hence attenuates hydrodynamic pressure drop. This combined with a higher P_b at R_b, at least in the present study, eliminates cavitation.

3. Under certain operating conditions, characterized by a modified Sommerfeld number S^*, several approximate solutions with various levels of simplification can be utilized to calculate the boiling radius $R_b(\theta)$ in a misaligned two-phase seal.

4. For the hot water application of the present study it was found that:

(a) When $S^* < 0.4$ the rotor face temperature in the liquid phase is very accurately predicted from an ''all liquid'' solution of the heat transfer problem.

(b) When $S^* < 0.2$ the boiling interface $R_b(\theta)$ is accurately predicted from a hydrostatic solution neglecting the hydrodynamic pressure component.

(c) When $S^* < 0.1$ the boiling interface is practically axisymmetric regardless of ϵ, and R_b is accurately predicted from the simplest solution for $\epsilon = 0$.

The present work seems to be the first attempt to analyze quantitatively the boiling interface in a misaligned face seal. Hence, no comparison could be made with previous published results. It is hoped that the finding of this work, and particularly the possibilities to use simplified solutions to this complex problem, will trigger further studies of the interesting phase change phenomenon in misaligned seals.

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DISCUSSION

Alan O. Lebeck[2]

Having performed both analysis and experimental work on two phase seals, I commend the authors for initiating studies on the effects of two-phase fluid behavior in a nonaxisymmetric seal interface. Several questions arise.

1. While the narrow bearing assumption is useful for liquid flows in seals, the use of this assumption for *two-phase seals* suggests that *tangential pressure flow in the gas phase can be neglected.* While this may be true for seals with large leakage paths, one imagines that *such pressure flows would be very important in narrow gap seals* such as, for example, wavy or grooved seals used for two phase applications. Could the authors comment on this issue?

2. How does the two-phase pressure distribution affect the tilt moment? If one were operating a radically tapered seal near boiling conditions, would the effect of phase change coupled with nonaxisymmetric effects contribute to seal instability?

3. How would nonaxisymmetric two-phase behavior affect the stability of operation of a wavy face seal operating in a two phase environment? Would the variation in the boiling radius enhance fluid pressure liftoff or would it decrease?

4. Could the authors suggest other areas of application of mechanical seals where this two-phase, nonaxisymmetric analysis can be applied?

R. Metcalfe[3]

This paper provides an interesting insight into some hydrodynamic aspects of two-phase seals. Can the authors please comment on the additional influence of typical seal ring conductivities and specific heats? It has been shown[4] that there can be considerable heat transfer around a seal due to alternating heating and cooling of the surface layer as the seal spins. Would this not act to increase the axisymmetry of the boiling radius and counter the hydrodynamic effect shown, for example, in the authors' Fig. 4?

Authors' Closure

The authors would like to thank Dr. Lebeck and Dr. Metcalfe for their comments and interest in the paper.

The narrow bearing assumption does not mean no tangential flow in the sealing gap. It only means that the tangential component of the flow is much smaller than the radial one and hence can be neglected in the Reynolds equation. This reasoning holds for the gas phase in two-phase seals as much as it holds for all-liquid or all-gas seals. In all these cases the circumferential pressure gradients can be much smaller than the radial pressure gradients, especially in high pressure applications like the present example with $p_o - p_i$ of 1 MPa.

The effect of the boiling on the seal forces and moments is the subject of a current research which hopefully will be completed soon. In the case of purely hydrostatic seals, however, (see Etsion and Pascovici, 1996a) the two-phase pressure distribution does contribute to reduce seal stability.

We did not analyze two-phase weavy seals so far and, hence, cannot provide complete answers regarding the changes in the liftoff. In general, boiling in high pressure seals tends to eliminate cavitation which is a major factor in generating liftoff in

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[4] Metcalfe et al, ''Eccentric Seals for Nuclear Pumps,'' *Proc. 14th Int. Conf. Fluid Sealing*, BHR Group, Cranfield, UK, April 1994.

weavy seals. On the other hand, the hydrostatic pressure increase in the gas phase tends to increase the liftoff.

Regarding the comments by Dr. Metcalfe, we agree that any factor contributing to better heat transfer will tend to increase the axisymmetry of the boiling radius. It should be noted, however, that in our case the nonaxisymmetric nature of the hydrodynamic pressure distribution is the major cause for the nonaxisymmetric nature of the boiling interface. This pressure distribution effect far exceeds the effect of the temperature distribution on the boiling radius.