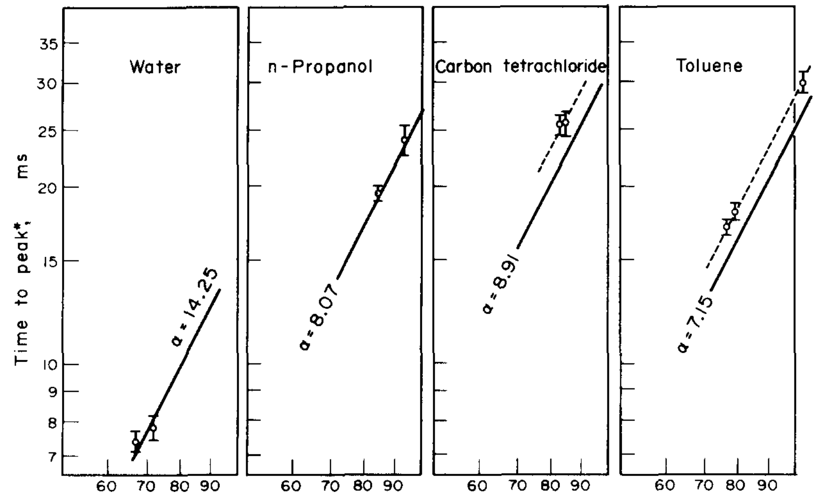

FIG. A4. Experimental data used for conclusions in subject communication, and comparison with an analytic model.

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NUCLEATE BOILING OF *n*-PENTANE, *n*-HEXANE AND SEVERAL MIXTURES OF THE TWO FROM VARIOUS TUBE ARRAYS

K. W. WALL* and E. L. PARK, JR.
University of Missouri—Rolla, Rolla, MO 65401, U.S.A.

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INTRODUCTION

THE CHARACTERISTICS of pool boiling outside single horizontal tubes have been intensely studied in the past 25 years. Considerable knowledge has been accumulated about pressure effects, critical heat flux, and nucleation, for various surface geometrics. However, two of the most important unknowns for the designers of boiling heat-transfer equipment, the effect of multicomponent mixtures and multitube bundle geometry on boiling performance have received only a small amount of attention [1–19].

Katz and co-workers [2, 3] boiled refrigerants from a vertical row of four horizontal heaters and found that the upper tubes in the bundle had a higher heat-transfer coefficient at the same heat flux. They also injected vapor into the system under the bottom of the lowest tube to determine what effect the vapor flow had on the heat-transfer rate. Injection of vapor produced the same results as those observed on the top heater in their four tube array.

Recent work [5–7] indicates that additional circulation and turbulence caused by rising bubbles can increase the bundle heat-transfer coefficient above that for a single tube. This increase would indicate that instead of a vapor penalty, a multitude enhancement correction must be applied for correlation.

Rhodes and Bridges [9] studied the effect of mixture composition on boiling heat transfer and found that the addition of either dilute sodim carbonate or oleic acid in water promoted boiling. Cichelli and Bonilla [10] found that binary mixtures boiled with a lower heat-transfer coefficient than that for either component when boiled alone. The lower fluxes found by Cichelli and Bonilla have been confirmed by numerous studies [11–14].

Van Stralen and Sluyter [15] found that the maximum heat flux for mixtures compared to the heat flux for the less volatile pure component increased steadily with increasing pressure. It was also noted that the maximum value of the critical heat flux occurred at a certain low concentration of the most volatile component.

In attempting to explain the problem of critical heat flux, van Stralen and co-workers [17–19] presented a theoretical approach for the mechanisms of the critical heat flux. When comparing binary data to this theory, a generalized correlation does not result.

EXPERIMENTAL EQUIPMENT

The experimental equipment used in this investigation can be conveniently classified into five subsystems: heat-transfer elements, boiling and condensing vessel, pressure measurement and control equipment, power supply system, and temperature measurement equipment.

The equipment was similar to equipment described previously [5, 6, 20, 21] therefore, the equipment description will not be covered in detail here.

The four heat-transfer elements used in this investigation had an outside diameter of 0.0266 m (1.048 in) and a length of 0.126 m (4.96 in). All heat-transfer elements were plated with gold in order to maintain the surface chemistry of the heat-transfer surface relatively constant during the tests.

The boiling and condensing system is shown in Fig. 1. The boiling and condensing sections were constructed of commercial 0.1524-m (6-in) Pyrex pipe tees and the vapor line connecting the two was a 0.1524-m (6-in) Pyrex pipe elbow. The system pressure was controlled to the nearest 338 N/m^2

*Dr. Wall is now with Du Pont Company, Wilmington, NC 28401, U.S.A.

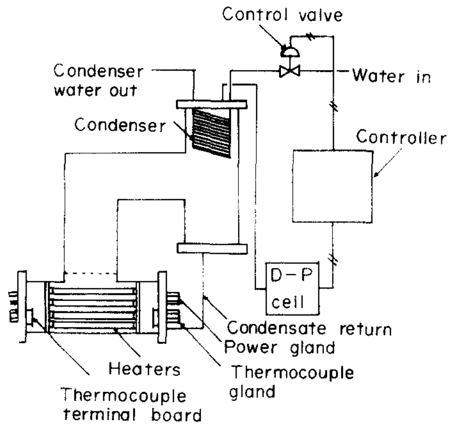

FIG. 1. Schematic diagram of the experimental apparatus.

(0.1 mm of mercury) by a control valve which varied the condenser water flow rate.

Direct current electrical power was supplied individually to each heater by four 60 V DC power supplies. The input amperage to each heater was read to ± 0.1 A; and the voltage drop across each heater could be read accurately to ± 0.001 V.

All temperatures were measured using 24 gauge copper–constantan thermocouples. Thermocouple output was read to ± 0.001 mV using a digital DC voltmeter.

EXPERIMENTAL PROCEDURE

The boiling chamber was filled until the pool depth was 2 in above the top heater.

Aging of heat-transfer surfaces has been found [5, 6, 22, 23] to be necessary in order to obtain reproducible nucleate boiling data. In this investigation, boiling for several hours at a high heat flux was used to age the surfaces. All of the surfaces were aged at the same time.

After aging was completed for each heater, the power to each heater was turned off and the surface temperature allowed to return to the pool temperature before any data were taken. The fluid was left in the apparatus at all times. After the heaters had been aged, data were taken as follows. The power supply was set to a 5 V output. As soon as equilibrium had been obtained, which was indicated by the lack of variation of the surface thermocouples, the four temperatures on the circumference of the heater were recorded along with saturation temperature of the fluid and the steady-state voltage and amperage supplied to the heat-transfer element. The next temperature level was obtained by increasing the power input by a desired amount. This procedure was continued until the critical heat flux was obtained.

Once a reference curve for each heater, with no other heaters boiling, had been obtained (a minimum of two reproducible runs): the multitube studies were performed. After the multitube studies had been completed, each tube in the bundle was boiled individually and its nucleate boiling curve measured. These check runs were performed to determine if the boiling curve had changed from its original position. If no deviation was found, any deviation from a heater's single tube curve was considered due to the boiling of the other tubes.

It should be noted that heater 4 is the top tube of a four tube array. Heater 3 is directly below heater 4. Heater 2 is directly below heater 3; and heater 1 is directly below heater 2.

RESULTS AND DISCUSSION

Figure 2 shows typical data for single tube tests before and after multitube tests to give the reader a feel for the reproductibility of the nucleate boiling tests conducted during this investigation.

It was observed that the nucleate boiling curves for the mixtures lie below those of either pure component. Cichelli

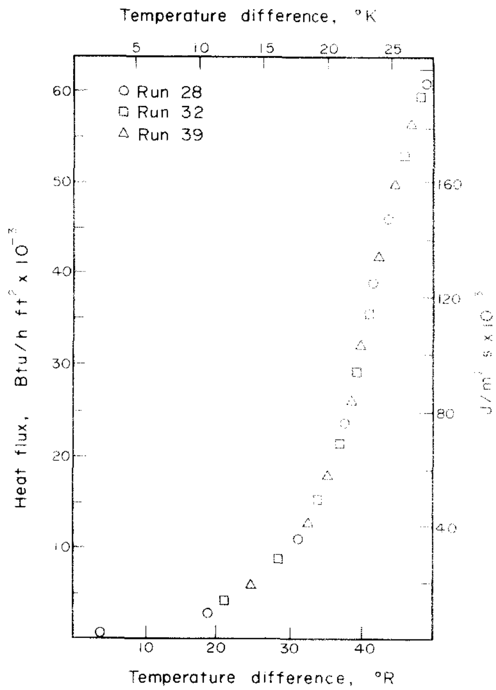

FIG. 2. Single tube nucleate boiling tests with 50% *n*-hexane–50% *n*-pentane.

and Bonilla [10] found that binary mixtures boiled with a lower heat-transfer coefficient than that for either pure component when boiled alone. Their results have been confirmed by many investigators. It is postulated that the lower heat-transfer rates are due to diffusional limitations of the less volatile component at the liquid boundary layer. Figure 3 illustrates the effect of mixture composition on the heat-transfer coefficient. Data are presented for heater 4 only, but the same trends are shown by data from the other heaters. Figure 3 clearly illustrates that boiling mixtures have heat-transfer rates that are lower than that of either pure component at a given temperature difference. It is also interesting to note that at constant temperature differences

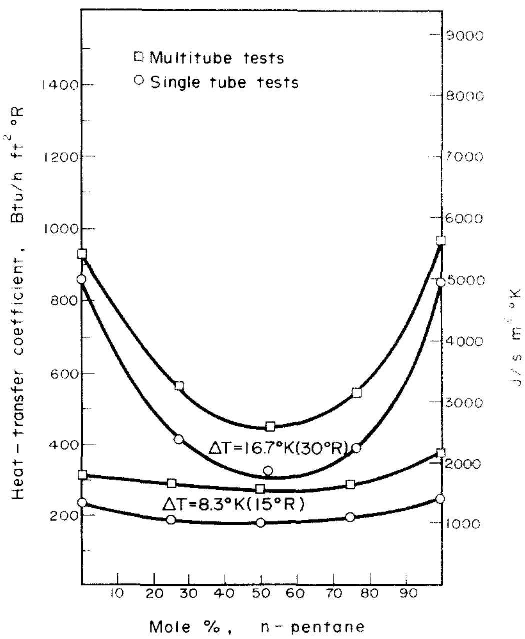

FIG. 3. The effect of mixture composition on the heat-transfer coefficient of heater 4 for single and multitube tests.

the heat-transfer coefficient goes through a minimum point. This minimum should occur at the minimum bubble production rate according to Grigor'er, Sarkisyan and Usmanov [24].

In the discussion of single tube results, it was noted that the temperature difference between the heater surface and the saturated liquid was greater (for a given heat flux) when boiling a mixture than that for either pure component when boiled alone. Figure 3 also shows the effect of mixture composition on the heat-transfer coefficient of heater 4 for single tube and multitube tests. The data are presented for constant ΔT's of 16.67°K (30°F) and 8.33°K (15°F). Similar trends are shown for all values of temperature differences. It is interesting to note that the difference in the heat-transfer coefficient between single tube and multitube tests increased when boiling a mixture over that of either pure component. This enhancement can be as high as 50% depending upon the concentration and temperature difference.

When boiling with multitubes, the heat-transfer coefficients for the upper tubes in the bundle were larger than the heat-transfer coefficients for the same heaters in single tube tests (see Fig. 3). The extent of this increase depended upon the number of tubes in the bundle and the fluid being boiled. This increase in heat-transfer coefficient, which is synonymous with a lower temperature difference, finds support in the literature. Data on small bundles with a few rows of tubes [2, 3, 5, 6, 20] indicate that additional circulation and turbulence caused by bubbles rising from lower tubes can significantly increase the average heat-transfer coefficient, so that instead of a penalty, a multitube enhancement correction must be applied for correlation. Katz and co-workers [2, 3] found that at high temperature differences where the agitation was large the increase in heat-transfer coefficients was negligible, but at low to moderate temperature differences there seemed to be an optimum agitation. (Below this optimum agitation the heat-transfer coefficients were increased, but above the optimum the effect was negligible.) Katz's results have been confirmed in this investigation.

In all bundles studied, only the upper tubes nucleate boiling curves were altered, primarily tubes 3 and 4. It was noted that the deviations between curves for heaters 3 and 4 are approximately equal, which leads one to believe that additional top tubes may exhibit the same result.

CONCLUSIONS

The effect that tubes at the bottom of a vertical tube array have on the tubes at the top of the array is similar whether a pure component or a mixture is being boiled, that is, the heat-transfer coefficient of the top tube is increased because of the agitation of the fluid by vapor flowing up from the bottom tubes. This increase is restricted to low nucleate boiling fluxes and is not found at fluxes approaching the critical heat flux. There is little or no change in the boiling behaviour of a bottom tube in a vertical array due to tubes boiling above it.

When mixtures are boiled the enhancement of the heat-transfer coefficient of a top tube due to tubes below it is greater than the enhancement when either pure component is boiled.

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