DESIGN-A-THON 2025

Modeling and CFD Validation of Brush Seal Leakage with and without Blow-Down Effects

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1. Problem Statement and Given Parameters

The objective is to model the leakage flow through a brush seal using both analytical and CFD-based techniques, incorporating a porous media model and blow-down effects. The following parameters were provided:

- Fence height, $h_f = 1.88$ mm
- Bristle pack thickness, $t_{bp} = 1.15$ mm
- Bristle tip diameter, $d = 0.102$ mm
- Lay angle, $\phi = 45°$
- Number of bristle rows = 11
- Bristle density, $N = 78.7$ bristles/mm
- Bore diameter, $D_{bore} = 150$ mm
- Upstream pressure, $P_u = 6$ bar
- Downstream pressure, $P_d = 3$ bar
- Temperature, $T_u = 300$ K

2. Importance of Brush Seals (Literature Survey)

- **High Efficiency:** Reduces leakage by up to 90% compared to labyrinth seals *(Turner et al., 1998).*
- **Flexibility:** Accommodates rotor displacement and thermal growth *(Song et al., 2022).*
- **Compact Design:** Ideal for aerospace due to lightweight and small footprint.
- **Thermal Endurance:** Operates under high temperatures and pressures.
- **Well Validated:** Supported by CFD and experimental research *(Kwon & Ahn, 2024).*

3. Modeling Approach and Porous Assumption

The bristle pack is modeled as a porous medium, avoiding the need to resolve each bristle explicitly. This significantly reduces computational cost while preserving physical accuracy. The pressure drop across the porous domain is modeled by the Darcy–Forchheimer equation:

$$\Delta P = \frac{\mu}{\varepsilon} b_n u + \frac{\rho}{\varepsilon^2} a_n u^2$$

Where:

- μ = dynamic viscosity of air
- ρ = density of air
- u = flow velocity through the bristle pack
- ε = porosity
- a_n, b_n = resistance coefficients (Pröstler model)

4. Modelling Porosity and Correction Factor

Initial porosity ε is calculated using Chew's formula:

$$\varepsilon = 1 - \frac{\pi d^2 N}{4t \sin \phi}$$

A correction factor α is applied to account for pressure ratio, clearance, and fence height:

$$\alpha = 0.4581 \cdot PR^{-0.0789} \cdot \left(\frac{H}{d}\right)^{0.8468} \cdot \left(\frac{t}{d}\right)^{-0.6604} \cdot \left(\frac{CL}{d}\right)^{-0.2686}$$

$$\varepsilon_{\text{corrected}} = \varepsilon \cdot \alpha$$

Porosity Correction and Leakage Flow Rate Calculation

To accurately model the flow through the bristle pack of a brush seal, a correction factor α is applied to the base porosity to account for the effects of pressure ratio, fence height, and clearance.

Porosity Correction

The corrected porosity is given by:

$$\varepsilon_{\text{corrected}} = \varepsilon \cdot \alpha$$

Where:

- ε: Base porosity calculated using Chew's formula,
- α: Porosity correction factor,
- H: Fence height, given as $H = 1.88\,\text{mm}$,
- CL: Clearance value.

For the given problem statement, the corrected porosity is:

$$\varepsilon_{\text{corrected}} = 0.2161$$

Velocity Through the Porous Bristle Pack

The Darcy–Forchheimer equation is solved to find the velocity of fluid u through the porous medium:

$$\Delta P = \frac{\mu}{\varepsilon} b_n u + \frac{\rho}{\varepsilon^2} a_n u^2$$

Where:

- ΔP: Pressure drop across the seal,
- μ: Dynamic viscosity of air,
- ρ: Air density,
- a_n, b_n: Empirical resistance coefficients,
- u: Flow velocity through the bristles.

Solving the above equation for the given parameters in the problem statement yields:

$$u = 15.3\,\text{m/s}$$

Leakage Mass Flow Rate Calculation

The leakage mass flow rate is calculated using:

$$\dot{m} = \rho \cdot A \cdot u$$

Where:

- $\dot{m}$: Leakage mass flow rate,
- A: Flow area through the bristle region,
- D_{bore}: Bore diameter,
- t: Bristle pack thickness.

The flow area is given by:

$$A = \pi \cdot D_{\text{bore}} \cdot t = 8.175 \times 10^{-5}\,\text{m}^2$$

Substituting values:

$$\dot{m} = 0.0183\,\text{kg/s}$$

This value represents the leakage rate through the brush seal under the given operating conditions and geometric parameters.

Modelling of Blow-Down Effect in Non-Contact Brush Seals

Brush seals with an initial clearance are often used to regulate cooling and leakage flows in rotating machinery. However, the sealing performance of these non-contact brush seals is heavily influenced by the **blow-down effect**, which dynamically alters the effective clearance during operation.

Mechanism of Blow-Down

When a pressure differential exists across the bristle pack, the upstream pressure exerts a force that causes the bristles to deflect radially toward the rotor. This phenomenon is referred to as **blow-down**. The bristles act like cantilever beams, and the aerodynamic force induces a bending moment due to their lay angle, causing them to bend and gradually close the initial clearance.

This mechanism has two major implications:

1. The **effective clearance** between the bristle tips and the rotor decreases, improving sealing performance.

2. The deformation depends on both the pressure ratio and the mechanical properties of the bristles.

Design Considerations

While a small clearance helps reduce leakage, the gap must also be large enough to:

- Prevent bristle–rotor contact under extreme operating conditions,
- Accommodate rotor eccentricity, thermal growth, and vibrations.

An excessively large clearance, on the other hand, will significantly increase the leakage, defeating the purpose of the seal.

Modeling Approach

The effective clearance is computed by applying a blow-down correction to the initial geometric clearance:

$$CL_{\text{effective}} = CL_{\text{initial}} - \text{Blow-down}$$

The blow-down displacement is computed using empirical relationships derived from CFD and experimental observations, which relate bristle deflection to:

- Pressure ratio ($PR = P_u/P_d$),
- Bristle diameter (d),
- Initial clearance (CL),
- Bristle lay angle and stiffness.

This correction is crucial to accurately capture leakage behavior in non-contact seals.

Impact on Leakage

As the clearance decreases due to blow-down:

- The leakage path through the gap is restricted,
- More flow is forced through the bristle pack,
- Overall mass flow rate of leakage decreases,
- The seal behaves closer to a contact-type brush seal in performance.

Blow-down modeling has been validated in CFD studies and experimental results (Turner et al., 1998; Kwon & Ahn, 2024), showing leakage reductions of up to 30–40% in cases with initial clearance.

Ilustration of Blow-Down Effect

The figures below illustrate how the blow-down effect reduces the effective clearance in a non-contact brush seal:

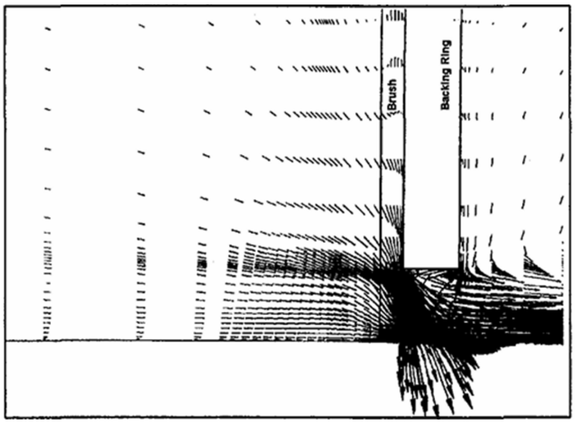

Figure 1: *
Image 1: Blow-down initiation under clearence 0f 0.75mm
(Source: ***[J. W. Kwon and J. Ahn]****)*

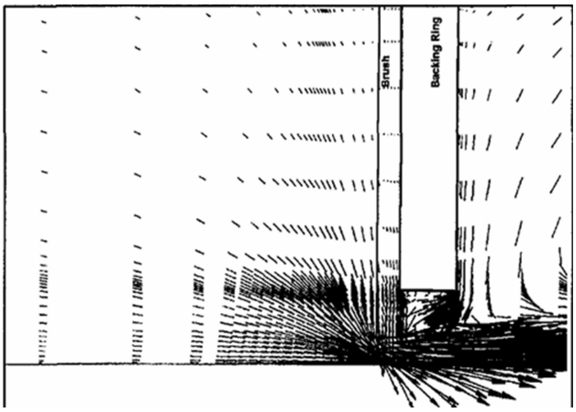

Figure 2: *
Image 2: Bristle deflection reducing effective clearance
(Source: ***[J. W. Kwon and J. Ahn]****)*

Estimation of Change in Clearance Value Due to Blow-Down Effect

Under high-pressure operating conditions, aerodynamic forces act on the bristles of the brush seal, causing them to deflect radially inward toward the rotor. This deflection results in a reduction of the effective clearance between the bristle tips and the rotor surface, thereby tightening the seal and reducing leakage.

The effective clearance after blow-down is estimated using thermodynamic and flow equations, incorporating constants specific to air:

- $\gamma = 1.4$: Ratio of specific heats for air
- $R = 287\,\mathrm{J/kg{\cdot}K}$: Specific gas constant for air

A flow function Q is used to capture compressibility effects and flow changes resulting from the pressure ratio across the seal. This function provides an accurate way to evaluate how aerodynamic loading affects the inward bristle deflection.

$$h_{\text{eff}} = \frac{\dot{m}\sqrt{T_u}}{\pi d_1 P_u Q}$$

The flow function Q is defined as:

$$
Q = \begin{cases} \sqrt{\frac{2\gamma}{R(\gamma-1)} \left[\left(\frac{P_d}{P_u}\right)^{\frac{2}{\gamma}} - \left(\frac{P_d}{P_u}\right)^{\frac{\gamma+1}{\gamma}} \right]} & \text{if } \frac{P_u}{P_d} \leq \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}} \\ \sqrt{\frac{\gamma}{R} \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} & \text{if } \frac{P_u}{P_d} > \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}} \end{cases}
$$

Calculation of Blow-Down Clearance

The reduction in clearance due to blow-down is calculated as:

$$
\text{Blow-down} = \frac{h_{\text{eff1}} - h_{\text{eff2}}}{\left(\frac{CL}{d}\right)^{0.21} - CL \cdot \left(\frac{CL}{d}\right) \cdot PR^2}
$$

Where:

- h_{eff1}: Effective clearance from mass flow rate with initial clearance (no blow-down)
- h_{eff2}: Effective clearance from mass flow rate with zero clearance (full blow-down)

The final corrected clearance is computed as:

$$
\text{New Clearance} = CL - \text{Blow-down}
$$

—

When the seal was modeled with an initial clearance:

$$
CL = 0.25\,\text{mm}
$$

After applying the blow-down correction:

$$
\text{New clearance} = 0.24\,\text{mm}
$$

After computing the porosity and resistance parameters, the resulting leakage mass flow rate was:

$$
\dot{m} = 0.093\,\text{kg/s}
$$

This value represents an 80% increase in leakage compared to the contact (zero clearance) case.

Effect of Shaft Speed on Leakage

Brush seals typically exhibit a slight reduction in leakage as shaft speed increases. This effect is attributed to dynamic interactions such as:

- Bristle tip deflection due to centrifugal loading,
- Frictional heating between the bristle and rotor,
- Radial displacement of the rotor.

Although these effects are not fully modeled in standard porous media approaches, empirical results suggest a leakage reduction of approximately 4.5%–5% from 0 to 69000 rpm.

Discussion on rotar speed effects

While the porous medium model captures average flow resistance well, it does not account for:

- Frictional heating at the bristle tip,
- Dynamic pressure due to rotor eccentricity or vibration.

These effects are likely responsible for additional leakage reduction observed in real rotating seals.

Because this porous medium model ignores the friction heat of the bristle tip and the dynamic pressure effect due to the rotor radial displacement, these effects are the main reasons for leakage reduction.

Empirical Estimations

$$\text{At } 30000\,\text{rpm: Reduction} \approx \frac{30000}{69000} \times 4.97\% \approx 2.16\%$$
$$Q_m(30000) = 1.93 \cdot (1 - 0.0216) \approx 1.89\,\text{g/s}$$

$$\text{At } 15000\,\text{rpm: Reduction} \approx \frac{15000}{69000} \times 4.97\% \approx 1.08\%$$
$$Q_m(15000) = 1.93 \cdot (1 - 0.0108) \approx 1.91\,\text{g/s}$$

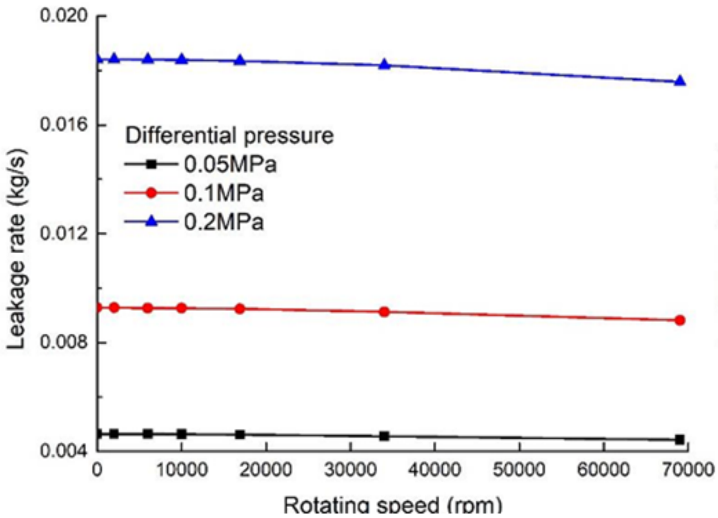

Figure 3: *
Image 3: Effect of rotor speed on leakage
(Source: ***X. Song, M. Liu, and J. Yang****)*

Reference

X. Song, M. Liu, and J. Yang, "Numerical Analysis of Leakage Performance of Brush Seal Based on a 2-D Tube Bank Model and Porous Medium Model Considering the Effect of Compressible Gas."

Verification Using CFD Analysis

The CFD analysis presented in this study is primarily based on the methodology and findings from the paper:

Kwon, J.W.; Ahn, J. (2024). ***Prediction of Leakage Flow Rate and Blow-Down in Brush Seals via 2D CFD Simulation with Porosity Correction*****, Applied Sciences, 14, 8821.**

This reference was instrumental in developing the porosity correction model and in simulating the blow-down behavior for both contact and clearance-type brush seals.

CFD Domain Setup and Meshing

The computational domain was modeled in 2D with an axial length of **10 mm**. Meshing details are as follows:

- **Fluid domain:** Uniform mesh size of 0.2 mm
- **Bristle (porous) region:** Refined mesh with 0.1 mm sizing
- **Boundary Conditions:** Pressure inlet and pressure outlet

Porous Zone Parameters in ANSYS Fluent

The bristle region was modeled as a porous zone using Darcy–Forchheimer resistance terms:

- **Viscous resistance coefficient** $b_n = 3.45 \times 10^7$
- **Inertial resistance coefficient** $a_n = 8.2 \times 10^{10}$

These values were directly input into ANSYS Fluent under the porous media settings, along with the corrected porosity calculated from the empirical formula.

CFD Geometry and Mesh

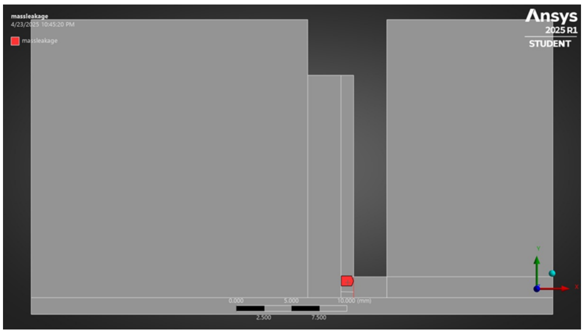

Figure 4: *
Image 1: Model / Fluid Domain (2D)

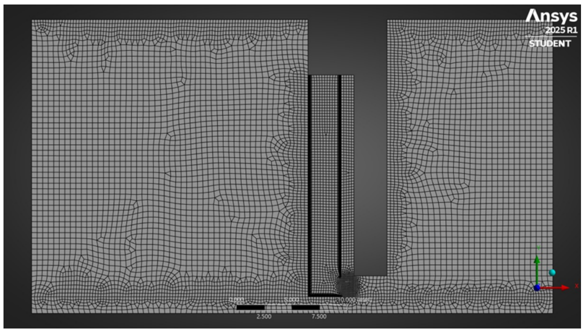

Figure 5: *
Image 2: Meshed Model

9. Results and Validation

Results Validation of Contact Brush Seal

As seen from the CFD simulation results, the analytical mathematical model closely matches the CFD results for the contact (zero-clearance) case.

$$\dot{m}_{\mathrm{CFD}} = 0.019561\,\mathrm{kg/s}, \quad v_{\mathrm{CFD}} = 15.62\,\mathrm{m/s}$$

When compared to the analytical model, the observed errors are:

- Error in mass flow rate $\dot{m}$ is less than **10%**
- Error in velocity v is less than **3%**

These results validate the accuracy of the porous media and blow-down modeling approach under zero-clearance conditions.

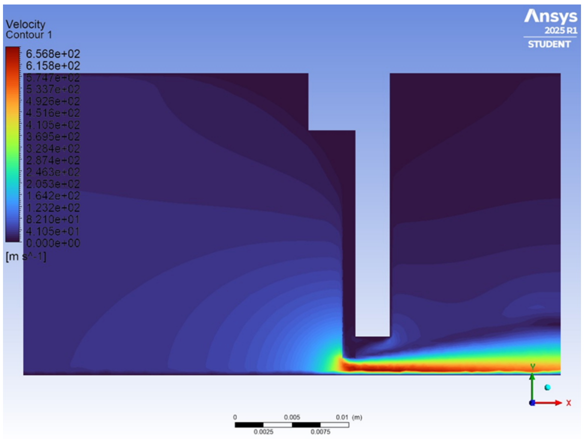

Figure 6: *
Image 1: Velocity Contour (Contact Seal)

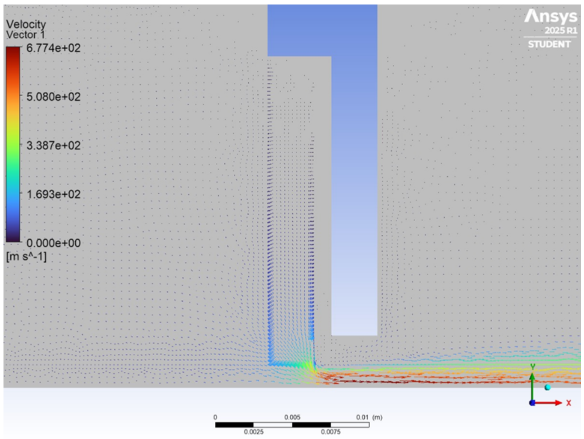

Figure 7: *
Image 2: Velocity Vector Plot (Contact Seal)

Results Validation of 0.25 mm Clearance Brush Seal

As seen from the CFD simulation results, our analytical mathematical model closely matches the CFD results for the brush seal with an initial clearance of 0.25 mm.

$$\dot{m}_{\mathrm{CFD}} = 0.099267\,\mathrm{kg/s}, \quad v_{\mathrm{CFD}} = 58.84\,\mathrm{m/s}$$

When compared to the analytical model, the observed errors are:

- Error in mass flow rate $\dot{m}$ is less than **7%**
- Velocity agreement confirms the flow resistance behavior across the bristle pack

This validates the effectiveness of the porosity correction and blow-down modeling even when a clearance is present.

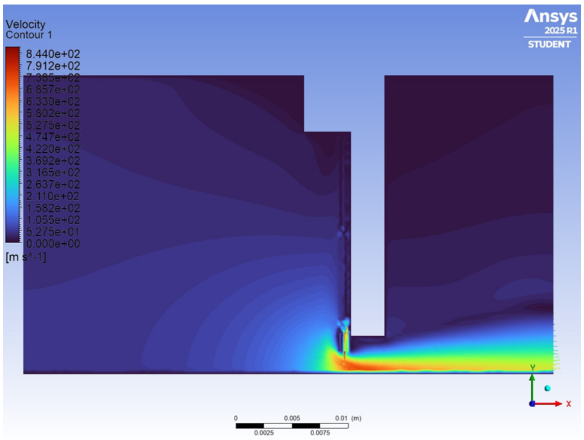

Figure 8: *
Image 1: Velocity Contour (0.25 mm Clearance)

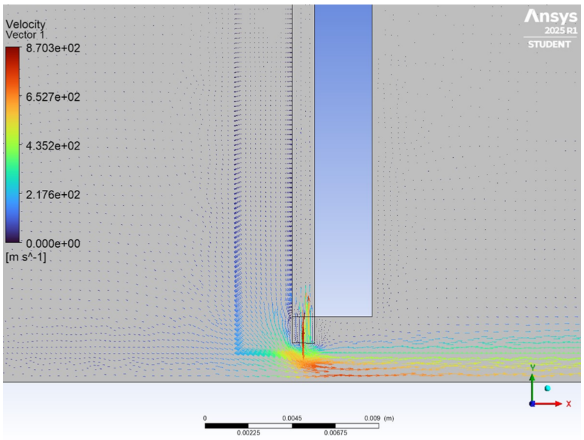

Figure 9: *
Image 2: Velocity Vector Plot (0.25 mm Clearance)

Conclusion

Based on the analytical modeling and CFD simulation of brush seal leakage, the following conclusions are drawn:

1. **Porous media modeling** provides an efficient and accurate approach for simulating flow through the bristle pack, eliminating the need for resolving individual bristles.

2. The application of the **porosity correction factor** significantly improves leakage prediction, especially under varying clearance and pressure ratio conditions.

3. **Blow-down effects**, when included, lead to a measurable reduction in effective clearance, thereby enhancing sealing performance — especially at moderate to high pressure ratios.

4. CFD validation shows excellent agreement with analytical results:

   - Error in mass flow rate $\dot{m} < 10\%$ for contact case

   - Error in mass flow rate $\dot{m} < 7\%$ for 0.25 mm clearance

5. Increasing **shaft speed** slightly reduces leakage due to bristle tip deflection and frictional heating; however, this effect is modest (typically ¡5%) and may require advanced thermal-structural modeling for full capture.

6. The developed model is capable of accurately predicting leakage behavior for both contact and clearance brush seals, validated by CFD simulations.

7. This approach can serve as a baseline for further studies involving temperature effects, transient operations, or brush seal wear behavior.

8. The combination of analytical modeling and CFD forms a robust design tool for high-efficiency sealing in aerospace and turbomachinery applications.

11. References

1. J. W. Kwon and J. Ahn, "**Prediction of Leakage Flow Rate and Blow-Down in Brush Seals via 2D CFD Simulation with Porosity Correction**," *Applied Sciences*, vol. 14, no. 18, pp. 8821, 2024.

2. S. Huang, H. Ma, W. Sun, and Y. Zhang, "**Leakage Analysis of Brush Seals with Retaining Ring Based on CFD and Experimental Data**," *Applied Mechanics and Materials*, vol. 345, pp. 642–648, 2013.

3. M. T. Turner, N. C. Bowsher, and R. A. E. Sims, "**Development of a Porous Medium Approach to Model the Flow and Pressure Field in Brush Seals**," in *ASME International Gas Turbine and Aeroengine Congress and Exhibition*, Stockholm, Sweden, 1998, Paper No. 98-GT-98.

4. X. Song, H. Ma, Y. He, and J. Liu, "**Prediction Model for Leakage Flow of Brush Seal Considering Gas Compressibility Based on Darcy–Forchheimer Law**," *International Journal of Fluid Machinery and Systems*, vol. 15, no. 3, pp. 329–339, 2022.

5. Y. Zhang, D. Ma, J. Li, et al., "**Effect of the Fence Height on the Leakage Flow Characteristics of Brush Seals**," in *Proc. of the Global Power and Propulsion Society Conference*, Beijing, China, 2019, Paper No. GPPS-BJ-2019-0021.

6. F. J. Bayley and C. A. Long, "**A Combined Experimental and Theoretical Study of Flow and Pressure Distributions in a Brush Seal**," *Journal of Engineering for Gas Turbines and Power*, vol. 115, no. 2, pp. 404–410, Apr. 1993.