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Analysis of carbon brush seals with long bristles

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1 Introduction

The present work introduces the analysis of a dynamic seal employed in rotating machinery to limit gas leakage between high and low pressure zones. The seal is comprised of a carbon brush consisting of closely serrated, long bristles of small diameter. The free length of the bristles exceeds the radial clearance between the rotor and the stator in which they are installed. The brush flexes in the axial direction along the rotor and fills the radial clearance between the rotor and the stator. Thus, a porous barrier is formed, impeding the flow of leakage.

The theoretical estimation of the leakage flow is particularly challenging due to the complexity of the porosity estimation. The behavior of brush depends not only on the density defined as number of bristles per circumferential length, but also by its deformation. This is accounted for by considering the bristles as beams that undergo large deformations. Contact interactions occur between the bristles and the rotor, as well as among the bristles themselves. Consequently, the bristles experience deformations not only due to contacts but also due to fluid forces acting upon them. By achieving a state of equilibrium between the flow forces and the deformed brush structure, a constant permeability is then established.

2 Objective and methods:

The objective of this study is the prediction of the leakage flow through the brush seal. A simplified model is established by considering only the contacts of a first row of bristles with the rotor and by neglecting the contacts between bristles. The distance between bristles varies between zero at their clamped end and an imposed spacing at their free end. A Darcy law describes the flow through the heterogeneous bristles. The permeability coefficients are estimated from the homogenized flow within representative cells orthogonal to and along the deformed bristles. The theoretical model predictions are compared with experimental results obtained on dedicated test rig.

2.1 Macroscopic Model and bristle deformation:

The bristles have very large aspect ratio between length (over 1.9mm) and diameter (5 μm) and are submitted to large non-linear deformations. A Kirchhoff beam theory is therefore employed for describing the deformed beam together with a finite element approach using third order Hermitian functions. A penalty formulation is used for taking into account the contact with the rotor. The first row of bristles is in contact with the rotor. The free end of the next rows is progressively shifted to larger radial values. The spacing between the free ends of the bristles is a parameter of approximation (Dp). The resulting form of the deformed characteristic brush section is shown in Figure1.

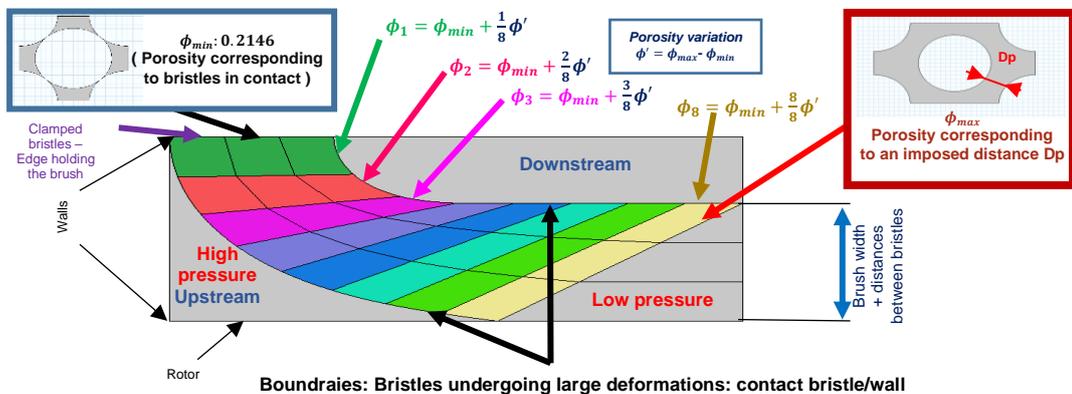


Figure 1: Macroscopic model domain

A boundary fitted curvilinear coordinate system is then associated to the deformed bristles. The coordinate system follows the first upstream, the last downstream bristle and the local normal direction. The porosity then varies along the coordinate system from its lowest value at the clamped end to its largest value at its free end. Two local problems are then solved in each point of the brush for the homogenized flow along and normal to the bristle. Local permeabilities are then calculated from the curvilinear coordinate system aligned with the bristles toward a cartesian coordinate system. The Darcy equation is then solved in a domain encompassing the upstream zone, the porous brush and the downstream zone as shown in Figure 1. A test rig was also developed and is depicted in Figure 2. It consists of a rotor deprived of rotation and enables testing carbon brush seals with five different interferences between the bristles and the rotor. Measured leakage flow rates are depicted in Figure 3. Comparisons of the Position 3 between the theoretical model and experimental results are depicted in Figure 4. The numerical values of the D_p parameter, ranging from **0.1 times bristle diameter** to **0.15 times bristle diameter**, show consistency with the experimental results. However, the variation of the experimental leakage flow rate cannot be closely matched by the present approach for two primary reasons. First, the deformation of the bristles considers only the rotor interference and disregards the influence of fluid forces. Second, the present approach assumes constant distance between deformed bristles, which is proportional to D_p parameter. These are strong assumptions that must be reviewed in future developments of the model.

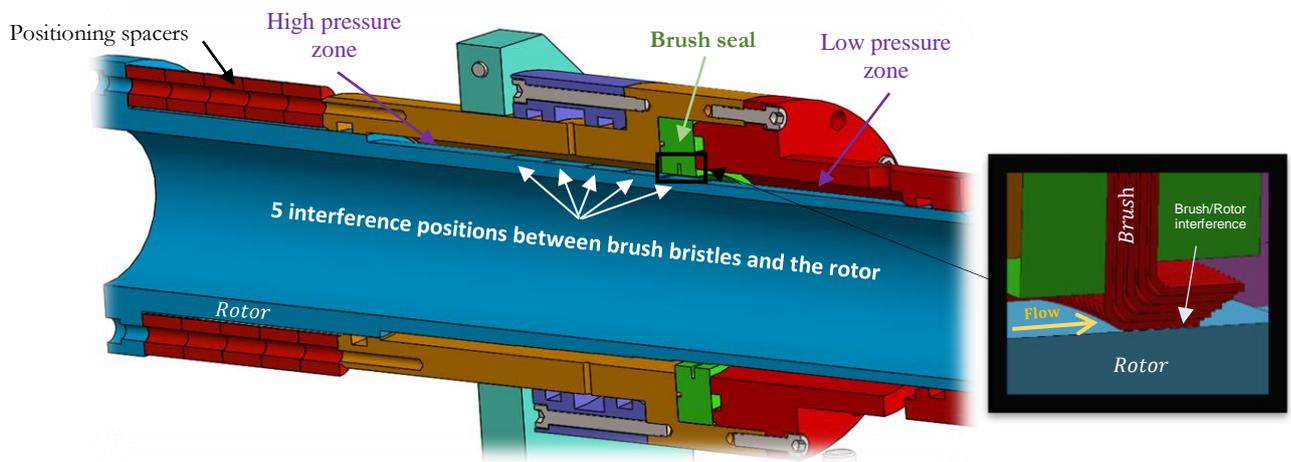


Figure 2: Test rig

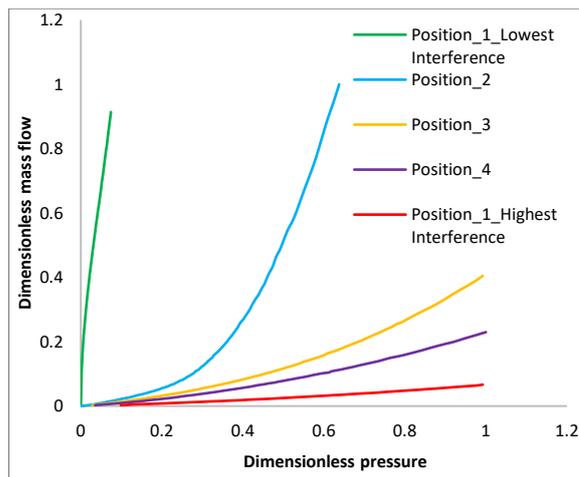


Figure 3: Experimental mass flow rate

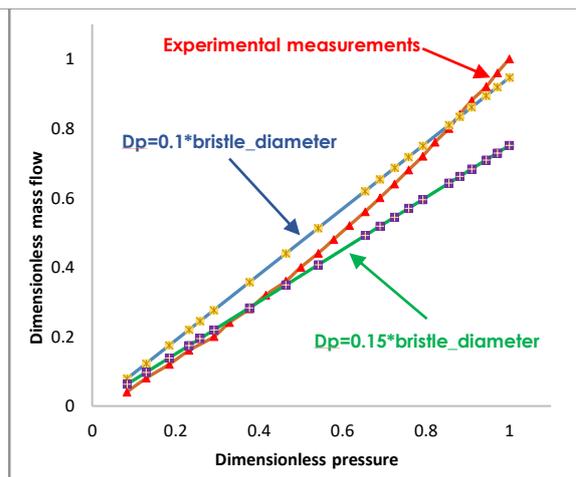


Figure 4: Comparisons between theoretical and experimental results

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