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TRANSITION BOILING OF NORMAL PENTANE FROM A HORIZONTAL FLAT GOLD SURFACE AT ONE ATMOSPHERE PRESSURE

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NOMENCLATURE

Q, heat flux per unit area per unit time;
Q_{in}, heat flux arriving at the boiling surface from the source;
Q_{out}, heat flux leaving the surface by boiling;
R_T, resistance to heat transfer;
T, temperature;
ΔT, surface temperature minus saturation temperature;
ΔT_{in}, source temperature minus surface temperature.

INTRODUCTION

DUE TO the physical difficulties of equipment operation in the transition region there has been little interest in this area until recent years. Though Nukiyama [1] labeled the transition region as a boiling regime, he made no attempt to define its mechanism of heat transfer.

Drew and Mueller [2] postulated, in 1937, the existence of a distinct mechanism, different from both nucleate and film, for the transition region. However, no mechanism was proposed. They reported some transition data but the data were qualitative in nature. Berenson [3], boiling normal pentane from flat surfaces, obtained transition data in the lower portion of the transition curve near the Liedenfrost point for copper, nickel, and inconel surfaces and a complete transition curve for an oxidized copper surface. Berenson concluded that transition boiling is a combination of nucleate and film boiling existing alternately on all parts of the surface, with the heat flux variation with temperature caused by the variation of the fraction of time in which each type boiling occurs. Thus, he postulates there is liquid–solid contact in the transition region and the boiling curve should be a function of surface condition.

Westwater and Santangelo [4] were able to obtain data in the lower 40 per cent of the curve for methanol boiling from a cylindrical heater. They concluded that transition boiling is entirely different from both nucleate and film boiling. They postulated that no liquid–solid contact exists in this region and that the vapor blanket is unstable and in violent motion.

Studies by Kovalev and co-workers [5] and Veres and Florschuetz [6] were successful only in obtaining transient transition boiling data due to thermal instability of the test apparatus. Kovalev [7] experienced the same difficulty but was able to propose certain stability criteria for operation in the transition region. He concluded that the condition,

$$\frac{1}{R_T} < -\left(\frac{dQ}{dT}\right)_{min} \tag{1}$$

must be satisfied for stable operation in this region. Here R_T is the total thermal resistance between the heating medium and the boiling surface and the derivative is the minimum slope of the boiling curve in the transition region.

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A recent study by Hesse [8] was successful in obtaining transition data from cylindrical heaters. The heating medium was water flowing on the inside of the tube while boiling occurred on the outside. He obtained the complete boiling curve for refrigerants (Freon) R12, R113 and R114 at several pressures from a nickel tube with outside diameter of approximately 0.55 in (0.014 m).

The effect of agitation on the transition region boiling curve has been reported by Pramuk and Westwater [9].

Kesselring, Rosche and Bankoff [11] obtained transition and film boiling data for Freon 113 from flattened horizontal stainless steel tubes. They reported that contact between the solid surface and the boiling liquid occurs during a portion of the transition boiling region but ceases before the minimum point is reached.

EXPERIMENTAL APPARATUS

Figure 1 is a schematic diagram of the equipment used during this investigation. The equipment will be briefly discussed here. For a complete equipment description the reader is referred to [11].

The heat transfer element was a copper disc 0.125 in (0.003175 m) thick and approximately 1.50 in (0.0381 m) in diameter. The surface on which boiling occurred (top surface) was gold plated to maintain a relatively constant surface chemistry. Boiling occurred on a portion of the surface 1 in (0.0254 m) in diameter. The bottom surface was bare copper treated with a promoter so that dropwise condensation of steam was obtained. Dropwise condensation was necessary because the relative instability of the transition regime requires low thermal resistance between the heating fluid (steam) and the boiling surface. An electrical heater in the steam chamber generated steam which condensed on the bottom of the heat-transfer surface and supplied heat for boiling on the top of the surface.

A single thermocouple well [diameter 0.056 in (0.00142 m)] was drilled radially into the geometric center of the disc. A 30 gauge teflon covered copper–constantan thermocouple was inserted in the thermocouple well. Solder having a plastic point of 377°F (465°K) was used to fill the well after insertion of the thermocouple. This thermocouple was used to record the surface temperature during data collection.

The pressure of the boiling chamber was sensed at the top of the vapor space above the liquid pool. The high-pressure leg of a d/p cell was connected at this point and the low-pressure leg was open to the atmosphere. The pneumatic signal from the d/p cell was transmitted to a proportional integral pneumatic recorder-controller. The d/p cell was calibrated so that a 1.0 lb/in^2 (6.89×10^3 n/m^2) pressure difference caused full scale deflection on the recorder-controller.

The pneumatic signal from the recorder-controller operated an air-to-close pneumatic control valve in the water inlet line to the condenser. To prevent the controller from cycling, a manual valve was placed upstream of the control valve. The pressure in the boiling vessel was thus controlled at one atmosphere (0.013×10^5 n/m^2) by the condenser water flow rate.

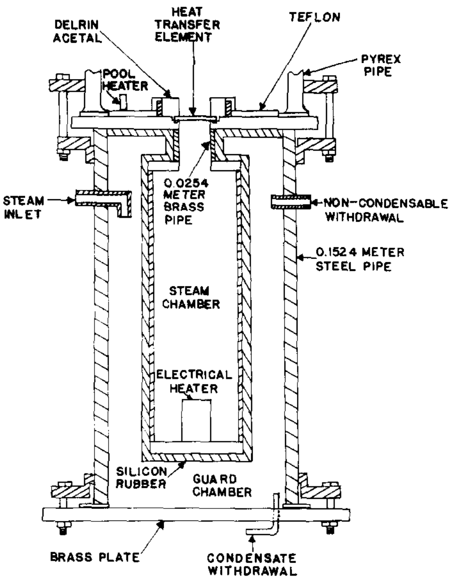

FIG. 1. Experimental apparatus.

The heater in the steam chamber was powered by voltage regulated direct current electrical power. The voltage was measured with a voltmeter which could be read to ± 0.1 V. Accuracy was $\pm 0.002\%$ of the 200 V full scale. The amperage was read with a multi-scale ammeter to ± 0.002 A on the 1.5 A scale and to ± 0.004 A on the 3 A scale. Accuracy on both scales was 0.5% of full scale. Heat balances around the equipment indicated the maximum loss of heat from the steam chamber was 4.4% of the input power to the chamber. Therefore the power passing through the heat-transfer surface to the pentane pool was taken as the input power to the steam chamber.

The temperatures of the surface and steam chamber were monitored using a two pen potentiometric strip chart recorder. The temperatures of the surface and steam chamber could be read to an accuracy of ± 0.15°F (± 0.083°K). Chromatographic analysis of the pentane indicated a purity in excess of 99 mol %.

TRANSITION REGION DATA COLLECTION

For transition data near the critical heat flux, the system was first brought to the critical heat flux point. Then more power was applied to the steam chamber heater until the boiling surface temperature began to increase. At that time the power input was quickly reduced below that producing critical heat flux and to a level consistent with the estimated equilibrium value corresponding to the immediate surface temperature. The system was then allowed to come to equilibrium as indicated by the chamber and surface temperature traces on the strip chart recorder. Resolution of the chamber temperature was 5 μV/division on the recorder. This resolution was necessary to properly determine steady state.

Transition data at points well removed from the critical heat flux were taken by approaching the data point from the Liedenfrost point. Entrance into the film boiling region was obtained by applying power in excess of the critical heat flux and allowing the surface temperature to rise until film boiling was achieved. Power was then reduced below the level corresponding to the Liedenfrost point and the surface temperature was allowed to drop. When the surface temperature reached a point where data were desired, additional power was applied until the surface temperature became constant as indicated by the strip chart recorder. The time between data points was generally 1–2 h.

Due to the inherent instability of boiling in the transition regime, less demanding criteria for steady state were applied in parts of the regime. In particular those data lying between 46 (25.6°K) and 70°F (38.9°K) temperature difference were required only to maintain steady state for one minute before data points were taken. It is believed that this area is so unstable that the effect of a slight increase in liquid loading on the condensing side of the heat-transfer surface or a large drop of water falling from the surface would be to dramatically change the surface temperature. Since the steam temperature changed very little from point to point in this region data points were frequently recorded as quickly as fifteen minutes apart.

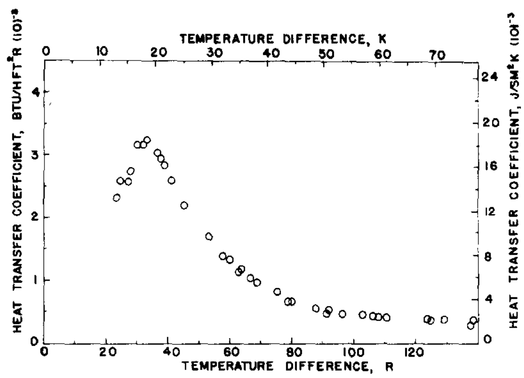

FIG. 2. Heat-transfer coefficient for *n*-pentane as a function of temperature difference at one atmosphere pressure.

RESULTS AND DISCUSSION

The results of this investigation of the transition boiling region are presented in Fig. 2. Apparently previous investigators [3–7] were unsuccessful in obtaining transition region boiling data due to equipment instabilities. Kovalev [7] was the first to recognize the need for some type of stability criteria to be met for operation in the transition region.

By considering a surface boiling in the transition region and examining the result of a small temperature change in the surface, the stability criteria can be determined. Assuming that the temperature change is positive, boiling can be stable and the surface temperature can return to its steady value if the heat leaving the surface (due to boiling) is greater than the heat arriving at the surface (from whatever source). At steady state the two heat fluxes are equal, therefore the condition

$$dQ_{out} - dQ_{in} \geq 0 \tag{2}$$

must be satisfied to maintain stability. For a small negative change in surface temperature the heat arriving must exceed the heat leaving. It is apparent that return to stability is possible as long as the difference $dQ_{out} - dQ_{in}$ and dT_{sur} have the same sign, that is, provided

$$\frac{dQ_{out}}{dT_{sur}} \geq \frac{dQ_{in}}{dT_{sur}}. \tag{3}$$

The heat flux into the surface can be represented as

$$Q_{in} = \frac{1}{R_T}\Delta T_{in}. \tag{4}$$

If in the limit of small temperature changes of the surface, the temperature at the heat source is not affected, and the thermal resistance between source and surface (R_T) is relatively unchanged, equation (4) may be differentiated to give

$$\frac{dQ_{in}}{dT_{sur}} = \frac{-1}{R_T}. \tag{5}$$

Insertion of this result into equation (3) and rearranging provides the stability criterion for boiling,

$$\frac{1}{R_T} \geq \frac{-dQ_{out}}{dT_{sur}}. \tag{6}$$

The derivative in equation (6) is merely the slope of the boiling curve and $(R_T)^{-1}$ may be thought of as the effective heat-transfer coefficient between heat source and boiling surface. This relation is valid in all portions of the boiling curve. Since the slope of the boiling curve is positive in the nucleate and film regions, these regions are always stable operating areas. However, low thermal resistance is an absolute necessity for stable operation in the transition region.

Using only two inches of copper between heat source and surface reduces the effective coefficient to less than 1400 Btu/h ft^2 F (4415.5 J/m^{2}s) and makes it impossible to operate stably in the transition region with most fluids. Previous workers had at least that equivalent resistance in their equipment and often much more, especially where condensing steam was used. It is for this reason they were unable to obtain data over the entire transition region.

This investigation was carried out with equipment which satisfied the previously mentioned stability criterion. It contained 0.125 in (0.003175 m) of copper (gold plated) and utilized dropwise condensation of steam to minimize system thermal resistance.

CONCLUSIONS

It has been demonstrated that when the stability requirement

$$\frac{1}{R_T} \geqslant \frac{-\mathrm{d}Q_{\text{out}}}{\mathrm{d}T_{\text{sur}}}$$

is satisfied for the boiling equipment stable boiling can be obtained over the entire transition region.

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HEAT TRANSFER FROM A CONSTANT TEMPERATURE CIRCULAR CYLINDER IN CROSS-FLOW

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NOMENCLATURE

- A, constant defined in equation (5);
- B, constant entering in equation (7);
- b, semiaxis of the ellipse defined in equation (1);
- C, constant entering in equation (6);
- Nu, Nusselt number;
- n, exponent used in equation (7);
- Pr, Prandtl number;
- Re, Reynolds number based on the diameter of the cylindrical wire;
- r, polar coordinate;
- T_1, normalized temperature in the outer region equal to $(T_b - T_\infty)/(T_a - T_\infty)$;
- T_2, normalized temperature in the inner region equal to $(T_a - T_b)/(T_a - T_\infty)$;
- T_a, temperature on the surface of the circular cylinder;
- T_b, temperature on the displaced boundary;
- T_∞, free stream temperature;
- $\mathbf{U}_1$, normalized velocity vector of the inviscid flow;
- ε, eccentricity of the ellipse defined in equation (1);
- θ, polar coordinate.

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INTRODUCTION

THE PROBLEM of forced convective heat transfer from a circular cylinder to a transverse flow is a classical one. Beginning with Boussinesq's investigation in 1905 [1], many theoretical contributions to this problem followed. A review of the theoretical and experimental literature can be found in [2].