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# BOILING HEAT TRANSFER FROM A TUBE TO IMMISCIBLE LIQUID–LIQUID MIXTURES

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**Abstract**—Experiments were run at atmospheric pressure with water plus each of Freon-113, Freon-112 and n-hexane. Boiling took place on a horizontal 0·25 in. copper tube, tested at separate locations both in the upper and the lower phase. The two liquids were in a pool and distinctly separate. In most cases the presence of the second liquid caused the heat flux to be greater than for one liquid only. The increase is a function of the boiling point depression, the mode of boiling, the quantity of the added liquid, and whether the added liquid floats or sinks.

## NOMENCLATURE

| | |
|---|---|
| $Q/A$, | heat flux [Btu/h ft$^2$]; |
| $\Delta T$, | temperature difference driving force, metal wall temperature minus temperature of liquid nearby [°F]; |
| $V_W$, | volume of liquid water in condensate.; |
| $V_T$, | total volume of condensate. |

(Conversion of units: 1 Btu/h ft$^2$ = 3·155 W/m$^2$)

## INTRODUCTION

BOILING immiscible mixtures are encountered in industrial practice. Steam distillation is the most common example. If the boiling takes place in a pool, the heat source can be located distinctly in either the heavy or light phase, and a number of heat-transfer arrangements become possible. By considering free convection, nucleate boiling, and film boiling at the heating surface and each of these also at the liquid–liquid interface, 18 cases exist as indicated in Table 1. No subcases are listed for variations in the volatility or degree of mixing of the two phases. It is obvious that the particular tube and mixture combination must be carefully defined if one hopes to predict the heat transfer. The object of this study was to investigate 7 of the 18 cases in Table 1. The chosen arrangements were Cases 2, 3, 5, 11, 13, 14 and 16. These provide much information on changes caused by adding a second immiscible phase to a one-phase boiling liquid. The tests utilized the capabilities of the experimental apparatus. A single horizontal heating tube was used.

Bragg and Westwater [1] showed that if the heat source is a flat horizontal plate at the bottom of the boiler, 11 cases can be described for an immiscible liquid–liquid mixture. They omitted cases with forced mixing but included variations in the volatility of each phase. The test mixtures were water–Freon-113 (similar to Case 3 of Table 1), water–perchlorethylene (similar to Case 3 or 6), and water–n-hexane (similar to Case 4, 5 or 6). They found an increase in the heat flux during film boiling of the lower phase upon addition of the upper phase.

Very few additional data have been published concerning boiling with immiscible mixtures. The results of the studies which have been made apply only to nucleate boiling and convective heat transfer and are confusing, because no precise description of the experimental conditions are given. Such a description should include which phase is in contact with the heating surface, the degree of mixing between the phases,

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and the location of the interface between the phases.

The first published test with immiscible mixtures were conducted by Bonilla and co-workers. The tests by Bonilla and Perry [2] involved nucleate boiling of a partially miscible water–n-butanol mixture on a flat plate. This is similar to Case 2 of Table 1. It was concluded from these studies that the heat transfer rate in this two-phase mixture heated from below was determined by the properties of the lower, more-volatile, water-rich layer. In later studies by Bonilla and Eisenburg [3], very slightly soluble water–styrene and immiscible water–butadiene mixtures were boiled on a flat plate. In the water–styrene system (similar to Case 2) water was the more volatile and denser phase. Pure water gave the highest flux, styrene gave a lower flux, and the immiscible systems gave the lowest fluxes for the nucleate boiling range tested. The heat flux depended on the amount of contact the styrene phase had with the heating surface. This was dependent on the degree of mixing. For the water–butadiene system, water was the more dense and less volatile component (similar to Case 4). No bubbles originated in the water phase, even at the highest $\Delta T$ of 160°F. The heat flux was equal to that predicted for water in natural convection.

*Table* 1. *Possible cases for heat transfer from a horizontal tube to an immiscible mixture*

| Case | Top phase | Bottom phase | Phase containing tube |
|---|---|---|---|
| 1. | Free convection | Free convection | Bottom |
| 2. | Free convection | Nucleate boiling | Bottom |
| 3. | Free convection | Film boiling | Bottom |
| 4. | Nucleate boiling | Free convection | Bottom |
| 5. | Nucleate boiling | Nucleate boiling | Bottom |
| 6. | Nucleate boiling | Film boiling | Bottom |
| 7. | Film boiling | Free convection | Bottom |
| 8. | Film boiling | Nucleate boiling | Bottom |
| 9. | Film boiling | Film boiling | Bottom |
| 10. | Free convection | Free convection | Top |
| 11. | Free convection | Nucleate boiling | Top |
| 12. | Free convection | Film boiling | Top |
| 13. | Nucleate boiling | Free convection | Top |
| 14. | Nucleate boiling | Nucleate boiling | Top |
| 15. | Nucleate boiling | Film boiling | Top |
| 16. | Film boiling | Free convection | Top |
| 17. | Film boiling | Nucleate boiling | Top |
| 18. | Film boiling | Film boiling | Top |

More recent studies on the nucleate boiling of immiscible systems were conducted by Van Wijk, Vos and Van Stralen [4]. These workers conducted tests with a horizontal hot platinum wire in partially miscible mixtures of water and methylethylketone, water and n-butanol, water and n-pentanol, and water and n-octanol. The results of these tests are inconclusive due to the lack of information on the experiment. This paper does not describe either the degree of mixing of the phases or the location of the wire with respect to the interface between the phases. It is impossible to classify their results in Table 1.

At least four studies of 2-phase systems have included mercury as one of the phases. All these are similar to Case 4 or Case 1. Quantitative data were taken by Gordon and co-workers [5] for water, methanol, and ethanol in nucleate boiling on a mercury surface. Heat transfer through the mercury was by conduction and convection. A great deal of turbulence was noted at the liquid–liquid interface at the higher nucleate boiling fluxes. Viskanta and Lottes [6] and Novakovic *et al.* [7], thought part of this turbulence was caused by Gordon's experimental setup which allowed boiling from the container side walls. To correct for this, both Viskanta, Lottes and Novakovic used a modified experiment to get nucleate boiling heat fluxes more characteristic of boiling at this liquid–liquid interface. All three of these pool boiling studies led to the conclusion that surface superheats for a specific heat flux were larger for boiling on a mercury surface than for boiling on a normal metallic surface. Because nucleate boiling is very dependent on surface texture, and impurities collect at the liquid–liquid interface, this type of boiling was studied by Hsu [8] and Viskanta *et al.* to determine the effect of liquid purity. Hsu shows conclusively that bubble formation is greatly dependent on liquid purity. A review of studies of boiling mixtures, through 1965, has been published [9].

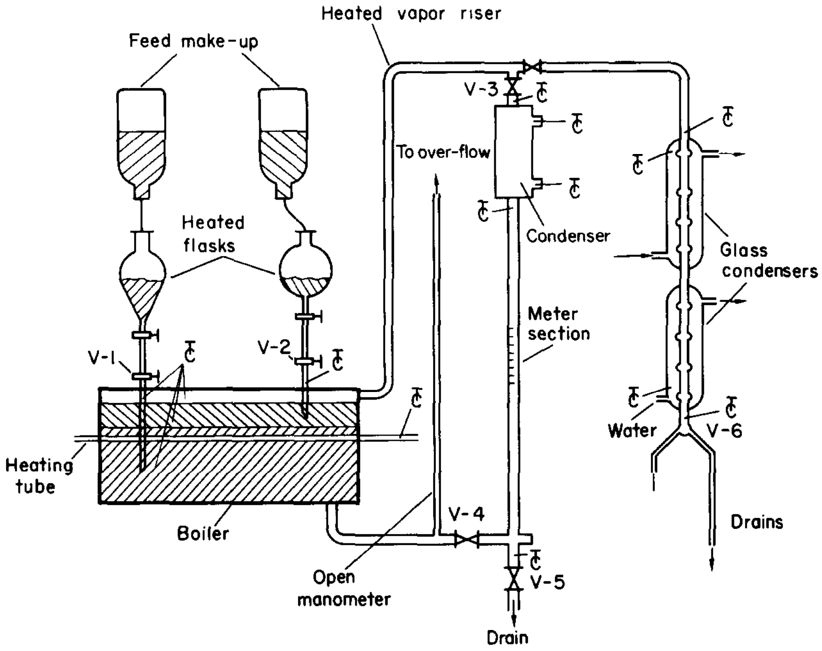

FIG. 1. Sketch of the apparatus.

## APPARATUS AND PROCEDURE

The apparatus consisted of a test boiler with a steam-heated copper tube, systems for handling the vapor produced, two steam supply systems, and an electrical system for measuring the temperature of the copper heating tube. A schematic drawing of the apparatus is shown in Fig. 1. Boiling occurred on the surface of a 20 gauge, $\frac{1}{4}$ in. o.d. copper tube, 9·98 in. long. The condensate was collected for measurement in either an open cycle or a closed cycle operation. Steam to heat the copper tube was supplied by either the lab supply or from an auxillary high pressure boiler. By using a vacuum arrangement with these two systems, steam pressures from about 7 psia up to 500 psig were obtainable. An electrical system was utilized so that the heating tube was used as a resistance thermometer to determine the average metal wall temperature. The temperature drop through the metal wall was computed to be about 0·1°F, a negligible value.

The boiler body was a rectangular stainless steel box with front and rear window openings, two round side holes, eight tapped fittings in the top, and four 1-in. nipple connections. Internally, the boiler was 8·75 in. high by 11·25 in. wide by 4 in. front-to-back. The window gaskets were of Teflon, and the windows were of $\frac{3}{8}$ in. Pyrex plate galss.

The heating tube was inserted through the side holes in the boiler which were located about 3·0 in. from the front and 4·5 in. from the bottom. The tube was sealed at the boiler body with Teflon. The tube was at a slight angle with the horizontal to facilitate steam condensate drainage. The heat transfer area was 7·84 in.$^2$ The surface was polished with successively finer grades of emery cloth ending with a 3/0 grade. The final finish was a polish with Cameo copper cleaner on a damp cloth and a water rinse, and a drying. The surface was shiny and lustrous at the start of each run.

The vapor generated in the boiler passed through the heated vapor riser and to either of two condensers. A brass tube-in-shell condenser which had a heat transfer area of 3 ft$^2$ was used for closed-cycle runs and for most of the film-boiling runs. The other condensing section of the second downcomer consisted of two 400 mm glass Allihn condensers connected in series. These glass condensers were convenient for some film-boiling runs with small amounts of water in the vapor.

Iron–constantan thermocouples were located at the points indicated in Fig. 1. These were sealed in either glass or stainless steel wells.

The heating tube was used as a resistance thermometer to determine its temperature. An 18 A d.c. current was passed through the tube and then through a standard 0·0005-Ω resistor. Voltage drops were measured to within 0·001 mV by use of a Leeds and Northrup Type K-4 potentiometer.

The system was run both open cycle and closed cycle. During open cycle runs pre-heated make-up feed was added to the boiler so as to maintain constant liquid levels. The condensate flow rate was measured and from this the heat-transfer rate was computed. The condensate heat duty was determined from measurements on the cooling water. These two determinations of the heat duty agreed within 8·4 per cent on the average.

High-speed motion pictures were taken on 16 mm film with a Wollensak Fastax WF-3 camera. These were used to obtain bubble diameters, frequencies, spacings, and occurrences at the liquid–liquid interface. Complete details of the apparatus, procedure, and bubble measurements are available [10].

## RESULTS

### *Freon*-113–*water*

Significant physical properties of the liquids used are given in Table 2. A Case 3 study was planned. First the film-boiling curve for pure Freon-113 was determined. This is given in Fig. 2. It does not differ much from the prediction [13] of the Bromley equation. The data are in good agreement with the results of Haley [14] which are shown also in Fig. 2.

Three runs were made next with the tube in Freon-113, during film boiling, as a 1-in. layer of preheated water was added on top the Freon. In every case the liquid and vapor temperature decreased, more or less as expected considering the addition of vapor pressures. The total pressure was constant, and the tube temperature was constant for each run. An increase in the heat flux by about 9 per cent occurred for each run, presumably because of the increase in $\Delta T$ resulting from the boiling point depression. The value of the heat transfer coefficient rose by about 7 per cent. These runs are indicated in Fig. 2 by the arrows passing from data points on the

*Table 2. Physical properties: primarily from* [11] *and* [12]

| | Specific gravity at room temp. | Latent heat of vaporization at B.P. $\left(\frac{\text{Btu}}{\text{lb}}\right)$ | Normal boiling pt. at 1 atm (°F) | Equil. steam dist. temp. (°F) | Equil. boil-up ratio $V_W/V_T$ at 1 atm $\left(\frac{\text{Vol. H}_2\text{O}}{\text{Vol. Total}}\right)$ | Solubility of $H_2O$ in organic (wt. %) | Solubility at organic in $H_2O$ (wt. %) |
|---|---|---|---|---|---|---|---|
| Freon-113<br>$CCl_2F$-$CClF_2$ | 1·55 | 63 | 117 | 112 | 0·015 | 0·0086<br>at 68°F | 0·017<br>at 68°F |
| Freon 112<br>$CCl_2F$–$CCl_2F$ | 1·63 | 67 | 199 | 169 | 0·088 | 0·0099<br>at 82°F | 0·013<br>at 82°F |
| n-Hexane<br>$C_6H_{14}$ | 0·66 | 145 | 155 | 142 | 0·036 | 0·011<br>at 68°F | 0·0036<br>at 61°F |
| Water<br>$H_2O$ | 1·00 | 970 | 212 | — | — | — | — |

curve for pure Freon-113 to points on the curve for the mixture. For these runs the heat balance closed within 3 per cent, thus the increase in flux resulting from the addition of water is real. The data of Bragg and Westwater [1] show about the same increase in $\Delta T$ but no measurable change in heat flux with this two-liquid system in film boiling on a flat plate.

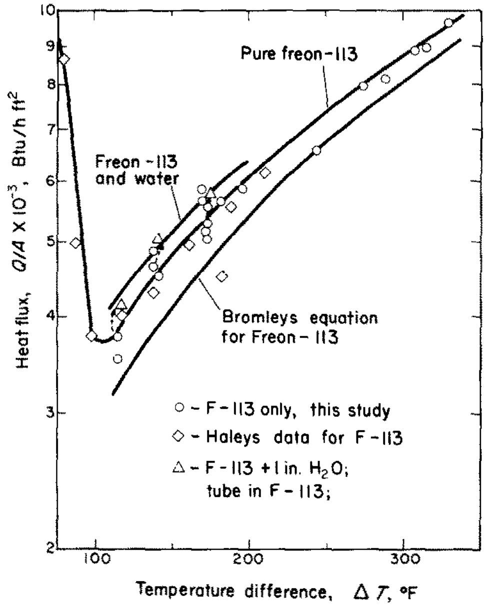

FIG. 2. Freon-113 in film boiling with a 1 in. layer of water on top. Case 3 of Table 1.

A series of runs were made to determine the effect of varying the thickness of the floating water layer on the heat transfer from the copper tube to Freon-113 in film boiling, Case 3. Heat flux, temperatures, and condensate composition measurements were made for added amounts of water varying from a single drop (0·02 ml), up to a layer 1·0 in. thick. The boiling point depression was determined after each addition by monitoring the thermocouples located in both liquid phases and the vapor phase. The Freon-113–water interface was located 1 in. above the tube. This depth of separation was used to prevent bulk water from being carried down to the tube surface. The water layer depth was limited to a maximum of 1 in. to prevent entrainment of liquid water in the vapor riser.

The temperature measurements, Fig. 3, show conclusively that there is an effect of water depth on the boiling depression for the mixture. The effect was slight up to an accumulated water

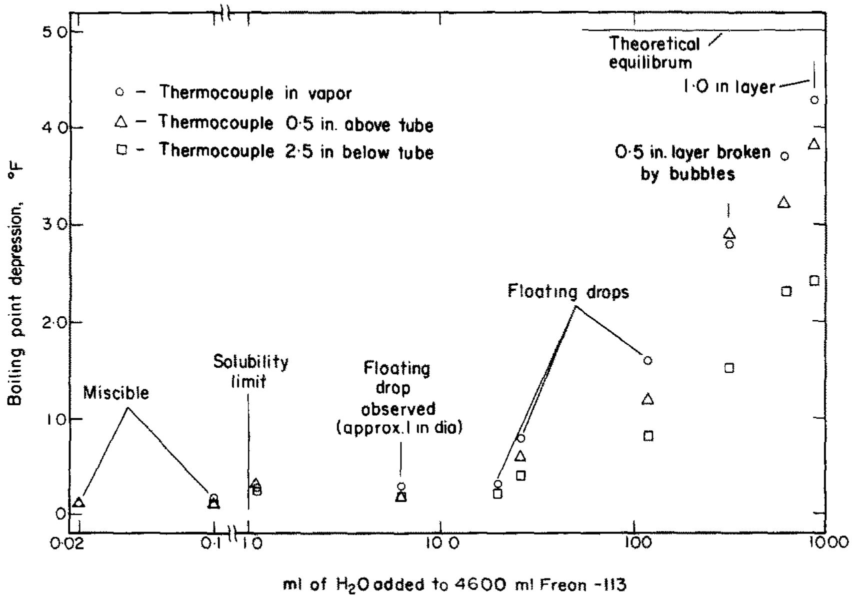

FIG. 3. Freon-113 in film boiling with water on top showing effect of water depth. Case 3.

volume of about 26 ml on 4600 ml of Freon-113, equivalent to 0·09 ml of water per cm$^2$, at which amount the depression was about 0·6°F. This depression increased with further additions of water up to a maximum depression in the vapor temperature of 4·3°F. This depression is about 85 per cent of the theoretical boiling point shift of 5°F. The theoretical value is computed by assuming addition of pure-component vapor pressures.

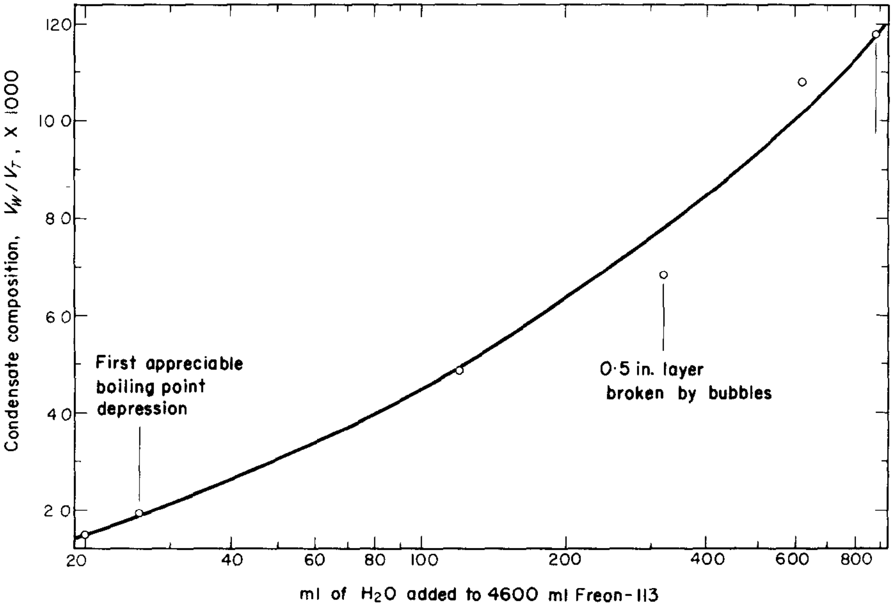

FIG. 4. Effect of water depth on vapor composition. Freon-113 in film boiling. Case 3.

The vapor composition also is affected by the depth of the water layer on the pool of Freon-113. Figure 4 shows that the composition becomes progressively richer in water as the water depth increases. With the greatest depth, 1 in. of water, the condensate contained 0·012 volume of water liquid per total volume of liquid condensate. This is about 80 per cent of the theoretical amount of water which would exist at equilibrium.

Textbooks which consider immiscible mixtures at thermodynamic equilibrium teach that the pure-component vapor pressures are additive if the vapor molecules have ready access to both liquid phases. The present study indicates that one floating drop on a large pool does not satisfy this condition. Neither is it satisfied by several floating drops of 1-in. dia. on a 45 in.$^2$ pool, as demonstrated in Figs. 3 and 4. In fact, thermodynamic equilibrium did not exist for any combination of the Freon-113–water system.

For a water depth of 1 in. the vapor molecules in the bulk vapor had no access to the Freon-113. The water layer was a "lid" on the Freon. However, Freon-113 bubbles were formed at the heating tube and rose through the Freon liquid and then through the liquid water. As the bubbles passed through the water, they exchanged heat and mass with the water. The depth of water which will result in bubbles of equilibrium temperature and composition is unknown, but it is obviously greater than 1 in.

The liquid–liquid interface location was varied systematically in a series of runs having a constant overall depth of 6·7 in. for the combined liquids. The tube was 2 in. below the liquid–vapor interface, and the tube temperature was constant at 227–231°F. The results are shown in Fig. 5. Point AA is for pure Freon-113 in film boiling. Point BB is for a test with 1 in. of water replacing 1 in. of Freon-113 and shows a small increase in heat flux (Case 3). The mode of boiling is still filmwise. Point DD is for the liquid–liquid interface at the midpoint of the tube, and the heat flux becomes about ten times the value at BB. Point EE is for the tube totally surrounded by water; the Freon-113 is present but resting 1·2 in. below the tube. For Points EE, FF and GG the water exhibited nucleate boiling on the tube, and the Freon-113 exhibited nucleate boiling at the water–Freon-113 interface (Case 14). Thus which phase a heating surface is located in is a crucial matter. In this series of tests, a Case 3 situation became Case 14 and a huge change in heat flux resulted, depending on which liquid surrounded the tube.

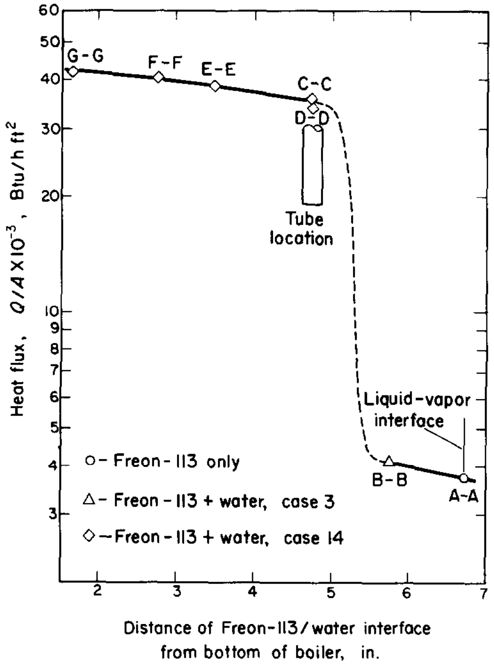

FIG. 5. Heat flux shift with change in Freon-113/water interface location. The tube temperature was 229–231°F.

Temperature profiles in the vertical direction were measured for the seven runs of Fig. 5. These are given in Fig. 6. Profile AA, which is essentially a constant temperature, is for pure Freon-113. Profile BB shows a flat temperature profile through both liquids at a temperature depression of 3·7°F. However, as the water contacts the tube, CC, a distinct rise in the water temperature occurs. When the tube is completely surrounded by water (EE, FF and GG) the water phase is about 15°F hotter than for BB. Pure water boils at 212°F and pure Freon-113 boils at 117°F. A mixture of the two in a pool as described herein may boil with a liquid temperature of 113 or 131°F depending on whether the heater is in the Freon-113 or in the water. The temperature of the resulting vapor can vary from 112 to 125°F. The calculated temperature for thermodynamic equilibrium is 112°F. The approach to equilibrium is closest when the tube is in the lower phase; it is quite poor when the tube is in the upper phase. Data for these runs showed a rise in the water content of the vapor as the water–Freon-113 interface receded below the heater surface. The low temperatures shown for the lower phase near the bottom of the boiler

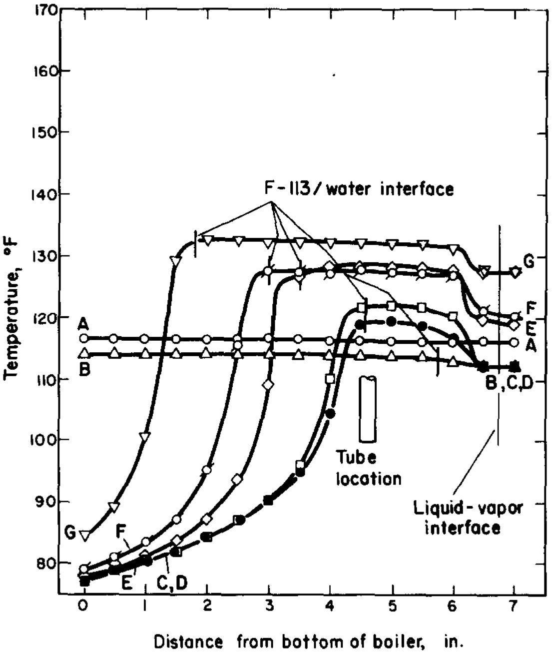

FIG. 6. Temperature profiles in the boiler, Freon-113/water. The data correspond to tests identified in Fig. 5.

were caused by the return of cool condensate to the bottom during closed-cycle operation. With no condensate return the lower temperature would become nearly constant in the 112–117°F range, but the conclusions stated above would be unaffected.

*Freon-*112*–water*

With this system it was possible to make studies of Cases 2, 3 and 14. The nucleate, transition, and film boiling regions of the boiling curve for pure Freon-112 were determined first, as shown in Fig. 7. The film-boiling data agree well with the Bromley equation.

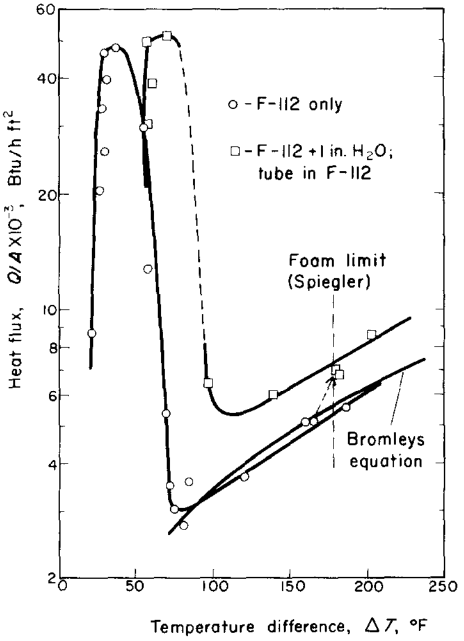

FIG. 7. Freon-112 boiling with a 1 in. layer of water on top. Cases 2 and 3.

The boiling curve was then determined with the tube surrounded by Freon-112 but with a 1 in. layer of water on top. The Freon-112–water interface was 1 in. above the tube. The entire boiling curve was affected, as shown in Fig. 7. The nucleate boiling portion of the curve (Case 2) was shifted horizontally toward higher $\Delta T$ values by about 29°F. The observed boiling point depression of the liquid Freon-112 was about 29°F, very near the equilibrium depression of 30°F.

The film boiling portion of the curve (Case 3) was shifted toward higher heat fluxes by about 41 per cent. This shift is real as proved by adding preheated water to a pool of boiling, pure Freon-112 and monitoring the ensuing charge. The verification run is indicated in Fig. 7 by the arrow connecting the corresponding data points. The increase in heat flux for Freon-112 is greater than for Freon-113 as water is added to both in film boiling (Case 3). Other than boiling point, the physical properties for the two Freons are similar. It is concluded that the magnitude of the increase in heat flux, during film boiling, when water is added is a function of the magnitude of the boiling point depression of the fluid contacting the heating surface. The measured depression in temperature of the Freon-112 was about 18°F (which is 60 per cent of the theoretical depression) whereas it was about 4°F for Freon-113.

For the Case 3 runs (film boiling of the lower phase), photography showed that the bubbles were released in rows in a regular manner from the tube. At the liquid–liquid interface they coalesced and reformed then new bubbles rose through the upper phase. Liquid drops also appeared at the liquid–liquid interface.

It is of some interest to predict the $\Delta T$ for the minimum heat flux during film boiling of a single liquid. This Leidenfrost point is well defined in the curves herein for pure Freon-112 and Freon-113. Spiegler's prediction, which he calls the Foam Limit [15] is shown for Freon-112 in Fig. 7. The predicted value is in error by 95°F.

Runs made with the tube in water and a layer of Freon-112 below the water (Case 14) are discussed later in this paper.

*n-Hexane–water*

Cases 5, 13 and 16 were studied with this system. The nucleate and film boiling regions for pure n-hexane were determined first, as shown in Fig. 8. The film boiling data agree well with the Bromley equation. Then runs were made with water present. For results shown in Fig. 8 the heating tube was in the n-hexane, the liquid–liquid interface was 1 in below the tube, and the liquid–vapor interface was 1 in. above the tube.

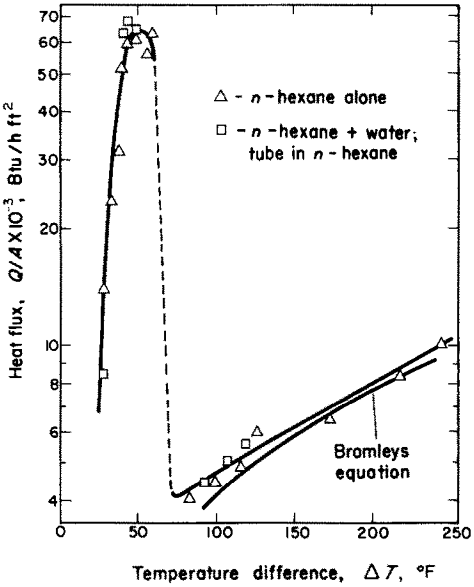

FIG. 8. n-Hexane boiling with a layer of water underneath. Cases 13 and 16.

Runs with nucleate boiling on the tube (Case 13) and with film boiling on the tube (Case 16) were carried out. Figure 8 shows that the effect of the added water, for Cases 13 and 16, was nil. Only a trace of water could be detected in the vapor. The theoretical depression for the hexane is 13°F. The observed depression was less than 3°F.

*Correlation of results with water contacting the tube*

Within the limits of the apparatus, the boiling curve for pure water was established as shown in Fig. 9. The free convection portion of the curve was approximated [16] by $Nu = 0{\cdot}53\ Ra^{\frac{1}{4}}$, the peak of the boiling curve was estimated [17] by Zuber's equation, and the film boiling portion was approximated [13] by Bromley's equation in the same graph are shown the results for the three mixtures with the tube in the water for each case, and with nucleate boiling of water for all data points except two labelled as free convection. Cases 5, 11 and 14 are represented.

The temperature difference used for the abscissa for the two Freon systems is the metal wall temperature minus the water temperature indicated by a thermocouple located about 0·5 in. above the tube center line. For n-hexane–water the $\Delta T$ is the metal temperature minus the n-hexane temperature 1·5 in. above the tube. This latter arbitrary value is for representational purposes only; the water temperature was ill defined when hexane was present because of steep temperature gradients. Data from Bragg [1] for free convection from a flate plate to a water pool covered by a layer of floating n-hexane are plotted also in Fig. 9. These free-convection data were taken at lower values of $\Delta T$ than considered in the present study. Bragg also obtained data for film boiling from a flat

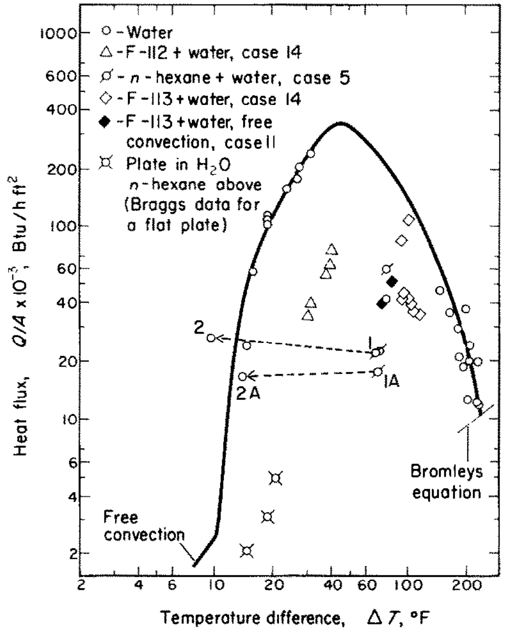

FIG. 9. Nucleate boiling of water in the presence of each of three immiscible liquids. The solid line shows the boiling curve for water alone.

plate to a water pool covered by n-hexane. Such film boiling data were not taken in the present study.

Little sense can be made from Fig. 9, but order appears when the data are replotted as shown in Fig. 10. Here the tube surface temperature is used as the abscissa. Most of the nucleate boiling data for water in the presence of the immiscible liquids correlate roughly with the data for water alone.

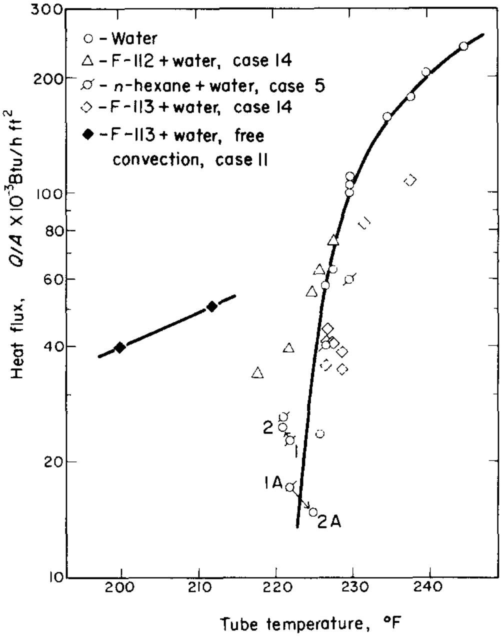

FIG. 10. Rough correlation of data from Fig. 9.

A vivid illustration of the effect of hexane floating on water in nucleate boiling is shown by the data points connected by arrows in Figs. 9 and 10. In the presence of water the observations were points 1 and 1A. After each of these observations were made, the system was operated in open cycle until all the hexane was gone. Make-up water was added at a rate sufficient to maintain a constant liquid depth. Just as the hexane disappeared, the boiling ceased, and the net vapor generation ceased. The boiling temperature of the water was depressed as long as both components were present, but the water alone could not boil at that temperature, 148°F. The temperature of the pure water rose soon to 212°F, and boiling resumed at points 2 and 2A. Fig. 10 shows that the result was a slight shift in the heat flux and the metal temperature. Figure 9 shows that the result was a large shift in the $\Delta T$.

These results for these immiscible systems indicate that the heat flux from the tube for the configurations of Cases 5, 11 and 14 may be roughly predicted from a knowledge of the heater temperature and the nucleate boiling data for the liquid contacting the tube. Presumably this is true only if the two liquid phases are distinct; vigorous agitation could alter the results. Bonilla and Eisenberg [3] reached similar conclusions from the data for water–styrene mixtures.

### *Motion picture analysis*

Bubble measurements were made from the motion pictures of the three pure organic liquids in film boiling and also for the two-phase liquid mixtures with the tube in the organic phase and film boiling existing on the tube. The average bubble diameters for the pure liquids were 0·26 in. for Freon-113, 0·24 in. for Freon-112, and 0·34 in. for n-hexane. These values agree satisfactorily with the respective values of 0·25, 0·23 and 0·34 in. predicted by Zuber's equation using half the most dangerous wavelength [17]. When water was present, the bubble volumes decreased by 44–54 per cent. The bubble center-to-center spacings at break-off averaged 0·48 in. for Freon-113, 0·48 in. for Freon 112, and 0·65 in. for n-hexane. These are close to the respective values of 0·49, 0·46 and 0·68 in. predicted by Zuber using the spacing as being equal to the most dangerous wavelength.

The hydrodynamic analyses of film boiling by Zuber [17] and modified by Berenson [18] and Lienhard *et al.* [19] show that the bubble diameter, spacing, and frequency are determined by the densities of the liquid and vapor and the liquid–vapor interfacial tension. The physical properties are essentially the same for a pure component alone as in the presence of an immiscible second liquid. Thus the change in diameter is not expected. The fact that the bubble spacing and frequency were unaffected in the present tests is as expected. It seems unlikely that the change in heat flux can be ascribed to interfacial tension or densities.

From measurements on the motion picture films, the volumetric rate of vapor generation on the hot tube was determined, and from this the heat flux was computed. The value was less than the true flux in almost every case, usually by about 50 per cent. The disagreement can mean that the bubbles are not oblate spheriods (as assumed for volume computations from measurements of two diameters). An alternate explanation is that a significant amount of heat transfer is by evaporation and condensation at opposite sides of a bubble—so called, latent heat transport—or by conduction and convection in the liquid near the tube.

Inasmuch as the liquid on a heater tube boils at a depressed temperature (compared to the pure liquid) when two components are present, the phenomenon is similar to subcooled boiling. Therefore the results were compared with a photographic study of subcooled film boiling done by Nishikawa [20, 21]. He used hot wires as the heat source. He found that the bubble diameters decreased with subcooling. He found also an increase in bubble frequency and a decrease in spacing. For the present tests, no change in frequency or spacing was detected. Thus the effects noted in the present study with immiscible systems cannot be described completely in terms of subcooling. To test this conclusively, it would be necessary to have subcooling tests performed with the pure components. No such data are available.

Finally, measurements were taken at the liquid–liquid interface for the Freon-113–water system, and the Freon-112–water system. These show that bubbles rising from the tube are held up at the liquid–liquid interface before rising through the upper phase. During this delay, the bubbles coalesce to form larger bubbles which rise through the upper phase. There was a greater hold-up of vapor at the interface for the Freon-112–water system than for the Freon-113–water system. This was shown by the bubble delay time at the interface. This value was about $2\frac{1}{2}$ times as large for the Freon-112–water combination as for the Freon-113–water system, namely, 0·17 vs. 0·07 s. This difference is significant, because the bubble frequencies from the tube were about the same for both systems.

## CONCLUSIONS

1. For a pool of two immiscible liquids boiling on a heated tube, significantly different results occur for the tube in the lower phase vs. the tube in the upper phase.
2. During film boiling, the presence of the second liquid phase causes the heat flux to be greater than for one liquid only. The increase is roughly proportional to the boiling point depression. This conclusion is supported by most of the data obtained by Bragg [1] for film boiling on a flat plate.
3. During nucleate boiling, the presence of the second liquid causes only a small change in the heat flux at a constant metal wall temperature.
4. The amount of the second liquid has a strong effect on the results. A continuous change in heat flux, temperatures, and vapor composition occurs as the upper liquid amount is increased from one drop to a layer 1 in. deep.
5. Eighteen different cases are possible; no information is available for 8 of these.

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## TRANSFERT DE CHALEUR PAR ÉBULLITION ENTRE UN TUBE ET UN MÉLANGE DE LIQUIDES NON MISCIBLES

**Résumé**—Des expériences sont effectuées à la pression atmosphérique avec de l'eau additionnée de Fréon 113 ou de Fréon 112 ou enfin de n-hexane. L'ébullition a lieu dans un tube de cuivre horizontal de 0,635 cm avec des mesures à des endroits différents dans la phase supérieure et dans la phase inférieure. Les deux liquides sont distinctement séparés. Dans la plupart des cas la présence du second liquide rend le flux thermique plus important qu'avec un seul liquide. L'accroissement est fonction de l'abaissement du point d'ébullition, du mode d'ébullition, de la quantité de liquide ajouté et aussi bien du comportement du liquide ajouté suivant qu'il flotte ou coule.

## WÄRMEÜBERGANG BEIM SIEDEN VON EINEM ROHR AN NICHTMISCHBARE FLÜSSIGKEIT-FLÜSSIGKEIT GEMISCHE

**Zusammenfassung**—Bei Atmosphärendruck wurden Versuche mit Wasser und Frigen-113, Frigen-112 sowie n-Hexan durchgeführt. Das Sieden erfolgte an einem 6.4 mm starken horizontelen Kupferrohr, an besonderen Stellen in der oberen und unteren Phase. Die beiden Flüssigkeiten befanden sich in einem Behälter und waren deutlich voneinander getrennt. In den meisten Fällen bedingte die Anwesenheit der zweiten Flüssigkeit einen höheren Wärmestrom als die nur einer Flussigkeit allein. Die Steigerung ist eine Funktion der Siedepunktserniedrigung, der Siedeart, der Menge der beigefügten Flüssigkeit und sie hängt auch davon ab, ob die beigefügte Flüssigkeit schwebt oder sinkt.

## ПЕРЕНОС ТЕПЛА ОТ ТРУБЫ К НЕСМЕШИВАЮЩИМСЯ СМЕСЯМ ЖИДКОСТЬ-ЖИДКОСТЬ ПРИ КИПЕНИИ

**Аннотация**—Эксперименты проводились при атмосферном давлении на воде с добавкой одного из веществ: фреона-113, фреона-112 или гексана. Исследовался процесс кипения

в горизонтальной медной трубе диаметром 0,25 дюйма, измерения проводились в различных участках как верхней, так и нижней фаз.

Наблюдалось четкое разделение жидкостей по всему объему. В большинстве случаев при наличии второй жидкости тепловой поток возрастал.

Увеличение зависит от понижения точки кипения, вида кипения, количества добавленной жидкости и соотношения плотностей жидкости.