distortion of the mating surfaces is not considered. Under some conditions both mechanical and thermal stresses may alter the shape of the fluid channel enough to significantly affect the flow pattern (and ultimately the stiffness) of the seal. Nevertheless this work may provide some insight into the transient behavior of two-phase seals and a basis for further investigation.

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DISCUSSION

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The authors have made another important contribution to the complex modeling of "two-phase face seal dynamics" by extending their analysis to include turbulent flow. The "squeeze film model" presented here can handle two extreme cases namely, conduction-dominated low leakage flow with discrete boiling, and convection-dominated high leakage turbulent flow with adiabatic wall condition. The authors have earlier developed a steady-state model (Yasuna and Hughes, 1990) for the intermediate regime which considers both conduction and convection modes of heat transfer. Is there any numerical difficulty in a "squeeze film model" for the above intermediate operation regime?

One interesting point to note from Fig. 4, is that the two-phase seal with the indicated coning develops about 90 N/μm of film stiffness at an operating film thickness of 1 μm for lower fluid temperatures. In comparison, a high pressure, high speed (e.g., 70 bars, 16000 RPM) gas seal of comparable size with hydrodynamic grooves can develop a film stiffness of 1000–2000 N/μm at an operating film of 3 μm. The main mode of perturbation to the fluid film in any seal is the angular misalignment or "total indicated run out (TIR)" of the seal faces which is in the neighborhood of 100 μm for gas compressors and 200 μm for pumps. Therefore, the film perturbation amplitude is about two orders of magnitude higher than the average film thickness. Hence, in order that the seal rings track each other without contact, the fluid film stiffness should be very high. In gas seals, the level of film stiffness, indicated above, ensures noncontacting operation. Although a two-phase seal has much higher stiffness than a corresponding liquid seal, its stiffness may not be high enough for complete noncontact operation, particularly so, in light of higher angular misalignment. However, a properly designed two-phase seal has the potential of greatly reducing the mechanical contact load between the seal faces.

Next, a semi-infinite conduction model is used in the paper. In actual seal configurations, however, the seal cavity is in close proximity to the seal faces. The cavity fluid constantly experiences turbulent mixing due to the rotor motion and the injection of cooling flow. The resulting high heat transfer coefficients of the seal outside surfaces would greatly influence the seal face temperature distribution. Therefore, it will be interesting to see how a finite heat transfer model affects the prediction.

In Figures 8(a) and 8(b), the response time scale is about 3 s which results in a thermal skin depth (Yasuna and Hughes, 1992) of about 10 mm, which is comparable to the seal face width. Therefore, the transient heat conduction may not be quite one-dimensional, as assumed in the paper, for this particular case.

In closing, the authors are to be commended for developing an intricate dynamic model which promises to explain some of the anomalous behaviors of two-phase seals.

Authors' Closure

The authors wish to thank Dr. Basu for his useful comments and insight into this problem. We agree with his observations.

Indeed, it would be useful to analyze the intermediate region between laminer and turbulent flow but at present the difficulties of transition flow and the heat transfer problem are beyond our capabilities.

While it is certainly true that our assumption of non contacting faces may be somewhat unrealistic for steady low leakage flow, that assumption is probably quite good after the seal has begun to pop open. It is precisely this condition where the seal begins to open catastrophically that is of greatest interest

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here. Further the assumption of adibatic flow becomes more valid as the seal opens up.

Of particular interest is the prediction that as saturation conditions are approached in the sealed liquid, the seal will eventually open catastrophically unless it is over balanced in the operating mode. Although our model may not predict the precise tracking trajectory, we believed the ultimate failure modes are probably predicted at least qualitatively correctly and designers should be cautioned against situations where the sealed liquid may approach saturation.