AN EXPERIMENTAL STUDY OF THE MINIMUM
FILM BOILING POINT FOR LIQUID-LIQUID SYSTEMS

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AN EXPERIMENTAL STUDY OF THE MINIMUM FILM BOILING POINT FOR LIQUID-LIQUID SYSTEMS

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Abstract

Film boiling data is reported for Freon-11, Freon-22, ethanol, and water boiling on a mercury surface. Measured heat fluxes and heat transfer coefficients are in good agreement with previous data. However, transition from film boiling occurs at much lower temperatures than would be expected from solid-liquid film boiling results. Film boiling of Freon-22 on water was attempted but transition occurred at much higher water temperatures than would be extrapolated from solid-liquid results.

NOMENCLATURE

A : Area
 h_{fg} : Latent heat of vaporization
 H : Heat transfer coefficient
Q : Heat
t : Thickness
 T_h : Temperature of the hot liquid
 T_{SAT} : Saturation temperature of the boiling liquid
 θ : Time
 ρ : Density of boiling liquid

INTRODUCTION

Extensive analytical and experimental efforts have provided considerable understanding of the film boiling process as it relates to film boiling of a liquid on a hot solid surface. Several specific problems such as quenching of molten globules,¹ cryogenic spills on water,² and understanding of experimental results for vapor explosions^{2,3} require a knowledge of film boiling of one liquid on another, and hence, how the wealth of knowledge on liquid-solid systems relate to such problems. This study specifically deals with Freons-11 and -22, ethanol, and water globules in film boiling on a mercury surface.

EXPERIMENTAL APPARATUS

The very simple apparatus used in this investigation is illustrated in Fig. 1. A mercury pool was heated from below, and its bulk temperature was monitored by an isolated sheathed thermocouple. A globule of the boiling liquid was placed on the surface and a photograph was taken at $t = 0.0$ sec. After a sufficient quantity of the liquid had boiled away, such that the decrease in planar area was readily apparent, another photograph was taken and the time interval between the two pictures was recorded. To eliminate any metastable hydrodynamic effects such as those witnessed for small Leidenfrost drops,⁴ both the initial and final globule dimensions were large compared to the critical wave length for Taylor instability⁵ as evidenced by "bubble

breakthrough" within the liquid mass at both points in time.

Fig. 1 Experimental Apparatus

Following the technique utilized by Borishansky⁶ and Bradfield,⁷ an electrical probe was inserted into the upper portions of the boiling liquid mass, but not into the mercury pool. This probe was connected in series with a 1 volt dry cell and a strip chart recorder, which was connected to the mercury pool. Such a system will clearly register if intimate contact is made between the two liquids. A 304 stainless-steel retainer ring was floated on the mercury pool to keep the boiling liquid in the vicinity of the contact probe and also away from the comparatively cool glass wall.

This system, which was housed inside of a vented hood, could generate mercury temperatures of 275°C. At this temperature, the mercury vaporization was significant, and this combined with the heat flux required to vaporize the boiling liquid equaled the maximum output of the hot plate.

Although the planar dimensions of the boiling liquids were large compared to the most dangerous wave length, the thickness of the globule was determined by its surface tension. The thickness was read from a scale inserted beside the boiling mass, and this parameter is probably the least

accurate of all the measurements, i.e., the turbulence of the interface limits the accuracy to 25%. All liquids used in this study were essentially saturated at one atmosphere when poured onto the mercury surface.

In addition to mapping the film boiling regime, data was also accumulated for the minimum temperature required to support film boiling for these liquid-liquid systems. These runs were taken by heating the mercury pool to a temperature well into the film boiling regime for a given fluid. A large mass of the boiling liquid was poured onto the mercury surface, the hot plate was turned off, and the mercury was allowed to cool due to the film boiling of the colder liquid. The cooling rate of the mercury pool, as well as visual observation, easily enabled one to ascertain when the lower limit of film boiling was achieved. At this point, it was essential that transition began on the surface of the mercury pool itself and not on the retainer ring, and that the boiling liquid mass was still exhibiting bubble breakthrough so that metastable effects would not be a major concern. If either of these conditions was violated, the run was discarded.

DISCUSSION OF RESULTS

Since the boiling liquid globule was photographed during a known time interval, first order estimates of the heat flux and heat transfer coefficients can be obtained from the vaporization rate of the boiling liquid and the temperature difference between the two liquid masses. The heat transferred to the boiling liquid can be related to the change in mass of the globule

$$dq = -h_{fg} dm \quad (1)$$

If the globule is assumed to be of constant thickness,

$$dq = -h_{fg} \rho t dA \quad (2)$$

Using a convective formulation, the rate of heat transfer between the liquids is

$$\frac{dq}{dt} = hA(T_h - T_{SAT}) \quad (3)$$

Combining Eqs. 2 and 3 yields

$$-h_{fg} \rho t \frac{dA}{dt} = hA(T_h - T_{SAT}) \quad (4)$$

If all quantities except A and θ are assumed constant, Eq. 4 can be integrated with respect to time and evaluated at the end points,

$$h = \frac{\ln A/A_1 h_{fg} \rho t}{(T_h - T_{SAT}) \Delta \theta} \quad (5)$$

Once the heat transfer coefficient is calculated, the heat flux can be obtained from

$$q/A = h(T_h - T_{SAT}) \quad (6)$$

The experimental results for the film boiling heat transfer coefficients for water, ethanol, Freon-11,

and Freon-22 are respectively displayed in Figs. 2, 3, 4, and 5. For comparison, similar results⁹ are shown for water and Freon-11 in film boiling from

Fig. 2 Heat Transfer Coefficient for Water

Fig. 3 Heat Transfer Coefficient for Ethanol

Fig. 4 Heat Transfer Coefficient for Freon-11

Fig. 5 Heat Transfer Coefficient for Freon-22

an aluminum plate. It is seen that any differences are well within the scatter of the data. Figures 6, 7, 8, and 9 illustrate the heat flux as a function of the wall superheat. Nucleate boiling

Fig. 6 Heat Flux Data for Water

Fig. 7 Heat Flux Data for Ethanol

Fig. 8 Heat Flux Data for Freon-11

Fig. 9 Heat Flux Data for Freon-22

results for ethanol and water on a mercury surface exhibit heat transfer coefficients that are at least an order of magnitude greater than those observed here.^{9,10}

Berenson's⁵ prediction for the temperature difference at the minimum heat flux in film boiling is compared to measured values of this study in Figs. 6 through 9. Although the experimental results transition at a higher temperature difference than predicted in Ref. 5, the most striking comparison is between the data and the correlation for the minimum film boiling temperature recommended by Henry¹¹ which demonstrates good agreement with the available liquid-solid film boiling results. This comparison is given in Table 1.

Table 1. MINIMUM FILM BOILING TEMPERATURES ON A HEATED MERCURY SURFACE

Fluid	Min. q/A	Visual	Minimum Temperatures		
			Ref. 5	Ref. 11	Eq. 7
Freon-11	-	99°C	93°C	132°C	99°C
Freon-22	-	35°C	20°C	66°C	26°C
Ethanol	-	180°C	152°C	291°C	163°C
Water	230°C	193°C	176°C	650°C	206°C

The correlation in Ref. 11 proposes surface cooling transients resulting from intimate contact and microlayer evaporation. Essentially continuous intimate contact between the mercury pool and the boiling liquid was observed by the contact probe for the conducting liquids of water and ethanol. Such contact was further evidenced by surface waves on the mercury which appeared to be generated following the bubble breakthrough in the boiling liquid. However, these fluids do not wet mercury very well, hence, the microlayer evaporation term would not apply, i.e., as the boiling liquid retracts following intimate contact, a thin microlayer of the cold liquid does not remain to further cool the surface due to vaporization. If the microlayer term is eliminated from the correlation given in Ref. 11, the surface thermal transients would be due to intimate contacting of the liquids or

$$\frac{T_H - T_I}{T_I - T_{SAT}} = \sqrt{\frac{k_L \rho_L C_L}{k_H \rho_H C_H}} \quad (7)$$

If Berenson's minimum temperature is used as the minimum interface temperature necessary to support the Taylor instability, minimum mercury temperatures can be calculated for the fluids used. These values are also listed in Table 1. When such values are compared to the mercury temperature for visually observed transition from film boiling, much better agreement is obtained. However, one interesting anomaly is inherent in the data. For water, the visual mechanism of assessing the minimum film boiling point (and thus the minimum temperature) yields consistently lower values than evaluating the point via the minimum heat flux as shown in Fig. 6. In fact at surface temperatures much less than the minimum heat flux point, the liquid globule was clearly in film boiling, i.e., the edges demonstrated an unwetted curvature, the liquid easily glided over the mercury surface, and no nucleate boiling type sounds were observed. One possible explanation for this anomaly is the extensive intimate contact between the liquids near the minimum point. This generates surface waves in both fluids which increases both the surface area and the turbulent mixing within both fluids and perhaps this results in the increasing heat fluxes as the point is approached. In any case, it presents a question on the definition of film boiling. Does film boiling begin when the boiling liquid glides over the heated surface in a frictionless manner, or at the point of minimum heat flux?

The basic conclusion from the above discussion is that transition from film boiling on a mercury surface occurs at a much lower temperature than one would predict from liquid-solid data. To see if this trend is consistent, film boiling of Freon-22 at one atmosphere on a water surface was attempted. Berenson's prediction for Freon-22 is 20°C while Henry's correlation yields a value of 33°C for the bulk water temperature. Film boiling could not be sustained at water temperatures as high as 45°C. When the Freon-22 drops were placed on the surface, ice would form immediately and nucleate boiling would follow. For water temperatures greater than 45°C small vapor explosions occurred and the drop was dispersed.

For one liquid-liquid system, the transition is much lower than one would expect based on solid-liquid data, and for another liquid-liquid, it is

much higher. One obvious difference between the systems is the buoyancy, i.e., mercury is more dense than all the fluids used while Freon-22 is heavier than water. However, the major difference between the systems are the wetting characteristics of the liquids upon contact. Water, ethanol, and Freon-11 do not wet mercury well at room temperatures. (Such information could not be obtained for Freon-22 on mercury.) Whereas Freon-22 appears to wet water very well. Therefore, the affinity of one liquid for another appears to play a greater role in determining the film boiling characteristics of a liquid-liquid system than it does for a liquid-solid configuration.

Two other experimental observations from this study are of note:

(1) Liquid-liquid film boiling differs from solid-liquid systems in that the hot liquid may have a significant vapor pressure itself. At mercury temperatures above 200°C, the globule of boiling liquid turned black as soon as it was placed on the mercury surface. This was a result of mercury vapor condensing on the colder liquid. Under these conditions, it is even more surprising that Berenson's model yields such good estimates of the film boiling process near the minimum point.

(2) With the water globules, it was an easy matter to extract an average wave length between the vapor domes. This was approximately 2.5 cm which is in agreement with the measurements of Ref. 8 and the most dangerous wave length criterion used by Berenson.

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