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PERFORMANCE LIMITS FOR SMOOTH-WALL GRAVITY-ASSISTED HEAT PIPES

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Abstract

Performance limits for vertical, smooth-wall heat pipes were obtained from experiments performed at the IFE of the University of Stuttgart and at the Los Alamos National Laboratory. The data are correlated with parameters derived from flooding in countercurrent, two-phase flows. Tests using smooth-walled, wickless heat pipes demonstrate the applicability of two-phase flow correlations for predicting performance limits in gravity-assisted heat pipes.

Nomenclature

A	area
D	diameter
g	acceleration of gravity
h _{fg}	latent heat of vaporization
L	length
q	power
u	velocity
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
σ	surface tension

Subscript

f	liquid
g	vapor or gas
i	f or g

Dimensionless groups

Bo	Bond Number
Ga	Galileo Number
Ku	Kutateladze Number
Re	Reynolds Number
We	Weber Number

Introduction

Most designs for gravity-assisted heat pipes incorporate a wick structure, sometimes quite simple, whose main function is to provide for internal distribution of the working fluid. These wick structures include screened wicks, where it was found that a gradient in the screen mesh from the inner wall of the heat pipe to the vapor passage, with the fine mesh next to the wall, provided for very satisfactory performance.⁽¹⁾ Other successful designs have included surface texturing of the heat pipe wall by means of grooves, threads, or knurls. These surfaces are prepared mechanically and require a separate operation in the preparation of the heat pipe. Performance limitations for these structures have been reported⁽²⁾ and correlated using a modified Weber number.⁽³⁾

In certain applications it is desirable to utilize gravity-assisted heat pipes whose orientation is restricted to the vertical or near vertical. The simplest possible heat pipe configuration for this application is one with a smooth or untextured internal wall. The economic motivation to construct such a heat pipe warrants an investigation into its performance limitations.

This paper reports on experiments conducted at the Los Alamos National Laboratory and at the IKE of the University of Stuttgart using smooth wall, gravity-assisted heat pipes. It was found that the performance limits of these heat pipes could be predicted by applying an empirical correlation obtained from countercurrent, gas-liquid flooding experiments.⁽⁴⁾ We believe that the establishment of this link between the vast body of two-phase flow data and the performance limitations of gravity-assisted heat pipes is an important first step in understanding the flow mechanisms internal to the heat pipe.

Empirical Correlations from Two-Phase Flows

Distinguishing between flooding and entrainment as the limiting flow mechanism in gravity-assisted heat pipes is difficult. In either case the mechanism, whether it be entrainment or flooding, results in liquid holdup in the heat pipe condenser, the effect of which is to interrupt the circulation of working fluid. Since the evaporator is no longer supplied with working fluid a dryout occurs that is evidenced by a rapid increase in the evaporator wall temperature. The onset of this condition is defined as a performance limit for the heat pipe.

Kutateladze⁽⁴⁾ has published correlations based on a stability criterion Ku (Kutateladze number) for a number of gas-liquid flows. The Kutateladze number is derived from the Weber number which is a dimensionless ratio of inertia and surface tension effects at the gas-liquid interface. The Weber number is given by

$$We = \frac{\rho_g u_g^2}{\sigma/L} \quad (1)$$

where L is a characteristic length associated with the interface. Recognizing that gravity plays a dominant role in the behavior of the falling liquid film, Kutateladze derived an expression for the characteristic length by equating the surface tension and hydrostatic forces to get

$$(\rho_f - \rho_g)gL = \sigma/L \quad (2)$$

which gives the following expression for L

$$L = \left[\frac{\sigma}{(\rho_f - \rho_g)g} \right]^{1/2} \quad (3)$$

Substituting for L in the Weber number and taking the square root gives

$$Ku = \frac{\rho_g^{1/2} U_g}{[\sigma g (\rho_f - \rho_g)]^{1/4}} \quad (4)$$

According to experiments (4) on counterflowing gases and liquids in vertical tubes, flooding was observed when

$$Ku = 3.5 Re^{-2/3} Ga^{1/6} \quad (5)$$

where the Reynolds number is based on the tube diameter and the Galileo number is defined as follows:

$$Ga = \frac{\sigma^{2/3}}{\nu_f^2 (\rho_f - \rho_g)^{3/2} g^{1/2}} \quad (6)$$

The Galileo number is a dimensionless group containing viscous, inertia and gravitational terms for the liquid phase or

$$Ga = \frac{(\text{Inertia})(\text{Hydrostatic})}{(\text{Viscous})^2} \quad (7)$$

We note that Kutateladze's correlation can be rewritten with the following physical interpretation. Starting with

$$Ku = c Re^{-2/3} Ga^{1/6} \quad (8)$$

and substituting for the dimensionless groups gives

$$\left[\frac{(\text{Inertia})_g}{(\text{Hydrostatic})} \right]^{1/2} = c \left(\frac{\text{Viscous}}{(\text{Inertia})} \right)^{2/3} \left[\frac{(\text{Inertia})(\text{Hydrostatic})}{(\text{Viscous})^2} \right]^{1/6} \quad (9)$$

where the subscript g refers to the gas phase and all other terms refer to the liquid phase. The above expression can be rewritten to give

$$[(\text{Inertia})_g (\text{Inertia})]^{1/2} = c (\text{Viscous})^{1/3} (\text{Hydrostatic})^{2/3} \quad (10)$$

or the gas and liquid inertia describing the flow limitation is a function of the viscous and hydrostatic forces in the liquid phase. Furthermore, the length parameter can be written in terms of the surface tension using Eq. (3).

Because all of the above processes are present in gravity-assisted heat pipes, it is reasonable to expect that the flooding correlation for counter-current two-phase flow can be successfully used to predict performance limits in gravity-assisted heat pipes. The method of obtaining the data is described in the following section.

Experiments

Performance limit data for smooth-wall thermosyphons were obtained at IKE using AW series heat pipes. The test apparatus and procedure have been reported previously (5). The AW series heat pipes ranged in i.d. from 5.0 to 11.5 mm and used water as the working fluid. Resistance heaters were used for heat addition in the evaporator and heat removal was via a water cooled calorimeter.

The Los Alamos experiments were an extension of the investigation of gravity-assisted heat pipes with simple wick structures reported at the London Heat Pipe Conference (3). A smooth-wall, stainless steel heat pipe with 38 mm i.d. was tested with working fluids of water, methanol, toluene, and acetone. Heat addition was by induction in the heat pipe wall and heat removal was via gas-gap calorimeter.

The IKE and Los Alamos data are complementary in that the heat pipe size was varied using a single working fluid in the IKE experiments, and a single heat pipe with different working fluids was used in the Los Alamos experiments.

Results

Correlating parameters for the heat pipe experiments were obtained from the Kutateladze correlation. Starting with Eq. (10) and substituting for the inertia, viscous, and hydrostatic terms as follows:

$$\text{inertia} = \rho_l U_l^2 \quad (11)$$

$$\text{viscous} = \mu_f \frac{U_f}{L} \quad (12)$$

$$\text{hydrostatic} = (\rho_f - \rho_g)gL \quad (13)$$

and using continuity

$$q/hfg = \rho_l U_l A_l \quad (14)$$

together with Eq. (3) gives

$$Re_m = c Ga^{0.4} \left(\frac{\nu_g}{\nu_f} \right)^{0.3} Bo^{0.3} \quad (15)$$

where a modified Reynolds number has been defined as

$$Re_m = \frac{qD}{h_{fg} A \sqrt{\nu_l} \nu_f} \quad (16)$$

and the Bond number, a dimensionless diameter, is given as

$$Bo = \left[D^2 \frac{(\rho_f - \rho_g)g}{\sigma} \right]^{1/2} \quad (17)$$

Figure 1 shows the data from both the IKE and Los Alamos experiments. A least squares fit of the

data is shown by the solid line. Complete agreement with the Kutateladze correlation, Eq. (5), would have resulted in a slope of 1.0. Since the slope of the experimental data is greater than 1.0, the exponents in Eq. (15) must be modified as follows:

$$Re_m = C Ga^{0.54} \left(\frac{\rho_g}{\rho_f} \right)^{0.42} Bo^{0.42} \quad (16)$$

The coefficient in Eq. (18) is nearly 1.0. Although the exponents in the correlation obtained from the heat pipe data are larger than those predicted by the Kutateladze correlation, the dimensionless correlating parameters, which were derived from the Kutateladze correlation, appear appropriate for analyzing the smooth-wall, heat pipe data.

If the exponents in the final correlation are assumed to be 0.5 then

$$Re_m = C Ga^{0.5} \left(\frac{\rho_g}{\rho_f} \right)^{0.5} Bo^{0.5} \quad (17)$$

Equation (19) reduces to

$$q/A_v = C \left[\frac{\mu_g}{D} \right]^{1/2} h_{fg} \quad (20)$$

which is similar in form to previous performance limit correlations for gravity-assisted heat pipes with textured internal surfaces.⁽³⁾ In those studies the tube diameter D is replaced by a characteristic depth, ϕ of the internal surface. Also the coefficient C was found to be a function of ϕ . The simplification of Eq. (18) illustrates the similarity of the smooth wall correlation with limit results obtained from other gravity-assisted heat pipe studies.

Conclusions

Performance limits in smooth-wall, gravity-assisted heat pipes can be successfully correlated with dimensionless variables containing inertia forces for both the liquid and vapor and viscous and hydrostatic forces for the liquid. Furthermore, the correlating parameters are the same as those used in describing flooding phenomena in vertical, countercurrent gas-liquid flows. This

Fig. 1. Smooth-wall, gravity-assisted heat pipe correlation.

result illustrates the similarity between flooding in countercurrent two-phase flows and in gravity-assisted heat pipes.

References

1. Kemme, J. E., "Vapor Flow Considerations in Conventional and Gravity-Assist Heat Pipes," 2nd International Heat Pipe Conference, Bologna, Italy, 1976.
2. Nguyen-Chi, H. and M. Groll, "The Influence of Wall Roughness on the Maximum Performance of Closed Two-Phase Thermosyphons," AIAA 15th Thermophysics Conference, Snowmass, Colorado, July 1980.
3. Prenger, F. C. and J. E. Kemme, "Performance Limits in Gravity-Assist Heat Pipes with Simple Wick Structures," 4th International Heat Pipe Conference, London, England, September 1981.
4. Kutateladze, K. K., "Elements of the Hydrodynamics of Gas-Liquid Systems," Fluid Mechanics-Soviet Research, Vol. 1, 1972.
5. Nguyen-Chi, H., M. Groll, and Th. Dang-Van, "Experimental Investigation of Closed Two-Phase Thermosyphons," AIAA 14th Thermophysics Conference, Orlando, Florida, June 1979.