

Results indicate that in most cases squeeze film damping and thermal transient effects are important in the analysis of transient seal response. For step increases in film thickness, the response is usually a decay as the rotor asymptotically approaches the initial steady-state conditions. Alternately for step decreases (of sufficient magnitude) in film thickness, the seal either “pops” open (in a monotonic fashion) or fails (collapses or pops open) due to the onset of oscillatory instabilities. Under certain conditions the response to small step decreases in film thickness appears to be stable and the rotor approaches the steady state asymptotically or in an oscillatory (but stable) manner.

It is not possible at this time to present a general stability map, but we can tentatively conclude that seals should be designed such that they are balanced (in the steady state) in a region of large positive stiffness. Even a small amount of coning would appear to assure stability for even large disturbances. Further it appears that the magnitude of the response parameter (a measure of thermal inertia) is important when considering response times and overshoot (in cases where the rotor tends to asymptotically return to steady-state conditions).

Two limitations to this model should be noted. First the assumption of one dimensional (axial) heat transfer in the seal plates for the transient model results in responses which never return precisely to the associated steady-state values. This is because transient heat flux variations (from the steady state) will always be felt at all later times and hence there will always be some temperature deviation (again from the steady state) throughout the leakage path. However for the test cases presented estimated values for the skin depth are sufficiently small so as to support the above assumption. An exact thermal analysis requires modeling the seal plates with finite dimensions, thus restricting the applicability of each computer code execution to a specific seal design rather than to a broad range of rotor/stator (axial) thicknesses. The second limitation is the discrete boiling and laminar flow assumptions, which are valid only for small film thicknesses where the leakage is low. As the seal gap increases, thermal convection becomes important and laminar two phase flow may appear over a portion of the seal face (Yasuna and Hughes, 1990). As the seal begins to pop open, the flow eventually becomes turbulent and adiabatic (Beatty and Hughes, 1986). A transient analysis including two phase turbulent fluid modeling is necessary to examine the full range of dynamic seal response.

DISCUSSION

A. O. Lebeck¹

The authors have moved the analysis of two phase seal behavior an important step forward. Their dynamic analysis has the potential to explain face seal puffing. I would hope they would extend their analysis to consider two current applications in more detail. First, many flat faced seals operate with some degree of contact for most operating conditions but may, if their geometric balance ratio is low, pop open or puff at certain temperatures in the two phase regime. By including contact load support and contact friction heating, the authors' model should predict such behavior. While there exist static models that predict this point of instability, it would be very helpful using the dynamic model to see if the static predictions are correct and to better understand this behavior. Second,

¹Mechanical Seal Technology, Inc., Albuquerque, NM 87109.

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for radially tapered seals that operate under noncontacting conditions, the authors showed no instability or cyclic response. Could the authors investigate a wide range of conditions to see if this is always true, or is the stability condition both operation condition and design specific? This question has important implications for the application of such radially tapered seals in two phase applications.

R. Metcalfe²

I'm pleased to see the authors' progress toward fuller modeling of “popping-open” phenomena in face seals. The complexity of this has been well demonstrated by tests and analysis at my company and others, and I appreciate that the authors are making no rash claims that this paper now gives the complete answers.

²Technical Director-FSTU, Engineering Technologies Division, Chalk River Laboratories, Chalk River, Ontario.

Most of the authors' basic assumptions are well-explained; smooth seal faces, no tilting, no radial conduction and convection, laminar flow, axisymmetry, ideal fluid properties and no axial friction. Would they confirm that they also neglect deformation of the seal faces, liquid-to-vapor transition time, and inlet and exit losses? These are three further effects AECL has been analyzing recently in relation to our measurements of onset of "chattering" and "popping-open" of reactor coolant pump seals. Other important governing parameters appear to be roughness, axial friction at the secondary seal and non-axisymmetric tilting. Thermal deformation is generally important because this affects the initial coning significantly.

I commend the authors for their approach. Their conclusions, necessarily limited by their assumptions, seem to be both sound and generally relevant to the problem of preventing "popping-open." My sole hesitation is the unqualified endorsement of positive coning, which in AECL's experience is not "good" under all conditions. The authors' comments would be appreciated.

Authors' Closure

The authors wish to thank Dr. Lebeck and Dr. Metcalfe for their insightful comments on our paper. As Dr. Metcalfe indicated, there are several limiting assumptions associated with our model. These were necessary to reduce the problem to

a (computationally) tractable form while still permitting squeeze film and thermal effects to be considered.

In response to Dr. Metcalfe's question, in addition to the stated assumptions inlet losses, phase change transition kinetics and thermoelastic deformations were not considered in the present model. Inlet losses are typically negligible under low leakage conditions, and the inclusion of seal deformations requires an additional iterative loop and hence would significantly increase the already excessive computational overhead. Nevertheless mechanical and thermal distortions eventually must be considered.

Dr. Lebeck indicated that contact load support and friction heating may be important for flat faced seals under most operating conditions. These effects certainly should be considered in situations where seals tend to collapse, but are moot in situations where seals tend to "pop" open. It is unclear whether contact is important for the range of film thickness examined herein, yet ultimately a revised model including contact effects must be developed to analyze the full range of seal operation.

Both Dr. Lebeck and Dr. Metcalfe requested further analyses of coned seals. Various coning slopes were analyzed, and none of the results indicated an unstable nor even cyclic response under laminar flow conditions. However, more recently the present model has been extended to track seal dynamics under turbulent flow conditions, and preliminary results indicate axial instabilities under certain operating conditions. Further analyses are forthcoming.