AN EXPERIMENTAL INVESTIGATION OF THE THICKNESS OF THE LIQUID-FILM DEPOSITED AT THE TRAILING END OF A LIQUID PLUG MOVING IN THE CAPILLARY TUBE OF A PULSATING HEAT PIPE

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ABSTRACT

For the theoretical modelling of pulsating heat pipes it is necessary to estimate the thickness of the liquid film deposited at the trailing edge of a liquid plug as it moves through a small diameter tube. A simple experimental set-up and procedure whereby this liquid film thickness may be determined is described and a correlation for the thickness is statistically derived. Using water as the working fluid at temperatures between 0 and 60 °C and velocities of 0.3 to 1.8 m/s the average film thickness varied between 100 and 200 µm and depended primarily on the surface tension of the liquid.

Keywords: Pulsating heat pipe, liquid film thickness, experimental correlation, oscillatory heat pipe.

1. INTRODUCTION

A pulsating (or oscillatory or oscillating) heat pipe (PHP) is a heat transfer device invented some twenty years ago (Akarchi, 1990 and 1993) and by 1995 had already been intensively researched and many application areas considered. In particular its potential in the cooling of electronic equipment had been emphasized (Akarchi and Polášek, 1996). A PHP consists of a relative long sealed capillary tube that has been wound back and forth in one plane; reminiscent of a river as it meanders along in a relatively horizontal plain. It is evacuated and then charged with a working fluid (for example water, ammonia, methanol or Freon) at a liquid fill ratio (liquid to total volume) of 50%. The liquid in the pipe then tends to naturally distributed itself into many ostensibly randomly spaced and sized liquid-slugs and vapour-bubbles as shown in Fig. 1, provided that the pipe diameter is in the order of 0.5 to 1.8 of the so-called capillary length L , as given by:

$$L = \sqrt{\frac{\sigma}{(\rho_l - \rho_v)g}} \quad (1)$$

If the diameter is too large, the liquid will tends to stratify into a single liquid layer and a vapour layer, and if the diameter is too small then the intensity of the relative movement between the liquid and vapour may be inhibited due to capillarity.

If the one end of the PHP is heated and the other end cooled (see Fig. 1) heat is transferred from the heat source to the cooler heat sink.

Fig. 1 A pulsating heat pipe consisting of liquid plugs and vapour bubbles in a small-diameter pipe.

This is seen to always spontaneously occur in the so-called bottom heat mode (that is when the heated end is below the cooled end) even at low (<40 °C) temperature differences. The liquid plug vapour bubble behaviour in this heat mode is characterised (as observed in glass PHPs) by a seemingly sudden and chaotic burst of rapid motion of the plugs and bubbles, back and forth, and around the bends, followed by a relatively quiescent dwell period. This rapid motion followed by

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Fig. 2 Experimental set-up.

quiescent periods continues for as long as there is a temperature difference between the heated and cooled ends, hence the name *pulsing heat pipe*, and heat continues to be transferred. This is what may be called a low heat flux operating condition. If the heated section is above the cooled end (called the *top heat mode*) heat pipe will start to transfer heat, and against gravity, when the temperature difference exceeds about 60 °C (Dobson and Graf, 2003). This can be called the high heat flux operating condition and the flow behaviour in this mode may be characterised by a uni-directional annular type of flow reminiscent of the annular convective two-phase flow and heat transfer flow pattern regime (Carey, 1992).

The relatively simple liquid plug-vapour bubble geometry in low heat flux mode lends itself to theoretical analysis and mathematical formulation by applying the equations of change; that is the conservation of mass, momentum and energy, to the relatively discrete liquid and vapour control volumes, and using the constituent working fluid property equations for closure. Wong, *et al.* (1999) proposed a simple liquid plug and vapour bubble theoretical model. Dobson and Harms (1999) however included a film thickness in their simply liquid plug and vapour bubble model and showed that the model tended to capture the oscillatory behaviour of PHPs. This theoretical approach was also applied to a single vapour bubble-two-liquid plug open oscillatory heat pipe and it was able to successfully capture the chaotic behaviour that is observed in to occur in this type of PHP (Dobson, 2002 and 2003). Other papers by Zhang and Faghri, 2002; Shafii, Faghri and Zhang (2003); Khandekar and Groll (2008); Shao and Zhang (2010) have also presented theoretical models, and others (Charoensawan, *et al.*) have experimentally explored the detailed behaviour of PHPs. Tripath, Khandekar and Panigrahi (2010) consider the liquid-vapour-solid contact region. Only one other paper (Senjaya, Inoue and Suzuki, 2010) pertinently considers the liquid film thickness. In this paper no mention is made of what the thickness of the liquid left behind by the trailing edge of the liquid plug might be but assumes however that the film thickness is the same in both the evaporating and condensing sections.

If the PHP is charged with a 50% fill ratio of working fluid then, correspondingly, about 50% of the inside pipe surface area is in contact with liquid plugs the rest of the inside surface is in contact with vapour bubbles. Once the PHP starts working the moving liquid plugs leave behind at their trailing ends a thin layer of fluid of finite thickness on the pipe surface and at the leading front take up liquid left behind by the preceding liquid plugs. At any one time thus 50% of the heat transfer, ignoring any axial heat transfer, is associated with liquid plugs. For the remaining surface the heat transfer will then be associated with

a relatively intact liquid film; increasing in thickness in the condensing sections and decreasing in thickness in the evaporating sections.

For the theoretical modelling of pulsating heat pipes an idea of the thickness of the liquid film deposited at the trailing edge as it moves through a capillary tube is thus needed. It is the object of this paper to present a simple experimental procedure whereby this liquid layer may be estimated for water. The experimental set-up and procedure is given and the observed liquid behaviour is described. The results are statistically analysed and a correlation for the liquid thickness is presented and conclusions are drawn.

Fig. 3 Experimentally observed behaviour a liquid plug moving in a capillary tube.

2. EXPERIMENTAL SET-UP

A simple experimental set-up was devised to determine the average thickness of the liquid film deposited by the trailing-end of a liquid plug as it moves along in a small diameter pipe. The experimental set-up consists of a vertically orientated capillary tube clamped to a retort stand as shown in Fig. 2. The top end the capillary tube is connected to a syringe using a short length of plastic tubing. A video camera (JVC GV-DS1) is positioned as shown and is used to capture the movement of the liquid. A desk lamp is positioned behind a sheet of paper to attain the required lighting.

Before clamping the capillary tube to the stand the dry mass of the tube is measured (using a Precisa 40SM-200A, serial no. 73464 scale). The liquid to be tested is heated to the desired temperature and then positioned in a container at the bottom end of the capillary tube so that the end portion of the capillary tube is submerged in the liquid. The syringe is then used to draw the liquid up into the capillary tube until the desired level of the liquid is obtained. (The higher the liquid is drawn up into the tube the faster the average velocity of the liquid as it flows downwards under the influence of gravity.) The container is then lowered to allow the liquid to move freely out of the lower end of the capillary tube. The plastic tubing is quickly disconnected from the capillary tube and the liquid plug starts to move down the capillary tube due to gravity. This movement of the liquid plug is captured by the video camera.

3. OBSERVATIONS

The initial length of the liquid column L_{pi} drawn into the capillary tube by the syringe is shown in Fig. 3(a). After the plastic tube is disconnected the liquid plug starts to move down and a liquid film is deposited at the trailing end as shown in Fig. 3(b). A portion of the

liquid plug of a length $L_{p,min}$ will remain in the tube depending on the magnitude of the momentum of the liquid plug, the friction and the surface tension as shown in Fig. 3(c). As the liquid film flows down the tube the remaining plug of liquid increases from $L_{p,min}$ to say $L_{p,final}$. As the thickness of the liquid film decreases the uniform film breaks up into several droplets along the inside, also several small liquid plugs are formed along the tube. Some of the liquid film flows into the portion of the liquid plug at the exit as shown in Fig. 3(c). The flow of the liquid film into the liquid plug will cause it to grow as shown Fig. 3(d). Only a limited mass of liquid in the plug can be supported by the capillary forces against gravity, and a few liquid droplets may break away from the bottom as shown in Fig. 3(e). After a while equilibrium is achieved as shown in Fig. 3(f).

Fig. 4 Predicted film thickness, using Eq. (7), as a function of the experimentally determined values.

4. ANALYSIS AND RESULTS

The average film thickness of the liquid deposited by the trailing end of the liquid plug δ_{ef} is given by the following equation

$$\delta_{ef} = \frac{d_i}{2} - \frac{1}{2} \sqrt{d_i^2 - \frac{4m_{ef}}{\pi(L_{pi} - L_{p,min})\rho_\ell}} \quad (2)$$

where d_i is the inside diameter of the capillary tube, L_{pi} is the initial length (height) of the liquid column, and $L_{p,min}$ is the minimum instantaneous height of the liquid column at the instant just as the trailing liquid starts to replenish the minimum amount of liquid remaining in the tube. ρ_ℓ is the density of the liquid, m_{ef} is the total mass of the liquid film deposited on the surface of the tube and may be determined using Eq. (3) as

$$m_{ef} = m_{t\ell} - m_{td} - \frac{1}{4}\pi d_i^2 \rho_\ell L_{p,min} + m_{drops} \quad (3)$$

where, $m_{t\ell}$ is the mass of the tube partially filled with liquid, m_{td} is the dry mass of the tube, $\frac{1}{4}\pi d_i^2 \rho_\ell L_{p,min}$ is the mass of the liquid plug left in the tube due to surface tension, and m_{drops} is the mass of the any liquid drops that may have fallen from the remaining liquid as its height increases due to it being replenished by the liquid film.

The average velocity of the trailing end of the liquid plug as it falls in the tube is determined using Eq. (4)

$$v_p = \frac{L_{pi} - L_{p,min}}{\Delta t} \quad (4)$$

It is not unreasonable to assume that the variables primarily affecting the thickness of the liquid film might include the inside diameter of the capillary tube d_i , the surface tension σ and viscosity μ of the liquid water, and the average velocity of the trailing end of the liquid plug v_p . The effect of each of these variables may be evaluated using statistical analysis by assuming a power function relationship, as is often done in determining semi-empirical equations for heat transfer coefficients (Mills, 1999), as

$$\delta_{ef} = a_0 d_i^{a_1} \sigma^{a_2} v_p^{a_3} \mu^{a_4} \quad (5)$$

By taking the natural logarithm of both sides of Eq. (5) gives

$$\ln \delta_{ef} = \ln a_0 + a_1 \ln d_i + a_2 \ln \sigma + a_3 \ln v_p + a_4 \ln \mu \quad (6)$$

The constants may be found using a standard multi-linear regression technique. This technique was applied to a data set using distilled de-aerated water as the working fluid, inside diameters 1.5 to 2.86 mm, temperatures between 0 and 60 °C, and hence with surface tensions of 0.0671 to 0.0786 N/m and dynamic viscosities of 0.00049 to 0.00176 Pas, and average velocities of 0.33 to 1.8 m/s. The results of this analysis is given by way of Eq. 6 and to correlating coefficient $R^2 = 82\%$ as

$$\delta_{ef} = 6031 d_i^{0.485} \sigma^{1.931} v_p^{0.0942} \mu^{-0.130} \quad (7)$$

where δ_{ef} is in μm if d_i is in μm , σ is in N/m, v is in m/s and μ is in Pas. Fig. 4 shows the predicted values of the film thickness as a function of the experimentally determined values. It is seen that the predicted values tend to correspond to within about $\pm 15\%$ of the experimentally determined values.

Table 1 Sensitivity analysis showing change in the predicted film thickness, using Eq. (7), for a 10% increase in a variable.

Variable	d	σ	v_p	μ
Average value	2.18 mm	0.0726 N/m	1.07 m/s	0.00113 Pas
Original δ_{ef}	135 μm	135 μm	135 μm	135 μm
10% increase	0.218 mm	0.00726 N/m	0.107 m/s	0.000113 Pas
New δ_{ef}	141 μm	162 μm	136 μm	133 μm
(New-old)/old	4.73 %	20.20 %	0.90 %	-1.23 %

An idea of the sensitivity of the correlating variables on the liquid film thickness can be obtained by systematically considering a 10% increase in the linear average of the upper and lower limits of each of the variables, in turn, keeping the other variable constant and taken as the average values of the upper and lower limits. Table 1 shows the percentage change in film thickness δ_{ef} , using the correlation given by Eq. (7), for a 10% increase in the average value of each variable, keeping the other variables all constant. For example, for the average values given in the first row of Table 1 the correlation gives a film thickness 135 μm ; if the surface tension σ only is increased by 10% then the film thickness increases by 20.20% to 162 μm . The diameter, with a percentage difference between the new and old values of 4.73% is the next most significant variable, whilst the plug velocity and

viscosity tend to show a more-or-less negligible effect on the film thickness.

5 DISCUSSION and CONCLUSIONS

In section 1 it was shown that there will always be a significant portion of the inside surface area that is covered by a thin layer of liquid, be it increasing in thickness in the condensing region or decreasing in the evaporating section. Further, should dry-out occur in the evaporator section it will not be for long before a passing liquid plug re-wets the surface. This is expected to be the case in both the vapour bubble-liquid plug model associated with the relatively low heat flux mode of operation as well as for the annular uni-directional model case associated with a high heat flux mode. As such, knowing the actual liquid film thickness is important in any attempt at theoretical modelling the performance of a pulsating heat pipe.

The correlation derived in section 4, based on the simple experiment experimental set-up and the procedure described in section 3 shows that the surface tension (see Table 1) is the dominant variable affecting the film thickness, the diameter is the next most important but viscosity and velocity appear to have a very small effect. This is interesting because for condensate thickness for film-wise condensation on a wall, other than for the heat transfer properties, the viscosity is important, albeit to a $\frac{1}{4}$ power (Mills, 1999). On reflection this is probable due to the small radius of curvature associated with film-wise condensation compared with the small radius of curvature of the liquid-vapour interface in a small diameter tube where the surface tension is thus more important.

Further, from so-called *film-theory* the heat transfer coefficient may be given in terms of the thermal conductivity divided by the film thickness as $k/\delta \approx 0.65/0.0001 = 6500 \text{ W/m}^2\cdot^\circ\text{C}$, which from an overall heat transfer point of view may not appear important if the outside heat transfer coefficient is much smaller, thereby dwarfing the effect of the inside heat transfer coefficient on the overall heat transfer rate. Nonetheless, this argument does not lessen the effect of the inside heat transfer coefficient on the rate at which the film is increasing or decreasing (and even drying out). The rate at which the inside film thickness changes is indicative of the rate at which the vapour pressure changes and consequently the rate and intensity at which the pulsations occur in the PHP.

Water was used in this study, because it is so easy to use from an experimental point of view. The correlation given by Eq. (7) predicts average thicknesses of the liquid film deposited on the wall by the trailing end of a liquid plug of between 100 and 200 μm , for water temperatures of between 0 and 60 $^\circ\text{C}$ (and hence surface tensions of between 0.0671 and 0.0786 N/m and dynamic viscosities of between 0.00049 and 0.00176 Pas) and liquid plug velocities of 0.33 to 1.8 m/s. Equation (7) can be used for water with reasonable confidence within these limits. It may however not necessarily be as accurate for other working fluids; this still needs to be fully investigated and tested. Nevertheless the given correlation can be used to evaluate the theoretical accuracy/validity of a mathematical simulation model.

ACKNOWLEDGEMENTS

This work was partially funded by a grant from CAE (Pty) LTD, Atlantis, South Africa.

NOMENCLATURE

d	diameter (m)
k	thermal conductivity ($\text{W/m}\cdot^\circ\text{C}$)
L	length (m)
m	mass (kg)

g	gravitational constant m/s^2
R^2	coefficient of determination
t	time (s)

v	velocity (m/s)
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Greek Symbols

δ	film-thickness (m)
ρ	density (kg/m^3)
σ	surface tension (N/m)
μ	dynamic viscosity (Pas)

Subscripts

f	liquid-film
i	initial condition
ℓ	liquid
min	minimum
p	liquid-plug
t	tube
v	vapour

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