negligible effects of the transitional turbulence model in this case.

The segment of the brush-labyrinth seal with the resolved bristle matrix is meshed with hexahedral elements using the structured approach in ANSYS ICEM CFD. Grid generation is an almost fully automatic procedure based on

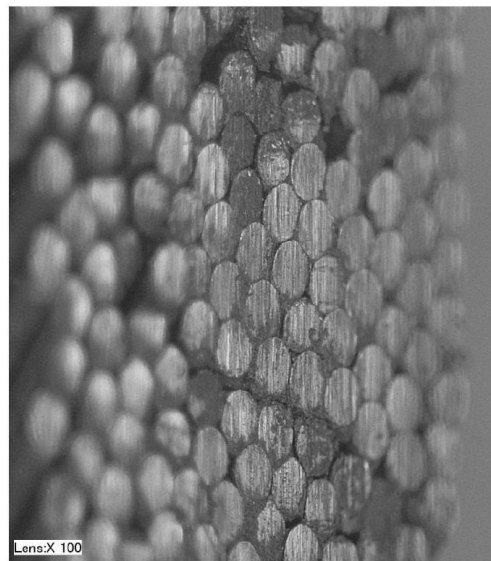


Figure 3: Photograph of the bristle pack B1 (100-X magnification)

tcl/tk and ICEM CFD replay scripts. The total number of nodes in the resolved matrix model is about 21 million for both B1 and B2 bristle packs. The grid spacing between the bristles is controlled to get  $y^+$  values acceptable for the used transitional turbulence model. For the inlet pressure of 0.4 MPa the  $y^+$  values are in the range of 0.002 to 7.5 for the line-on-line brush seal B1 and 0.001 to 4.9 for the clearance brush seal B2.

## RESULTS AND DISCUSSION

The experimental results shown in this section were obtained on the test rig at the Institute of Energy Systems, Technische Universität München. The sealing configuration SSS consisting of three labyrinth teeth with the tooth radial clearance either 0.27 mm or 0.5 mm is used for comparison. Experimental results for the seal SSS with the radial clearance of 0.27 mm and seal SSB B2 are taken from (Deckner, 2010).

The CFD calculations are performed on a 12-core Linux-based computer with 32 GB RAM. The following convergence criteria are used: maximum root mean square (RMS) equation residuals of  $1.0E-5$ ; maximum global balances of 1%; constant mass flow rate. The target criterion on the RSM energy equation residuals is not met in all calculated cases with the resolved bristle matrix model. A single CFD run takes on average about 12 hours for the porous-medium-based model and about 36 hours for the resolved bristle matrix model.

### Experimental Leakage Performance and Local Pressure Differentials

Figure 4 shows the leakage performance of various labyrinth and brush-labyrinth sealing configurations in terms of effective clearance calculated for air as follows ( $\gamma = 1.4$ ,  $R_s = 287.04$  J/kg/K):

$$h^{\text{eff}} = \frac{\dot{m} \sqrt{T_0}}{\pi p_0 D_r Q}, \quad Q = \begin{cases} \sqrt{\frac{2\gamma}{R_s(\gamma-1)} \left[ \left( \frac{p_0}{p_3} \right)^{-\frac{2}{\gamma}} - \left( \frac{p_0}{p_3} \right)^{-\frac{\gamma+1}{\gamma}} \right]}, & \text{if } \frac{p_0}{p_3} \leq \left( \frac{2}{\gamma+1} \right)^{\frac{\gamma}{\gamma-1}} \\ \sqrt{\frac{\gamma}{R_s} \left( \frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}}}, & \text{otherwise} \end{cases} \quad (4)$$

The seal SSB with the bristle pack B1 has the smallest effective clearance due to the line-on-line arrangement. At high pressure ratios the seal SSB with the bristle pack B2 demonstrates effective clearance characteristic similar to the seal SSB B1 due to the blow-down effect. Both labyrinth seals have considerably higher effective clearance values. Increasing the tooth radial clearance from 0.27 mm to 0.5 mm nearly doubles the effective clearance.

Figure 5 shows the effect of preswirl velocity and shaft rotational speed on the experimental local pressure differentials and leakage for the SSB seals with line-on-line (B1) and clearance (B2) bristle packs. In the seal SSB B1, both operating parameters have a significant influence on the pressure differential  $\Delta p$  in cavities 1 and 2. Local pressure differential in the brush seal cavity 3 remains almost unchanged. Experimental leakage decreases with increasing rotational speed. In contrast to the seal SSB B1, rising preswirl ratio increases considerably the leakage in the clearance seal SSB B2. This could be due to the bristle lift-off.

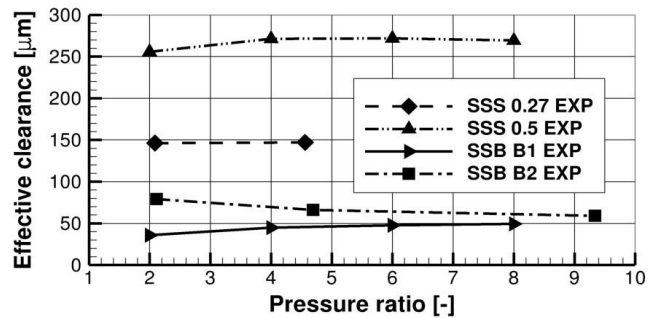


Figure 4: Experimental effective clearance of labyrinth and brush-labyrinth seals

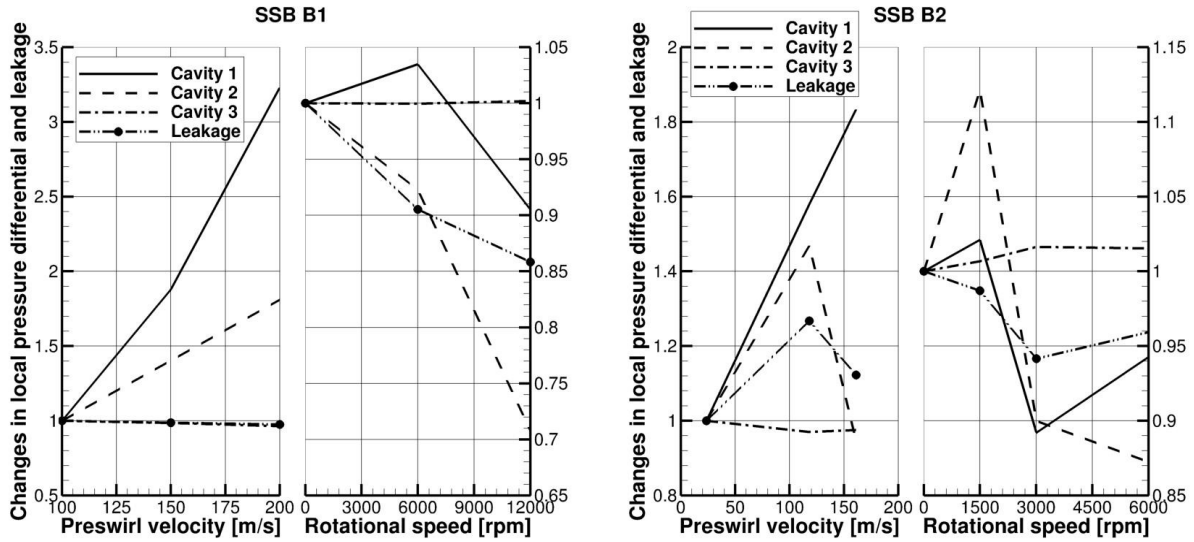


Figure 5: Effect of preswirl velocity and rotational speed on the experimental local pressure differential and leakage (SSB B1 and SSB B2 seals)

### Calibration of the Porous Medium Model

Table 3 summarizes the results of the calibration of porous medium models for the bristle packs B1 and B2. Leakage calibration is performed for the pressure differential of 0.3 MPa. The porous medium model M2 has to be used with a more compressed bristle pack than in the model M1. The bristle pack thickness is even below the theoretical minimal value for the seal SSB B1. The last column in Table 3 shows results of the calibration by changing the resistance coefficients directly. The bristle pack thickness values are taken from the resolved model (1.85 mm for B1 and 1.53 mm for B2). In this case, to get the correct leakage value all resistance coefficients must be augmented by a corresponding coefficient (4.2 and 2.6 for the bristle packs B1 and B2 respectively).

### Comparison between Different Models and Experimental Data

Figure 6 compares experimental values and predictions of the effective clearance versus pressure ratio for the two labyrinth-brush seals with different bristle packs. The smaller error bars of the experimental data for the seal SSB B1 are due to the use of different, more accurate pressure control system. Calculations for the seal SSB B1 are performed for different pressure ratios using the same mesh due to the line-on-line arrangement. Meshes with different free radial clearance between the bristle tips and shaft are generated to take into account the blow-down effect in the seal SSB B2. Result of optical measurements are used to set the free radial clearance value depending on the pressure drop (Pugachev and Deckner, 2012). An inter-bristle spacing and bristle pack thickness are kept constant in both SSB B1 and SSB B2 models. The porous medium model demonstrates the largest deviations for the seal SSB B1. Results for the seal SSB B2 reveal that the resolved model tends to predict lower effective clearance values.

Comparison between resolved and porous medium models for the velocity, pressure, and pressure gradient along the streamwise and axial directions is presented in Figure 7 and Figure 8. Res-

Table 3: Results of the calibration of the porous medium models (inlet pressure 0.4 MPa)

	$b_b^{\min}/\varepsilon$	$b_b/\varepsilon$ (M1)	$b_b/\varepsilon$ (M2)	$b_b/\varepsilon$ (M1 mod. coeff.)
B1	1.662 mm / 0.105	1.68 mm / 0.115	1.64 mm / 0.093	1.85 mm / 0.196 (4.2)
B2	1.210 mm / 0.100	1.40 mm / 0.223	1.33 mm / 0.182	1.53 mm / 0.289 (2.6)

ults are shown for the total pressure differential of 0.3 MPa. Positions of lines, along which the results are reported, are shown in Figure 2 ( $s = 0$  corresponds to the bristle tip region). Regarding the streamwise direction, both models provide qualitatively similar results for the line-on-line and clearance brush seals. The porous medium model generally underpredicts the maximal values of velocity and pressure gradient. The smaller pressure gradient in the fence height region (back plate radial clearance) results in more gentle sloping of the pressure drop comparing to the results predicted by the resolved model.

The same results for the axial direction is shown in Figure 8. The porous medium model predicts a very low axial velocity in the bristle pack B1 in comparison with the resolved model. The matching is considerably better for the clearance bristle pack B2. Predictions for the pressure and pressure gradient are in qualitative agreement for both bristle packs.

Results obtained with two other porous medium models (M2 and M1 mod.), which are not presented, demonstrate similar agreement with the resolved model.

Figure 9 compares experimental and predicted values for the local pressure differentials in the sealing cavities 1, 2, and 3. The brush seal has the largest pressure differential in both sealing configurations and for all inlet pressures. Therefore, there is virtually no difference between experiments and predictions by the porous and resolved models (cavity 3 in Figure 9). Results for labyrinth cavities 1 and 2 reveal larger deviations. Generally, the resolved model shows a better agreement with the experimental values than the porous medium model. Comparing different bristle packs, B2 demonstrates higher local pressure drops in the sealing cavities 1 and 2 due to the free radial clearance in the brush seal.

## CONCLUSIONS

This work compares the CFD model based on the porous medium approach with the inter-bristle flow modeling to predict flow field in brush seals. A typical brush-labyrinth sealing configuration applied as a shrouded-rotor seal is considered. Two bristle packs (in the line-on-line and clearance arrangements) used in different sealing configurations are modeled. The predictions for the leakage and axial pressure distribution are compared with the experimental data.

The porous medium approach can be used to predict global performance characteristics of brush seals with a small computational effort. Comparison between various sets of the resistance coefficients in the porous medium models demonstrates relatively small difference in the distribution of pressure and velocity in the bristle matrix. The variation of the bristle pack thickness in radial and circumferential directions, which is the case in reality, can be implemented in the porous medium model, but is not considered in this work.

Modeling the inter-bristle flow needs extremely large computational resources. Therefore, only a segment of the brush-labyrinth seal with the assumption of hexagonal packing is considered. The resolved model can be used for the prediction of forces and torques acting on the individual bristles with subsequent calculation of bristle deformation, as well as for prediction of temperature distribution in the bristle material. Also, the results obtained with the resolved model can be used to reanalyze the porous medium models.

Comparison of the local characteristics shows that the both models are in qualitative agreement, but with partially large deviations in absolute values. Using a one-point calibration of the porous

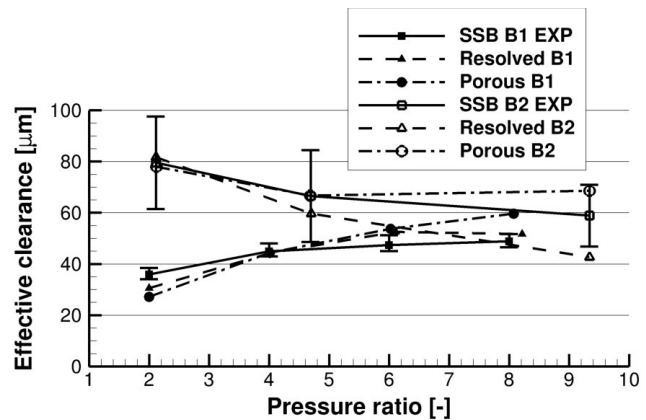


Figure 6: **Experimental and predicted effective clearance for the SSB B1 and SSB B2 seals**

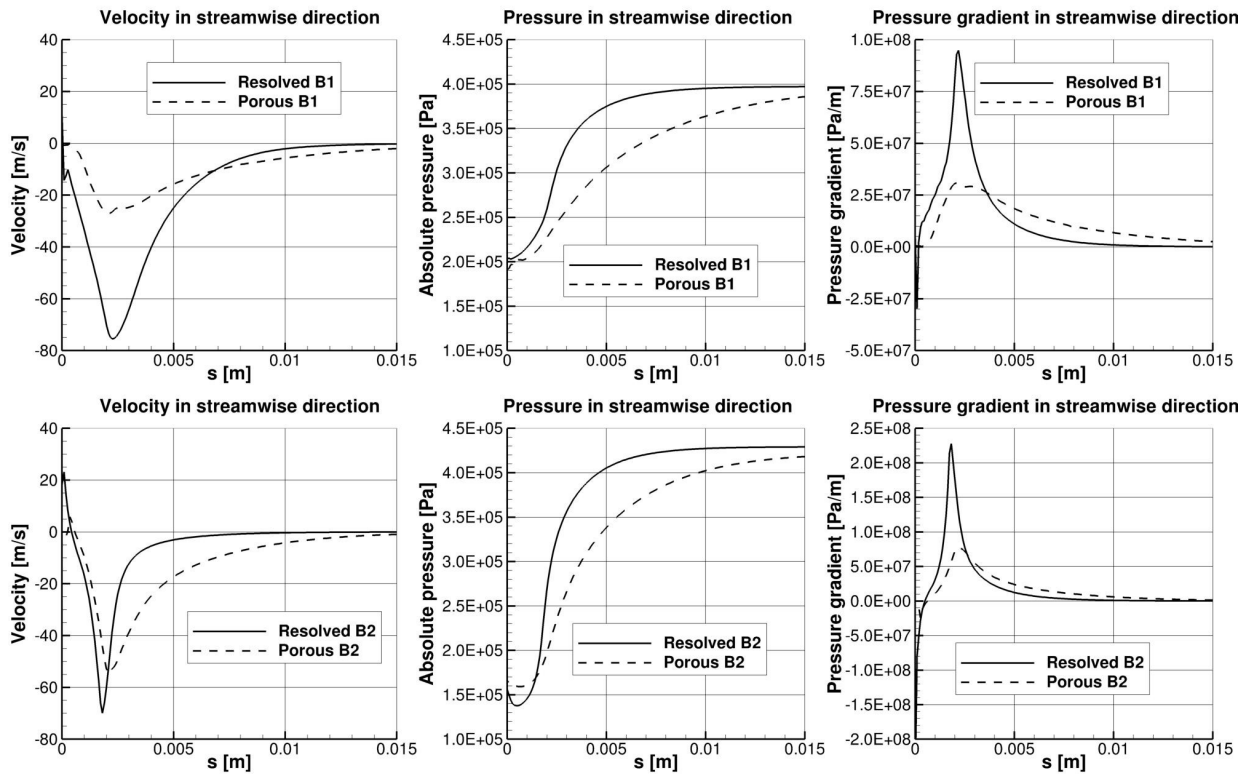


Figure 7: Comparison between the porous medium model M1 and the resolved model for the streamwise direction (SSB B1 and SSB B2 seals)

medium model provides reasonable predictions of leakage for other inlet pressures, while the discrepancies in the local pressure differentials in the labyrinth cavities become higher with increasing inlet pressure. At the same operating conditions sealing configuration with the clearance brush seal demonstrates more severe flow field in the bristle pack region with higher pressure gradients and velocities comparing with the line-on-line brush seal arrangement.

The results of this work can be used further in performing coupled simulations with taking into account contact interaction and deformation of bristles as well as for the development of more accurate porous-medium-based models.

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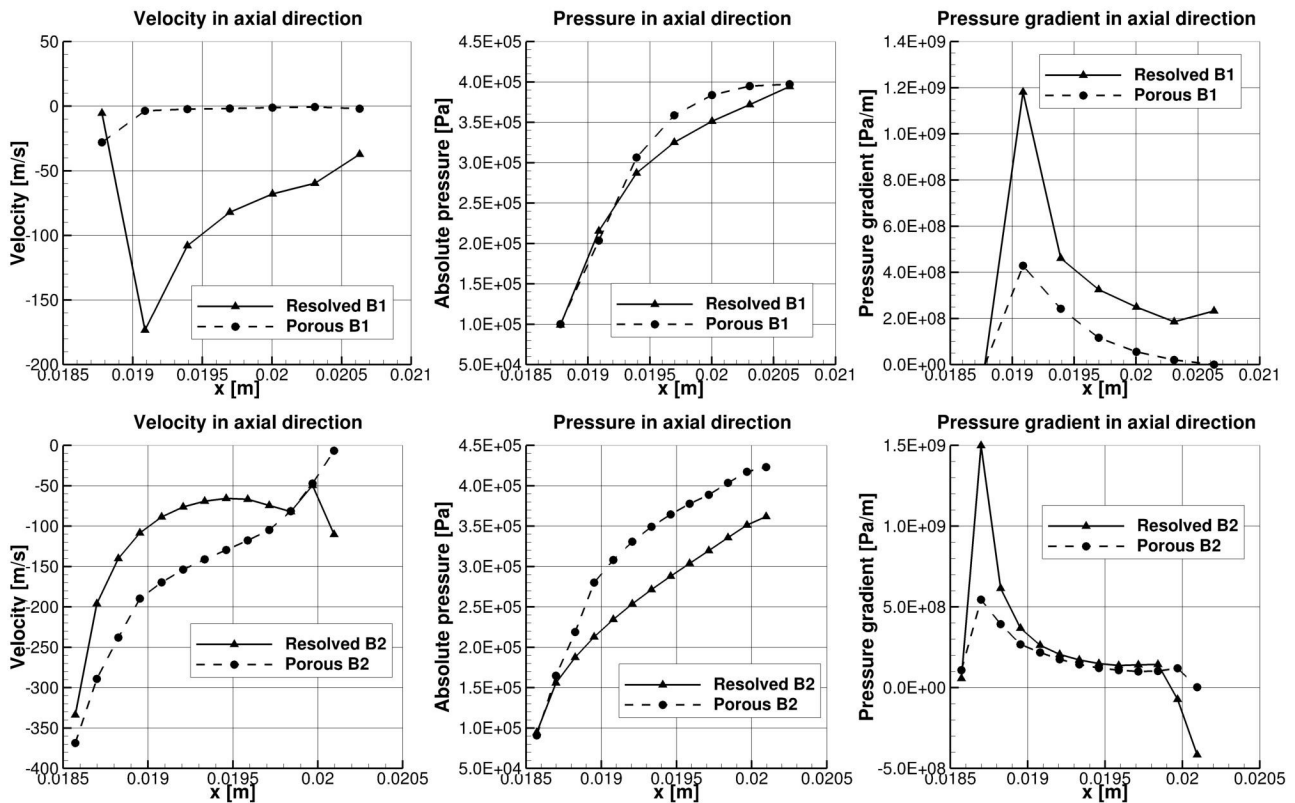


Figure 8: Comparison between the porous medium model M1 and the resolved model for the axial direction (SSB B1 and SSB B2 seals)

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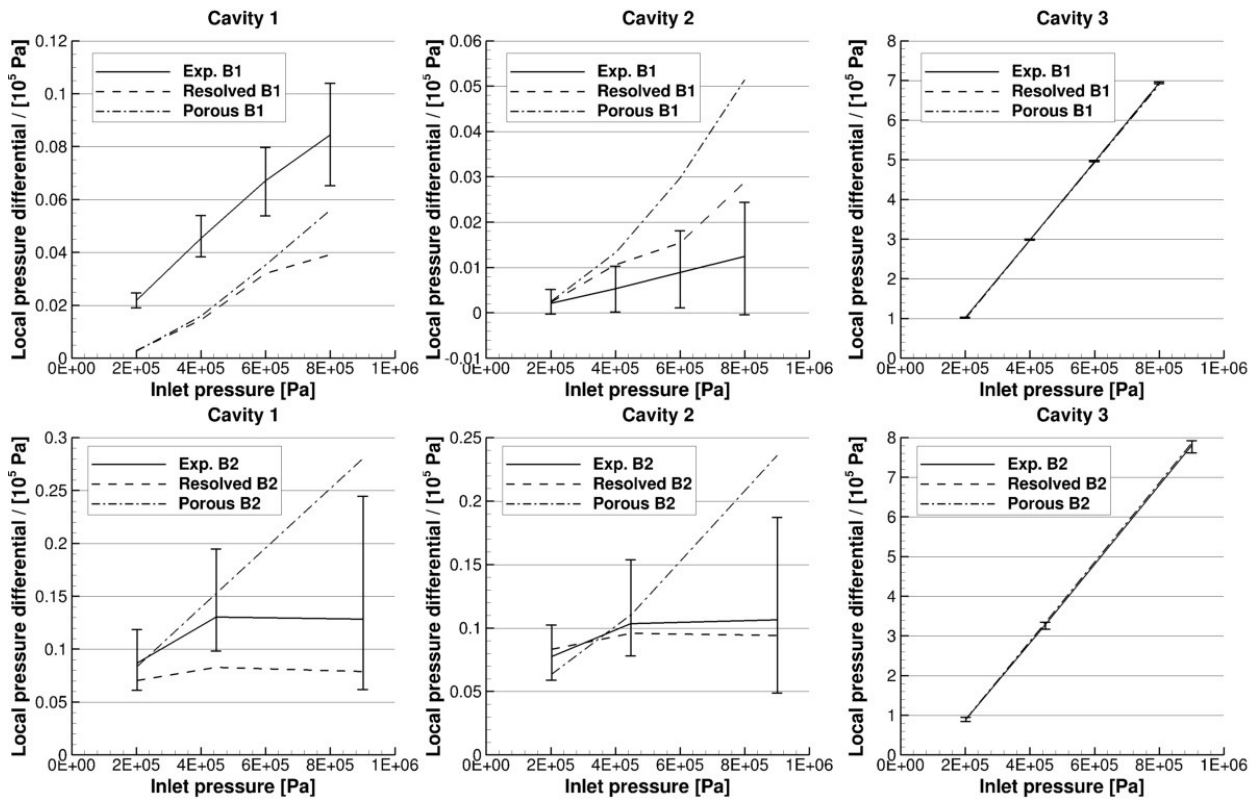


Figure 9: Experimental and predicted local pressure differentials (SSB B1 and SSB B2 seals)

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## APPENDIX

Table 4: Bristle pack geometry (all dimensions are in mm)

Point No.	1	2	3	4	5	6	7	8	9	10	11	12
B1 (line-on-line brush seal, labyrinth tooth radial clearance 0.5 mm)												
X	23.35	23.35	23.10	21.60	21.60	18.85	18.85	18.60	18.33	17.67	16.35	16.35
Y	96.00	91.13	91.13	94.34	104.93	104.93	91.13	91.13	91.88	93.13	93.63	96.00
B2 (clearance brush seal, labyrinth tooth radial clearance 0.27 mm)												
X	24.00	22.91	21.50	21.50	18.60	18.60	18.10	16.10	–	–	–	–
Y	96.00	91.10	91.10	100.60	100.60	91.10	91.10	96.00	–	–	–	–