DISCUSSION

Theoretical Investigation of Heat Pipes Operating at Low Vapor Pressures

G. S. DZAKOWIC

The author is to be commended for his study which extends the earlier incompressible flow analysis proposed by Cotter (author's reference no. [1]). When the design operating temperature is above ambient conditions, a heat pipe will encounter a sonic vapor flow limit during heating up due to very low vapor pressure and vapor density. There is, however, a peculiarity with sodium vapor flow which bears elaboration. Any comments that Dr. Levy may have on this would be most appreciated.

An analysis of sodium heat pipe test data made by this writer for flow with a sonic velocity at the exit of the evaporator showed that neither a perfect gas model nor a condensation model was suitable for the description of sodium vapor flow. The perfect gas model is unacceptable for sodium vapor because the real gas specific heat deviates greatly from that of the perfect gas model. Because the author did not complete the perfect gas analysis for axial temperature and pressure profiles, and because the author did not recommend the use of this model, no further elaboration of this view needs to be given.

The second model described in the paper considers a liquid-vapor phase equilibrium maintained at all axial positions in the evaporator. Under this assumption, condensation of the vapor flow must take place in the evaporator region as a result of supersaturation of the vapor due to its expansion to attain a sonic velocity. Condensation appears to be highly unlikely in view of the fact that nucleation sites which are required in most cases for the commencement of condensation are not available in the vapor passage. The view that spontaneous nucleation can be occurring for condensation of the vapor is discredited by Shapiro, author's reference [7] pp. 203, 204, who notes that a liquid-vapor equilibrium should not be anticipated in an expanding vapor flow until a relatively high degree of supersaturation of the vapor occurs. This is necessary to produce a spontaneous condensation phenomena.

To estimate the degree of supersaturation of sodium vapor, it is most fruitful to examine a third view for sonic flow which applies to the particular case of alkali metal vapors (lithium, sodium, rubidium, potassium, and cesium). These vapors are reported to undergo a dissociation-recombination reaction (dimer ⇌ monomer) in their equilibrium forms. The bonding energy which is absorbed or released with temperature change is treated as part of the specific heat capacity of the vapor. In the particular case of equilibrium sodium vapor, and for the temperatures of heat pipe startup (nominal 400 deg C to 600 deg C), the vapor equilibrium specific heat is four times that for the perfect monatomic gas. Moreover, the apparent specific heat capacity of equilibrium sodium vapor even exceeds that of liquid sodium.

On the other hand, the sonic velocity for equilibrium vapor decreases the magnitude of the frozen sonic velocity by a constant multiplier of 0.77. In terms of heat transport capability subject to a sonic limit in the heat pipe, the heat transport is decreased by 28 percent for the perfect gas curve shown in Fig. 8. An equilibrium sonic velocity limit would produce a curve similar to curve A (Fig 8), however, the heat transport capability would be 0.77 of the assigned values. When compared with the author's uncertainty in the condensation model, namely curves B and C, the uncertainty of heat transport capability between equilibrium and frozen vapor flow limits is relatively small. Applying an energy balance to the equilibrium sodium vapor flow in a heat pipe, an axial temperature decrease of approximately 45 deg C is needed to accelerate the vapor to an equilibrium sonic velocity. This magnitude of vapor temperature decrease is only slightly more than that illustrated in Fig. (3).

Interpreting this result in another way, one notes that if the vapor maintains an equilibrium with itself (monomer ⇌ dimer) then the degree of supersaturation for sodium vapor remains small, and condensation in the evaporator section of the vapor flow should not take place. Moreover, it seems reasonable that dissociation will take place before condensation, since the latter process requires nucleation sites whereas the dissociation reaction does not.

Author's Closure

Dr. Dzakowic has raised some interesting points regarding the choice of an equation of state for the sodium vapor. He is particularly concerned about the validity of the assumption of liquid-vapor phase equilibrium throughout the vapor passage of the evaporator section. After a review of the homogeneous nucleation literature, I have concluded that he is probably correct about the condensation problem. Calculations show that within the temperature range of interest, the critical degree of supersaturation required to cause condensation in sodium vapor is larger than the expected axial temperature variation. This would indicate as has been suggested that spontaneous nucleation does not occur. Therefore, to accurately compute the axial variations of pressure and temperature of the vapor and the maximum rate of heat transfer based on sonic velocity limitations, one should treat the

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vapor as a single phase fluid solving equations (2), (3), and (4) along with a vapor equation of state which takes into consideration the presence of both the monomer and dimer constituents. A rough estimate of the maximum rate of heat transfer can be obtained from equation (14). This quantity appears to be relatively insensitive to the particular equation of state which is used.

Stress-Concentration Factors in Shouldered Shafts Subjects to Combinations of Flexure and Torsion

N. L. Svensson

This paper provides an interesting study of a problem having considerable significance in shaft design problems. The value of the contribution would, however, be greatly improved through some analysis which provides a more general determination.

Using the observation that the directions of principal stress are not changed by the presence of the discontinuity it may be shown that

\[(\sigma_{ax})_{\text{max}} = K_T \cdot \frac{16M_T}{\pi d^3}\]

and

\[(\sigma_{ar})_{\text{max}} = K_s \cdot \frac{16M}{\pi d^3}\]

where \(K_T, K_s\) are stress-concentration factors in torsion and bending, respectively. \(M_T, M\) are torque and bending moment, \(a, \theta\) axial and circumferential coordinates.

The authors' work shows that the location of these maximum stresses is not identical. However, it is apparent that the stresses are not changing rapidly in the vicinity of the maximum stress point. It is expected that as \(r/d\) is decreased, this separation becomes smaller.

Therefore, assuming that peak stresses occur in the same location, the stresses are additive and we have

\[\tau_{\text{max}} = \frac{16M_T}{\pi d^3} [K_T^2 + K_s^2 R^2]^{1/2}\]

where \(R = M/M_T\).

The nominal maximum shear stress

\[\tau = \frac{16M_T}{\pi d^3} [1 + R^2]^{1/2}\]

Therefore the stress-concentration factor under combined load is

\[K_C = \left[\frac{K_T^2 + K_s^2 R^2}{1 + R^2}\right]^{1/2}\]

This expression takes values intermediate between \(K_T\) and \(K_s\) as \(R\) varies from 0 to \(\infty\). The relationship then forms the basis for a theoretical appraisal of the authors' experimental results.

Authors' Closure

The discussion presented by Mr. N. L. Svensson does provide an interesting analytic method of data evaluation and extrapolation within the framework of the stated assumptions. Several methods of evaluation were studied by the authors but each was discarded, since the only accurate evaluation would be relative to a theoretical solution for the three dimensional stress distribution in the region of maximum stress.

Subsequent theoretical solutions show highly nonlinear stress variations with a radial position in the section. These radial stress variations couple with stress variations along the shaft to produce fluctuations of maximum stress at the surface. Therefore with only slight position changes in location, it is possible to change the maximum combined stress several percent. The rate of change of the stress concentration factor is quite rapid in some cases as typified by a 2.5 percent change in a \(z/d\) shaft length of only 0.023 for a \(d/D\) ratio of 0.84 and \(r/d\) of 0.40.

Until such time as a reliable and accurate theoretical solution for three dimensional stress distribution in the region of maximum stress becomes available, the authors must look upon Mr. Svensson's procedure as a very good approximation but not necessarily descriptive of actual quantitative stress conditions in real shaft prototypes.