A TWO-PHASE BULK FLOW MODEL FOR PREDICTION OF FORCE COEFFICIENTS IN WET GAS LABYRINTH SEALS AND POCKET DAMPER SEALS

Dr. Luis San Andrés, Mast-Childs Chair Professor
Dr. Jing Yang, Assistant Research Engineer
June 2020

SIGNIFICANCE

Since their invention in 1991 [1], pocket damper seals (PDS) that generate a large effective damping coefficient are applied in high performance turbomachinery, in particular centrifugal compressors. Figure 1 displays a photograph of a typical PDS for a commercial application.

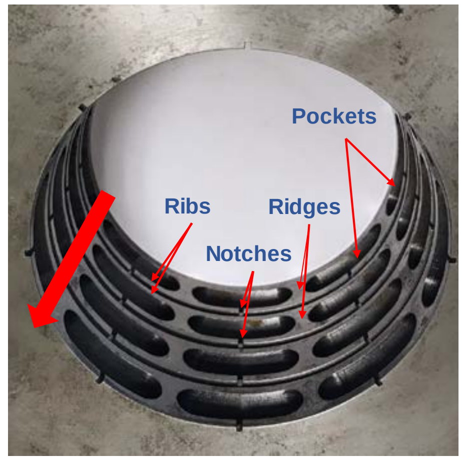


Fig. 1 Photograph of typical pocket damper seal.

Current and upcoming multiple-phase pump and compression systems in subsea production facilities must demonstrate long-term operation and continuous availability. Uniform clearance seals and labyrinth seals produce persistent subsynchronous rotor vibrations in these subsea systems. Recently, however, a wet compressor incorporating a PDS operated stably where a labyrinth seal (LS) could not [2]. The ridges in the pockets stop the circulation of trapped liquid.

The bulk-flow model (BFM) is a time-efficient way to predict the leakage and dynamic force coefficients for PDSs. In 1999, Li and San Andrés [3] developed PDSEAL®, a one-control-volume BFM for gas LSs and PDSs. As for *wet* gas seals, there are two-phase BFMs applicable to smooth surface annular seals [4-5], and none for PDSs in spite they generate large damping and promote rotor stability under wet gas operation. Thus, it is urgent to develop a proven BFM for wet gas PDSs, The tool by default would also apply to labyrinth seals (LS) because of their simplicity.

A SIMPLE MODEL PREDICTING LEAKAGE FOR WET GAS PDS / LS

During the past year, work produced a simple tool for predicting the leakage and cavity pressures in a PDS or a LS operating with a wet gas [6]. The formulation derives from an adaptation of Neumann's leakage equation across a tooth and uses the physical properties of a homogeneous two-phase flow mixture.

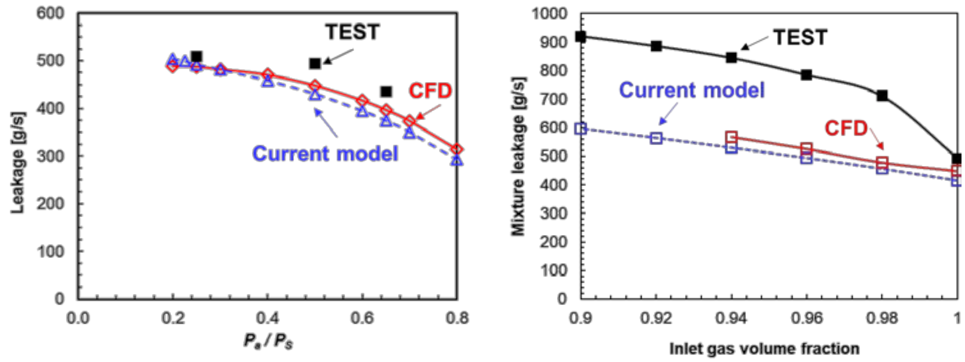
For a four-rib, eight-pocket fully partitioned PDS [7] with clearance C_r = 0.18 mm and length-diameter ratio L/D = 0.38 supplied with a silicone oil (ISO-VG10) in air mixture, Table 1 lists the current model predicted, measured and CFD predicted leakage (mixture and gas content). The PDS operates at supply pressure P_S = 2.3 bar and inlet liquid volume fraction (LVF) = 0.4%; and P_S = 3.2 bar and LVF = 2.2%. The discharge is at ambient pressure, P_a = 1 bar. The rotor speed is 5,250 rpm (surface speed 35 m/s). Note an inlet LVF = 2.2% corresponds to a large liquid mass fraction of ~ 84%. The simple model predicted leakage agrees with the test data and CFD results. Other results for pure gas operation (not shown here) show also excellent correlation [6].

Table 1. Current model predicted, measured and CFD predicted leakage for a four-blade pocket damper seal. Test data and CFD results from Ref. [7]. Fully partitioned PDS, clearance C_r = 0.18 mm, L / D = 0.38.

		Mixture [g/s]			Gas [g/s]		
	Inlet	Code	TEST	CFD	Code	TEST	CFD
P_S = 2.3 bar	LVF = 0.4%	27.8	27.2 ±3	28.4	12.0	11.7	12.3
P_S = 3.2 bar	LVF = 2.2%	68.6	68.7 ±3	69.3	10.9	11.2	11.0

A second validation case corresponds to an eight-blade, eight-pocket fully partitioned PDS (C_r = 0.20 mm and L/D = 0.75) [8], operating with supply pressure P_S = 70 bar, pressure ratio $PR = (P_a / P_S)$ = 0.2 ~ 0.8, and rotor speed at Ω = 10 krpm (ΩR = 61 m/s). For pure gas operation (LVF=0 → gas volume fraction= GVF=1), see Fig. 2(a), the simple model predicted leakage differs at most by 14% with the measured leakage. For the PDS supplied with a wet gas (inlet GVF = 0.9 ~ 0.98) and *PR* = 0.5, the simple model and CFD predictions are in close agreement with each other; alas they are 30% below the reported leakage in [8]. Note the air mass flow rate reported in [8] is likely in error.

In sum, the current simple two-phase flow model offers + accurate predictions as compared to PDS leakage measurements at low pressures and CFD model results at a high-pressure PDS.



(a) Gas leakage vs. *PR* (inlet GVF = 1) **(b) Mixture leakage vs. inlet GVF**

Fig. 2 Current model predicted, CFD predicted, and measured [8] leakage for a PDS. (a) Leakage vs. *PR* (inlet GVF = 1), (b) Mixture leakage vs. inlet GVF (GVF = 0.9 ~ 1) and *PR* = 0.5. Clearance C_r = 0.20 mm, L / D = 0.75, P_S = 70 bar, rotor speed 10 krpm.

PROPOSED WORK 2020-2021 (Year IV)

Work will continue toward completing the two-phase BFM tool to predict the dynamic force coefficients for both LSs and PDSs supplied with a liquid in gas mixture. Specific tasks include:

1. Use two-component flow homogeneous mixture applied strictly to the BFM in Ref. [3].
2. Validate the BFM leakage and dynamic force coefficients for *dry* and a *wet* gas PDS against archival test data.

The research will produce an accurate predictive tool to better design, troubleshoot and validate the operation of PDSs/LSs supplied with a wet gas and applied into high performance compressors and steam turbines. The deliverable will include a new GUI for the computational program with examples of validation.

BUDGET FROM TRC FOR 2020-2021

Support for research engineer (20 h/week) x $ 5,075	$ 30,450
Fringe benefits (16.8%) and medical insurance ($747/month)	$ 9,598
Support for a undergraduate student $2,500 x 50% effort of 10 months	$ 6,250
HPRC fees and PC upgrade	$ 1,702
Research engineer travel & registration to technical conference	$ 2,000
Total Cost:	**$ 50,000**
Remaining balance by Aug. 31, 2020:	**-$ 32,336**
2020-2021 Total Requested:	**$ 17,664**

REFERENCES

[1] Vance, J. M and Schultz, R. R., 1993, "A New Damper Seal for Turbomachinery," ASME Proc. of 14th Biennial Conference on Mechanical Vibration and Noise, Vibration of Rotating Systems, **60**, pp 139-148.

[2] Vannini, G., Bertoneri, M., Nielsen, K. K, Ludiciani, P., and Stronach, R., 2016, "Experimental Results and Computational Fluid Dynamics Simulations of Labyrinth and Pocket Damper Seals for Wet Gas Compression," ASME J. Eng. Gas Turbines Power, **138**(5), pp. 052501.

[3] Li, J., and San Andrés, L., 1999, "A Bulk-Flow Analysis of Multiple-Pocket Gas Damper Seals," ASME J. Eng. Gas Turb. Power, **121**, pp. 355-363.

[4] San Andrés, L., 2012, "Rotordynamic Force Coefficients of Bubbly Mixture Annular Pressure Seals," ASME J. Gas Turbines Power, **134**(2), p. 022503.

[5] San Andrés, L., Lu. X., 2020, "A Nonhomogeneous Bulk Flow Model for Prediction of the Static and Dynamic Forced Performance of Two Phase Flow Annular Seals," TRC-SEAL-02-2020, Turbomachinery Research Consortium (TRC) Final Report.

[6] San Andrés, L., and Yang, J., 2020, "A Simple Two-Phase Bulk-Flow Model for Prediction of Force Coefficients in Wet Gas Labyrinth Seals and Pocket Damper Seals," TRC-SEAL-03-2020, Turbomachinery Research Consortium (TRC) Progress Report.

[7] Yang, J., San Andrés, L., and Lu, X., 2019, "Leakage and Dynamic Force Coefficients of a Pocket Damper Seal Operating Under a Wet Gas Condition: Tests VS. Predictions," ASME J. Eng. Gas Turbines Power, **141**(11), pp. 111001.

[8] Delgado, A., and Thiele, J., 2019, "Rotordynamic Characteristics of Fully Partitioned Pocket Damper Seal," Turbomachinery Research Consortium (TRC) Progress Report, Texas A&M University, College Station, TX.