EXPERIMENTAL AND THEORETICAL STUDIES OF REWETTING OF UNHEATED/HEATED GROOVED PLATES

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ABSTRACT

Theoretical and experimental investigations of the rewetting characteristics of thin liquid films over unheated and heated grooved plates were performed. Studied factors which affected the rewetting characteristics of the plate were mass flow rate of the rewetting liquid on the plate, the orientation of the plate (face up, face down or inclined) and smooth/groove surface conditions. The initial plate temperature was also varied, with experiments being performed between room temperature and 150 °C. It was found that the rewetting velocity increased with the initial plate temperature. But when the temperature was increased further above the Leidenfrost temperature (liquid front temperature), the rewetting velocity decreases with the initial plate temperature. Hydrodynamically controlled and conductively controlled rewetting models were presented to explain and to predict the rewetting characteristics in these two distinct regions. Also found was a higher rewetting velocity when the grooved plate was placed in the face up orientation than in the face down orientation.

INTRODUCTION

Rewetting of the heated surface of a monogroove heat pipe is an important issue in the design of space station radiators since the dry-out of coolant in the surface grooves due to thermal overload leads to the failure of the heat rejection system of the space station.

The present work investigated both experimentally and theoretically the rewetting on a heated, grooved plate to simulate rewetting of the circumferentical grooves in the inner surface of of a monogroove heat pipe. A wide range of conditions was studied to reveal rewetting characteristics of the grooved plate.

REWETTING OF UNHEATED GROOVED PLATE

Experiment Experiments were first conducted at the room temperature to study how the rewetting of an unheated, grooved plate was affected by the plate orientation and the mass flow rate of working liquid supplied to the plate. The experimental setup at the room temperature condition consists of a liquid supply system with an adjustable flow rate, a test section (containing the grooved plate) and a video recording system with high resolution frame by frame playback capability. The working liquid (2-propanol) is delivered to the test section by the liquid supply system and is driven within the grooves by surface tension. The grooved plate is fashioned from a sheet of oxygen-free copper and is chemically cleaned after every experimental run. Experimental runs are recorded with a Super-VHS-C camcorder. The tape is played back on the S-VHS VCR frame by frame to determine the position of the liquid front vs time (1/30 second per frame).

Results and Discussion The supplied liquid flow rate effects on transient wicking length and wetting velocity are shown in Fig.3. Three flow rates were used: $\dot{m} = 15$, 41 and 48 ml/min. The lowest flow rate was found to provide an inadequate amount of working fluid to rewet the plate. It was also found that at higher flow rate (41 ml/min or higher), increasing the flow rate had no effect on the rewetting of the plate. After this finding, the unheated tests were performed at the flow rate of 48 ml/min, and the heated tests at 31 ml/min. The prediction based on the hydrodynamically controlled model to be presented later is also shown in Fig.3. The comparison between the face up and face down cases (i.e. the horizontal grooved surface facing upward and downward, respectively) is shown in Fig.4. It was found that the rewetting velocity in the face up case is larger than that in the face down case. This is probably because the surface tension force in the face up case is larger than that of the face down case.

REWETTING OF HEATED GROOVED PLATE

Experiment The experimental apparatus consists of following components [Fig.2]: liquid supply system with an adjustable flow rate, an experimental platform which contains a grooved plate with embedded thermocouples evenly spaced along the bottom in the groove direction, a data acquisition system with multiplexer to simultaneously read and recored the signals from the thermocouples, a heater with a temperature controller for maintaining a constant heater temperature, a traveling thermocouple sensor used to measure temperatures along the top of the plate, a video recording system capable of recording and playing back high resolution pictures frame by frame, and a signal light to synchronize the computer data acquisition with the video.

The plate was chemically cleaned, and then heated at one end to the desired initial temperature. The video camera was activated, and a signal light was turned off to indicate the commencement of computer data acquisition. The working fluid was then introduced to the plate, and the rewetting process was recorded. If desired, surface temperatures were also measured using a traveling thermocouple. The traveling thermocouple was useful for determining the temperature of the liquid front, as well as for gauging the accuracy or serviceability of the embedded thermocouples. When working with 2-propanol extreme care should be taken to insure adequate insulation, ventilation and fire safety.

Rewetting experiments were conducted at various initial temperatures of the heated, grooved plates and with plates in the face up and face down orientations.

Results and Discussion Experiments were performed at several plate temperatures in both the face up and face down orientations. Confirmation of the flow rate effect was also performed, as the fluid delivery system is such that there is overflow from the end of the plate. Thus only fluid carried by capillary action rewets the plate. It was determined that through a range of flow rates there was a constant velocity with which the fluid would travel as discussed above. However if the flow rate was too high a hydraulic effect would be present. It should be noted that this flow rate will vary from plate to plate, as it is determined by the groove geometry and the number of grooves wetted.

The heated plate case which is presented is one in which the initial plate temperature is above 110 °C. The face up (Fig.6) and face down (Fig.7) orientations are compared. The figures are in two formats. At the top there is a contour plot depicting the temperature in relation to time and location. Below the surface plots are the temperature profiles along the length of the plate shown in 10 second intervals except the top two profiles which are 2.5 seconds apart. In both formats the location of the fluid front, which was obtained from study of the video, is superimposed.

Following the fluid front for the face up case (Fig.6), it is seen that the front travels between the 95°C and the 100°C contour lines and eventually stagnates at around 110 mm.

Following the fluid front for the face down case (Fig.7), the front crosses several contour lines and stagnates around 70 mm. It should be noted that during the face up (Fig.6) experiment, the thermocouple located at 80 mm malfunctioned. This resulted in the obvious contour and profile anomalies in the figures at the 80mm position.

The dramatic difference between the temperatures profiles in the face up and face down cases indicates a vapor diffusion layer effect. The 2-propanol vapor is more dense than air, and hence forms over the face up plate a vapor layer, through which vapor must diffuse through. This layer is not present in the face down case thus allowing for convection to dominate the heat transfer.

THEORY

In the rewetting process of monogroove heat pipe, it is important to predict the liquid advancing velocity. If the initial plate temperature is less than the Leidenfrost temperature, the advancing liquid is believed to be driven by a capillary force. The liquid advancing velocity is hydrodynamically controlled by the balance of surface tension force, friction force , gravitational force and the acceleration term as described by

$$\frac{\sigma}{R}A_1 = \tau_w A_w + mg sin\alpha + m\frac{du}{dt} \tag{1}$$

where R is the characteristic capillary radius, σ the surface tension, m the total mass of liquid in the grooves, A_1 the liquid cross section area, α the inclination angle of the plate, u the liquid front mean velocity, A_w the wetted wall area, and $\tau_w = f\rho u^2/8$ shear stress where f=$64/Re_{Dh}$. The initial condition for above equation is: u=0 when t=0.

To simplify the problem, R is assumed to be constant and equal to half of the groove width, which is equivalent to a contact angle of zero. From Fig.4, it can be seen that the prediction is in good agreement with the experimental data. For the face down case, the use of same capillary radius seems to overestimate the driving force. Since the rewetting velocity of the unheated plate in the face down position is slower than in the face up position, the effective capillary radius or contact angle may be affected by plate orientation. Therefore the groove plate was placed in various inclinations and the mean wicking length at the face down orientation was found to be slightly shorter than the face up position as shown in Fig.1. Thus the difference in the prediction between the face up and face down positions is nondiscernable when R is changed slightly, as shown in Fig.4.

For the plate with initial temperatures above the Leidenfrost temperature, the rewetting velocity is conduction controlled[1]. The plate temperature is determined by solving the conduction equation,

$$\frac{\partial \theta}{\partial \tau} = \frac{\partial^2 \theta}{\partial \eta^2} - B\theta \tag{2}$$

The initial condition is: $\tau = 0, \quad \theta(\eta, 0) = \theta_0(\eta)$ and the boundary conditions are: $\theta(0,\tau) = \theta_1(\tau)$, $\theta(\eta_{L1},\tau) = 1$ for wet region

$\theta(\eta_{L1},\tau) = 1$, $\theta(\eta_L,\tau) = \theta_2(\tau)$ for dry region

In the above, $\theta_0(\eta)$, $\theta_1(\tau)$ and $\theta_2(\tau)$ are specified by the experimental conditions. By using the variable space method [2], the equation (2) becomes:

$$\frac{d\theta}{d\tau}\Big|_n = \frac{\partial\theta_n}{\partial\eta}\frac{d\eta_{L1}}{d\tau}\frac{\eta_n}{\eta_{L1}} + \frac{\partial^2\theta_n}{\partial\eta^2} - B\theta_n \qquad for \quad 0 < \eta < \eta_{L1}$$

$$\frac{d\theta}{d\tau}\Big|_n = \frac{\partial\theta_n}{\partial\eta}\frac{d\eta_{L1}}{d\tau}\frac{\eta_L - \eta_n}{\eta_L - \eta_{L1}} + \frac{\partial^2\theta_n}{\partial\eta^2} \qquad for \quad \eta_{L1} < \eta < \eta_L \tag{3}$$

where η_{L1} is a non-dimensional distance of the liquid front and is determined by matching following condition:

$$\frac{\partial\theta}{\partial\eta}\Big|_{dry} = \frac{\partial\theta}{\partial\eta}\Big|_{wet} \tag{4}$$

Numerical calculation of eq.(3) was performed simultaneously for both the wet region and dry region. From the calculation it is found that the value of the liquid front temperature is very important for the heat conduction controlled model. In the current calculation, an experimental value of 95°C has been used to calculate liquid moving velocity and temperature profile. The predicted rewetting distance and plate temperature profiles are compared with experimental data as shown in Fig.5 and 6B.

CONCLUSION

This study reports experimental results of rewetting of heated and unheated, grooved plates. Theoretical models were presented to explain and predict the rewetting behavior. The following conclusions can be reached: (i) With sufficient supply of liquid flow rate, the advancing liquid front velocity is insensitive to the variation of the supplied liquid flow rate, since the liquid is driven by surface tension. (ii) The rewetting of the plate is hydrodynamically controlled when the initial plate temperature is lower than the Leidenfrost temperature. However, it becomes conduction-controlled when the initial plate temperature exceeds the Leidenfrost temperature. (iii) The rewetting speed in the face down case is slower than that in the face up case probably due to different capillary radius (contact angle).

ACKNOWLEDGEMENT

This work was supported by NASA Lewis Research Center, Grant No. NAG3-1381, under the technical management of J.A. Platt.

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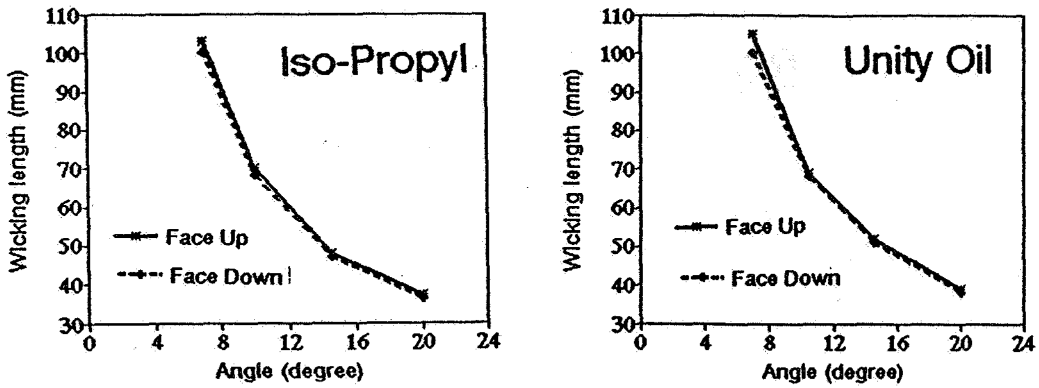

Fig.1 Wicking length L vs inclination angle α

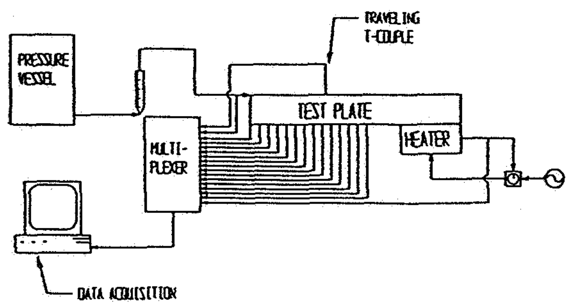

Fig.2 Schematic diagram of experiment setup

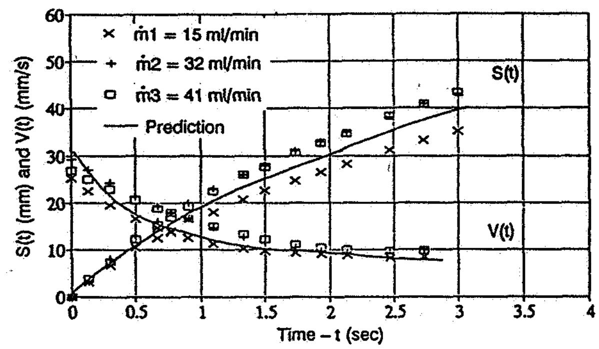

Fig.3 Mass flow rate effects on wicking distance and liquid front velocity

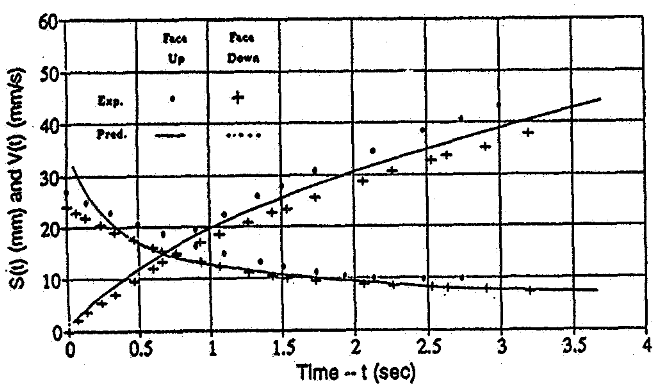

Fig.4 Predicted and experimental results of liquid front location and velocity on unheated plate under the face up and face down positions

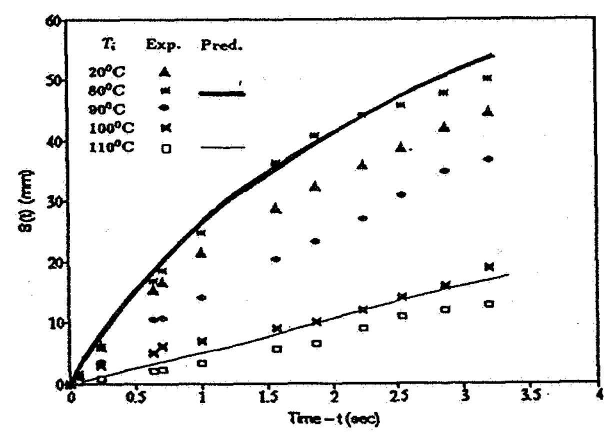

Fig.5 Predicted and experimental rewetting distance on heated groove plate with different initial plate temperatures

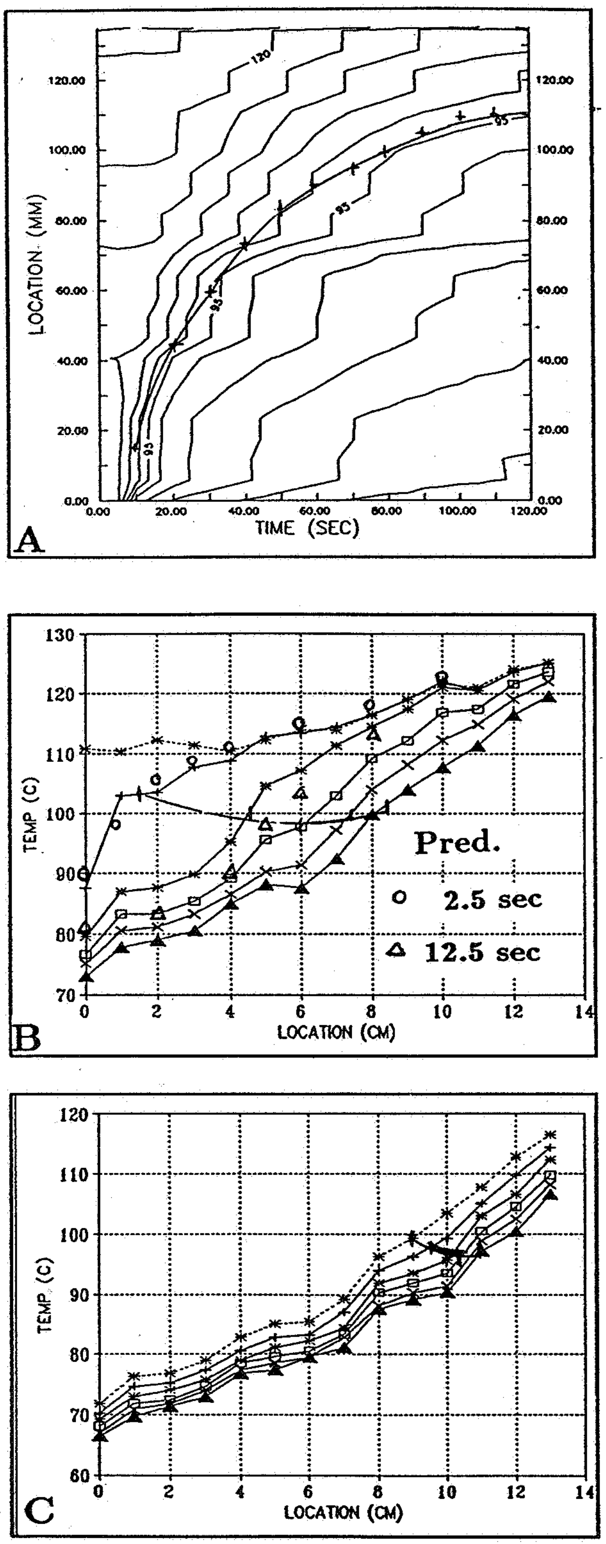

Fig.6 Temperature profiles for the face up case at $T_i > 110°C$

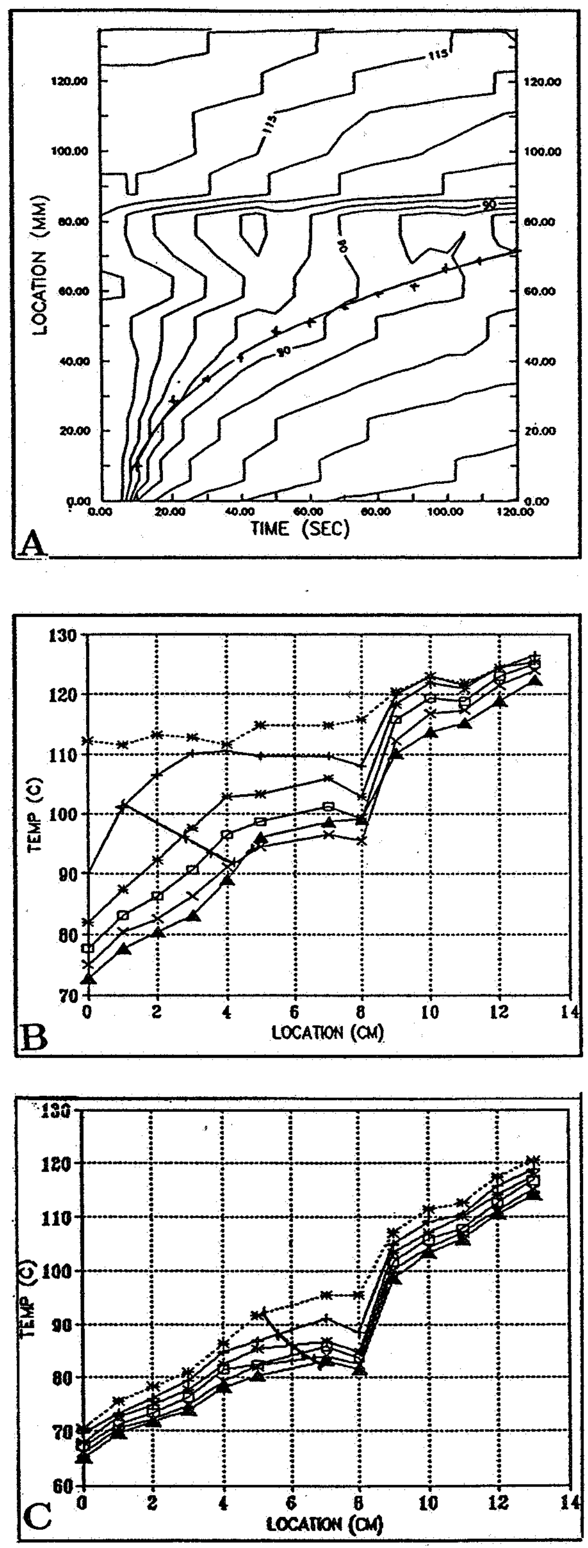

Fig.7 Temperature profiles for the face down case at $T_i > 110°C$