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OBSERVATIONS IN TRANSITION BOILING OF SUBCOOLED WATER UNDER FORCED CONVECTIVE CONDITIONS

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Abstract — This paper summarizes the results of an extensive forced convective transition boiling study. Boiling curves were obtained for water at near atmospheric pressure using a high thermal inertia test section. The following effects on the transition boiling section of the boiling curve were studied in detail (a) flow conditions (mass flux, subcooling), (b) method of analysis (1-D, 2-D conduction), (c) method of operation (transient, steady-state), and (d) experimental equipment (test section arrangement, test section construction, heated surface properties).

NOMENCLATURE

c_p, specific heat;
CHF, critical heat flux;
G, mass flux;
h, heat-transfer coefficient;
k, thermal conductivity;
O.D., outside diameter;
T, temperature;
t, time;
T.C., thermocouple.

Greek symbols

ΔT, temperature difference;
δ, wall thickness;
ρ, density.

Subscripts

min, minimum;
sub, subcooled.

1. INTRODUCTION

SAFETY analysis of water-cooled nuclear reactors requires accurate prediction of the rate of heat removal from fuel elements during a loss-of-coolant accident. The predicted temperature history of the fuel elements will depend strongly on the selection of correlations for the post-critical heat flux (post-CHF) region. The least studied post-CHF heat transfer mode is the transition boiling mode: an intermediate heat transfer mode where the surface temperature is too high to maintain stable nucleate boiling but too low to maintain stable film boiling.

A recent review by Groeneveld and Fung [1] showed that existing correlations for transition boiling do not agree with each other and their data base is questionable. A lack of understanding of the physical mechanisms governing forced convective transition boiling does not yet permit the development of a mechanistic heat transfer model.

The transition boiling heat transfer mode is unique among heat transfer modes in that surface heat flux decreases with an increase in surface temperature. Such a heat transfer mode is unstable in a heat flux controlled system and requires usually a cumbersome temperature controlled system or a transient technique [1]. Because of the complexity of the required experimental equipment, few researchers have attempted to obtain transition boiling under forced convective conditions.

During the past three years, the University of Ottawa, in cooperation with Chalk River Nuclear Laboratories, has developed a relatively simple technique for obtaining transition boiling data. The purpose of this paper is to summarize their results. In particular, the following effects on the transition and film boiling section of the boiling curve will be discussed: (a) flow conditions, (b) method of analysis, (c) method of operation (transient, steady-state), and (d) experimental equipment.

2. EXPERIMENTS

The experimental apparatus consists primarily of a temperature controlled hot water storage tank, a flow meter, a pump and the test section assembly as shown in Fig. 1. Different types of test sections were employed and are shown in Fig. 2. The test sections basically consist of a high thermal inertia cylindrical block with

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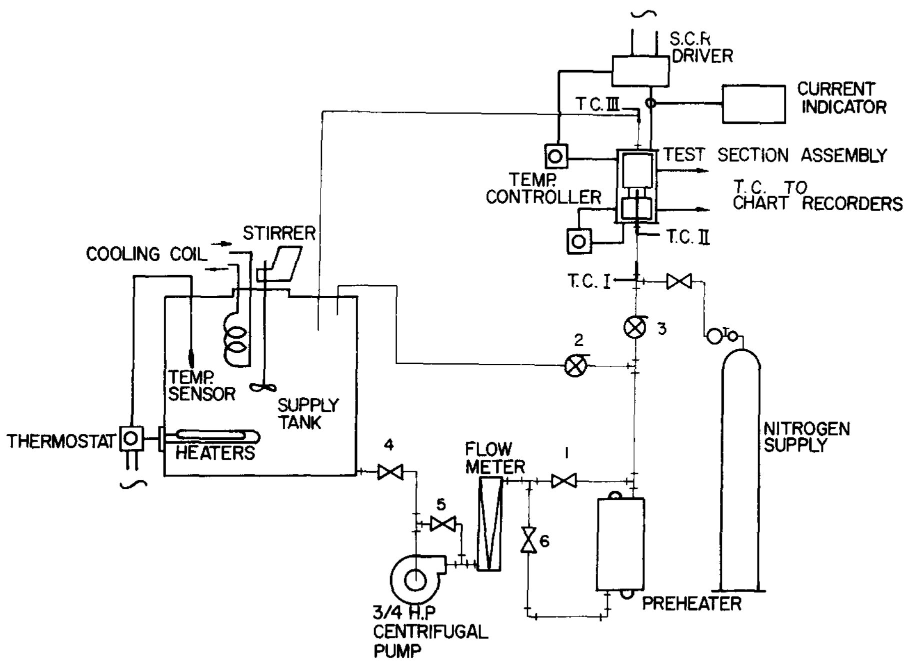

FIG. 1. Schematic diagram for the experimental loop.

or without a flow tube located along the centre line. The block is heated by cartridge heaters located in a concentric ring at some distance from the centre of the flow channel. A detailed description of the test sections will be presented in Section 6.1. Temperature measurements were taken at different axial planes within the test section using metal sheathed thermocouples located radially approximately 1.5 mm from the heated surface.

Two modes of operation are used in this study, a transient and a steady-state mode. In the transient mode, the empty test section is heated to a temperature well above the Leidenfrost point before introducing the flow. Subsequently the heaters are switched off, the coolant is injected into the test section and the temperature history (cooling curve) is recorded. The

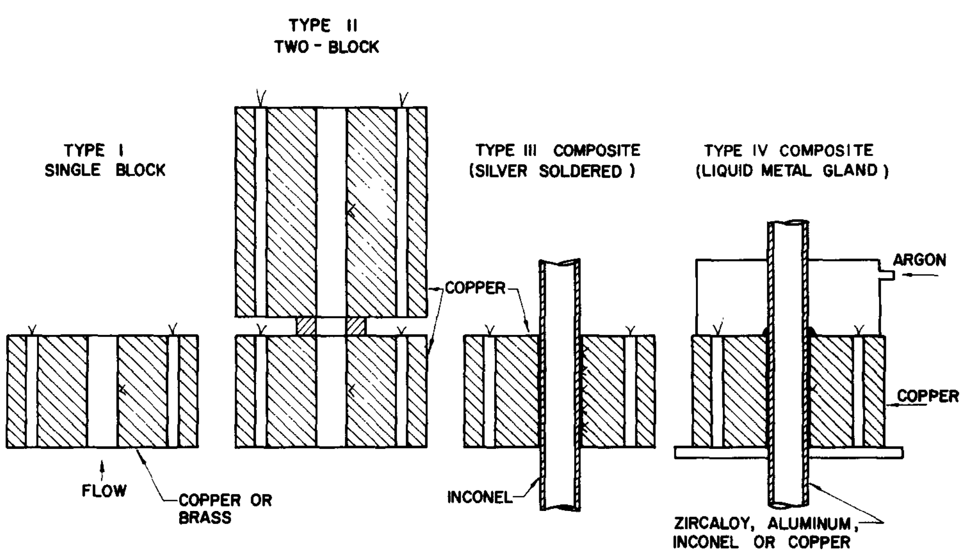

FIG. 2. Test section designs for transition boiling study. Note: for type I and II test sections, the distance of T.C. from inner wall varies from 0.76 to 1.52 mm. For type III and IV test sections, all T.C. are located on the outer wall of tubing.

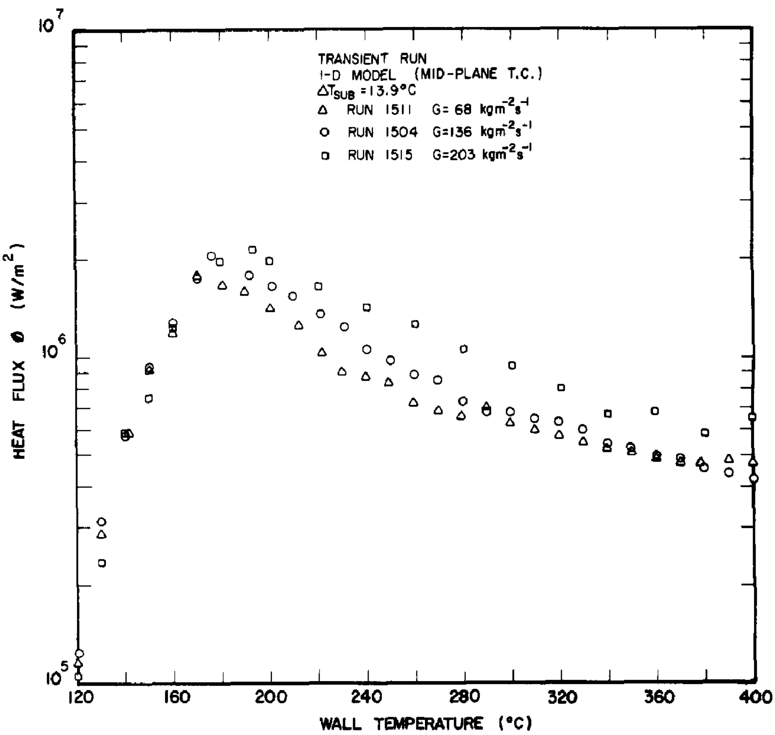

FIG. 3. Effect of mass flux on boiling curve (type III test section).

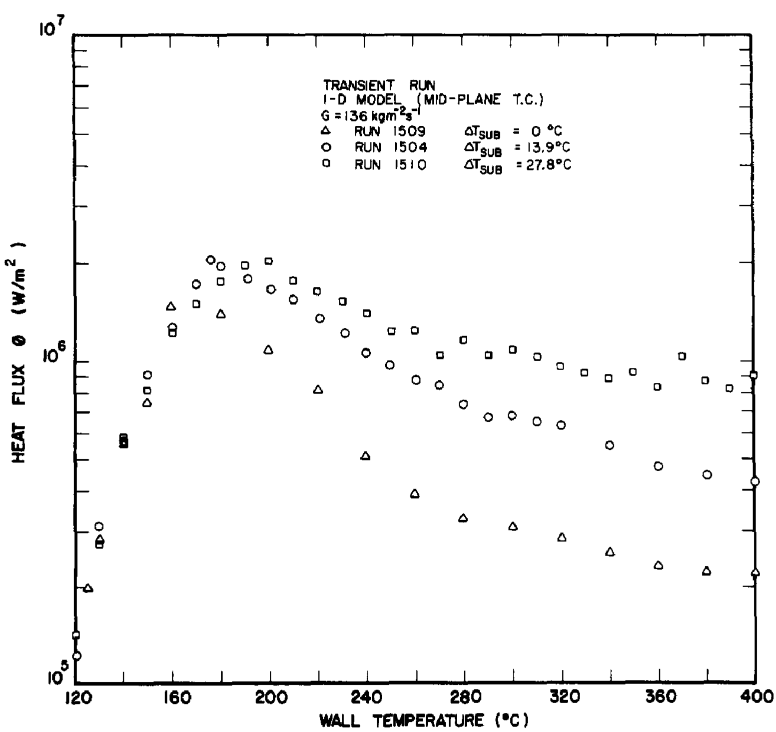

FIG. 4. Effect of inlet subcooling on boiling curve (type III test section).

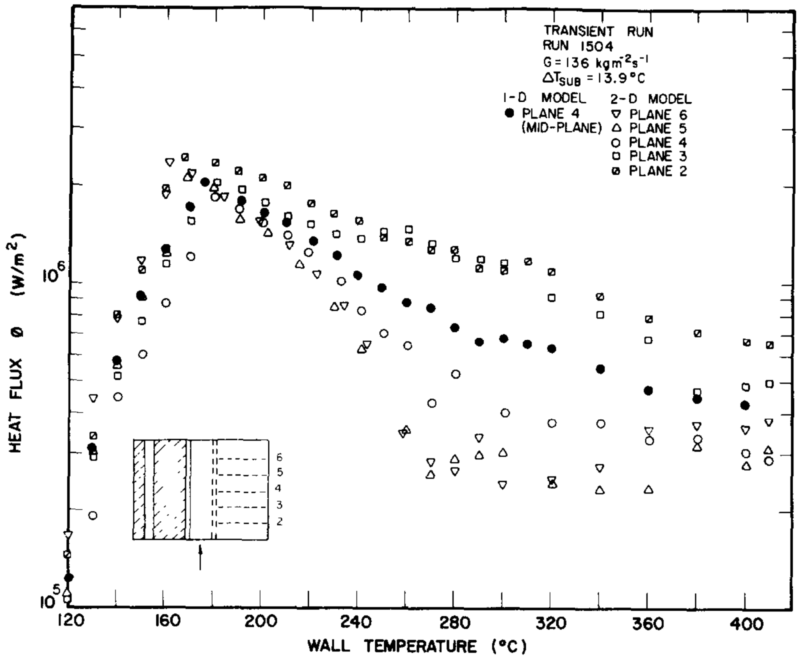

FIG. 5. Boiling curves for type III test section. Comparison of 1-D model with 2-D model for five thermocouple planes.

boiling curve can then be derived from the test section temperature history using the concept of rate of change of heat content within the test section [2].

In the steady-state mode, the empty test section is again heated to a temperature above the Leidenfrost point. The temperature is maintained at that level by a temperature controller while the coolant is introduced at a constant flowrate. By repeating the experiment for lower temperatures and measuring the corresponding power, a steady-state boiling curve can be constructed.

Further details of the experimental apparatus and procedure can be found in [3].

3. EFFECT OF FLOW CONDITIONS

3.1. *Mass flux*

The effect of mass flux on the boiling curve was investigated within the range of 68–203 kg m^{-2} s^{-1} for each of the test sections of Fig. 2. An example of the results is shown in Fig. 3 for the type III test section (Inconel surface). The observed trend was identical for all other test sections: an increase in mass flux moves the boiling curve to a higher level except for the nucleate boiling regime. This is as expected as both the CHF and the film boiling heat flux increase with an increase in mass flux. Since transition boiling is an intermediate heat transfer mode, the observed increase in transition boiling heat flux may be attributed to: (a) more efficient removal of bubbles because of the higher flow, (b) improved convective heat transfer during film boiling, and (c) improved wall–liquid interaction due to a higher turbulence level of the flow.

3.2. *Inlet subcooling*

The effect of inlet subcooling was investigated in each of the test sections by varying the inlet flow subcooling from 0°C to 28°C. Figure 4 shows that for the type III test section, the transition boiling heat flux increases with an increase in subcooling. The same trend was observed with the other test sections.

For a given inlet subcooling, the effect of local enthalpy was also observed by generating local boiling curves at different planes along the flow channel using a two-dimensional model as shown in Fig. 5. In general, it was found that the local boiling heat flux decreases with increased heated length and thus enthalpy.

Unlike mass flux, the inlet subcooling seems to have a significant effect on the flow stability during transition boiling. It was observed that at subcoolings greater than 28°C severe fluctuations in flow and surface temperature were accompanied by boiling noise. The flow fluctuations could be observed in a transparent flow channel installed for this purpose just upstream of the test section.

4. METHOD OF ANALYSIS

4.1. *One-dimensional conduction model (1-D model)*

The following methods were used when applying the 1-D model:

(1) Fourier equation method — the temperature profile across the test section is obtained through a solution of the Fourier conduction equation, assuming

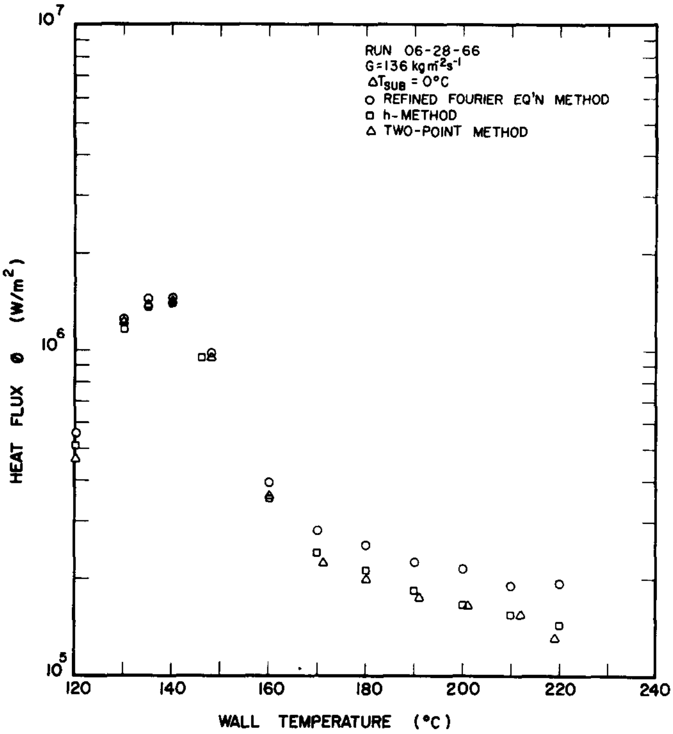

FIG. 6. Boiling curve for type I test section (copper block) using various analytical methods (1-dimensional conduction model).

that the inner wall temperature equals the measured temperature at the location of data thermocouple (usually located within 1.5 mm of the inner surface).

(2) Refined Fourier equation method [2] — this is similar to (1) except that inner wall temperature is calculated by extrapolating the temperature distribution between the location of the data thermocouple and the outer wall, assuming perfect insulation at the outer surface of the test section.

(3) h-method [2] — the heat loss through the outer wall is found from heat loss calibration runs and is included as a heat transfer coefficient h at the outer surface of the test section.

(4) The two-point method [2] — the temperature recording at the outer surface is used as a boundary condition instead of h.

Method (1) is the least accurate method and should only be used for thin-walled test sections. Figure 6 presents one of the typical results using methods (2), (3) and (4). Since method (2) assumes perfect insulation, it slightly overestimates the heat flux compared to the other two methods. Both the h-method and the two-point method yield close results except the former produces somewhat higher values in nucleate boiling and lower values in transition boiling. The h-method is recommended for 1-D analysis in transition boiling, since it is more accurate than the refined Fourier equation method, and it is simpler than the two-point method because only one data thermocouple recording is required.

4.2. *Two-dimensional conduction model (2-D model)*

The boiling curves based on 1-D model were generated without considering axial conduction, since the axial conduction was found to be very small in the type I copper test section [3]. This test section was not suitable for studying the effect of heated surface thermal properties on the boiling curve; to do this, type III test sections were constructed of thin-walled Inconel tubing silver-soldered to a thick copper cylindrical block (Fig. 2). This arrangement was chosen to maintain the long cooldown period during transition boiling, thus permitting frequent and accurate temperature measurements. With the type III test section larger axial temperature gradients were observed especially in the transition boiling regime. Thus a 2-D model [4, 5] was necessary to properly account for the effect of axial temperature gradient.

Basically, the 2-D model subdivides the test section in a number of rings. It allows one to calculate heat flux from a given ring (inside the test section) by computing the rate of change in heat content of that ring, plus axial conduction from neighboring sections at the same time, t. For simplicity, the test section has been assumed to be perfectly insulated in the analysis. The details of 2-D model were described in [4]. A typical set of boiling curves for a mass flux of 136 kg m^{-2} s^{-1} and an inlet subcooling of 13.9°C was constructed

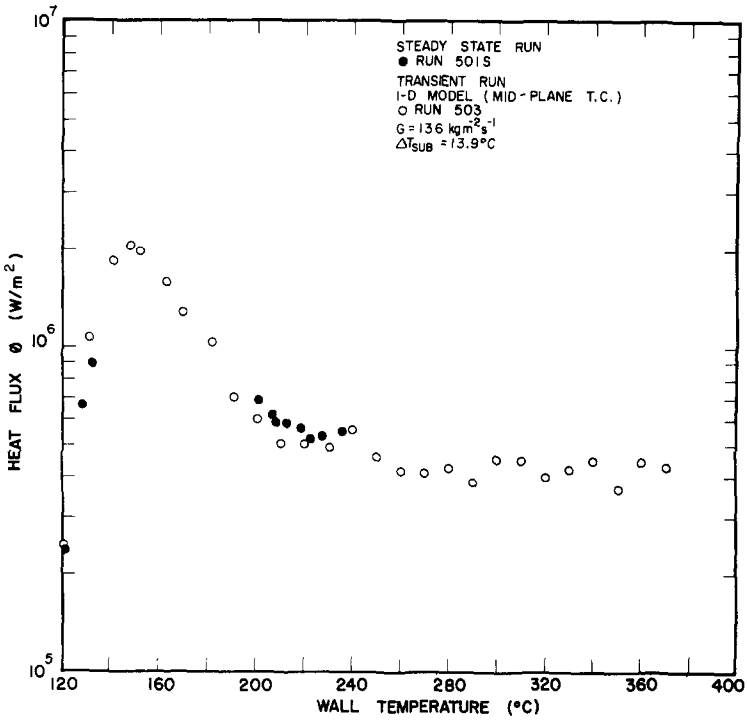

FIG. 7. Comparison of boiling curves obtained from steady-state and transient runs (type I test section, copper block).

using the 2-D model as shown in Fig. 5.

Examination of the boiling curves shows that the plane 6 boiling curve in the film boiling regime is always higher than plane 5 boiling curve. This is thought to be due to neglecting axial heat losses. Also, the plane 2 boiling curve in film and transition boiling regimes, in general, is found to be noticeably higher than other boiling curves regardless of the inlet subcooling and mass flux. This is attributed to: (a) the lower bulk fluid temperature, (b) entrance effects, and (c) neglecting axial heat losses. In the transition boiling regime, all the five boiling curves show a correct trend against the bulk fluid temperature. The radial heat loss to the surroundings should be negligibly small in comparison with a rather high level of radial conduction taking place inside the test section.

In some of the earlier tests, the type I copper test section was equipped with thermocouples at three axial locations. Boiling curves were derived for each of the three data thermocouples using a 1-D and 2-D models [4, 5]. The results showed that: (a) the mid-plane boiling curve based on either 2-D or 1-D model represents the average boiling curve for the entire test section, (b) the two mid-plane boiling curves based on 2-D and 1-D models, respectively, are approximately the same, and (c) the net effect of axial conduction on the surface heat flux at the mid-section, based on 2-D model is very small and for practical purposes can be neglected.

In the Inconel–copper composite test section, the mid-plane boiling curve of the 1-D model (taken from Fig. 4), is falling somewhere between the plane 3 and plane 4 boiling curves for the corresponding 2-D model (Fig. 5). This suggests that the zero axial conduction section has been shifted downstream from the mid-section. It also suggests that: boiling curves based on a 2-D model at the mid-plane represent the average heat flux over the entire test section, and boiling curves measured at the mid-plane based on a 2-D model are close to those based on a 1-D model. For this reason, parametric effects on boiling curves discussed in this paper are based on boiling curves measured at the mid-plane using a 1-D model.

5. EFFECT OF METHOD OF OPERATION

Measurements of boiling curves were made using two different modes of operation: the transient and the steady-state mode. Figure 7 shows a comparison between the transient boiling curve and the steady-state data obtained for the type I copper test section using a temperature controller [6]. Good agreement is observed between the steady-state data and the transient boiling curve. Due to insufficient heater power in the test section, the upper portion of the steady-state boiling curve could not be obtained.

Subsequent tests with a type III test section equipped with a larger number of heaters permitted the construction of a complete steady-state boiling curve as shown in Fig. 8 [7]. The transient boiling curve is also plotted in this figure for comparison. Again, the

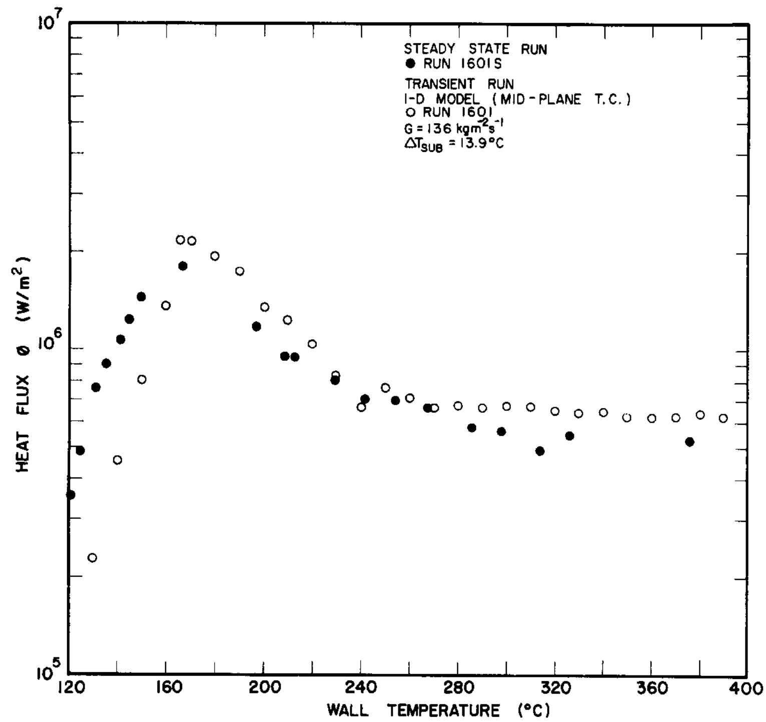

FIG. 8. Comparison of boiling curves obtained from steady-state and transient runs (type III test section).

agreement between these two curves is reasonable with the exception of the nucleate boiling regime. The agreement of heat flux values in transition and film boiling regimes was expected, as the high thermal capacity of the test section slowed down the quenching process to make the system act in a pseudo steady-state manner.

6. EFFECT OF EXPERIMENTAL EQUIPMENT

6.1. *General*

The simplest version of test section used in these experiments is a type I test section consisting of a short cylindrical copper or brass block, heated by cartridge heaters. The type II test section employed a combination of two copper blocks. In one series of experiments the short block was utilized as the test section while the long block remained unheated. In other series, the long block was used as the test section with the short block as an entrance heater.

The type III test section was designed to study the effect of heated surface thermal properties on transition boiling, by brazing an Inconel tube into a copper block using silver solder. Because of problems in brazing a Zircaloy tube or an aluminum tube to copper a type IV test section was designed in which Wood's metal (a liquid metal) was used instead to provide good thermal contact between the two materials. Schematic drawings of these test sections are shown in Fig. 2. In general, boiling curves generated with the test sections shown in Fig. 2 are sensitive to the thermal resistance between the test section and the thermocouples, the exact location of the thermocouple junction, the accuracy of each data thermocouple measurement, and the thermal resistance between the copper block and the flow tube.

6.2. *Effect of upstream history*

Measurements on the type II test section (two copper blocks with the short block as an entrance heater) produced lower post-CHF heat flux values than measurements on the type I test section (single copper block) [6]. Particularly, the heat flux with the type II test section during the initial stage of a transient test (film boiling regime) is much lower as shown in Fig. 9. This difference cannot be explained by the differences in local subcooling; it is thought that a more important reason is the presence of a vapour film at the entrance to the test section in the type II test section. Here, the vapor film is established in the entrance heater and can be considerably thicker than in the type I test section where the vapor film becomes established near the entrance of the test section. The thicker vapor film presents a greater resistance to heat transfer thus lowering the film boiling heat flux for the same equilibrium conditions compared with the type I test section results.

6.3. *Effect of surface properties of heated surfaces*

During the course of this transition boiling study, five different heated surface materials were tested using types I, III and IV test sections. In the type III test

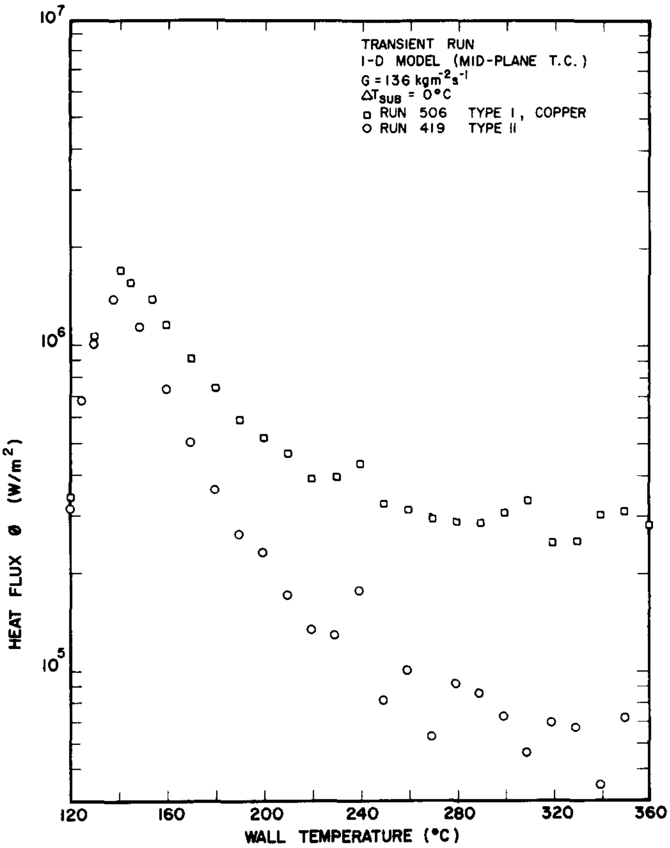

FIG. 9. Comparison of boiling curves of type I and type II test sections.

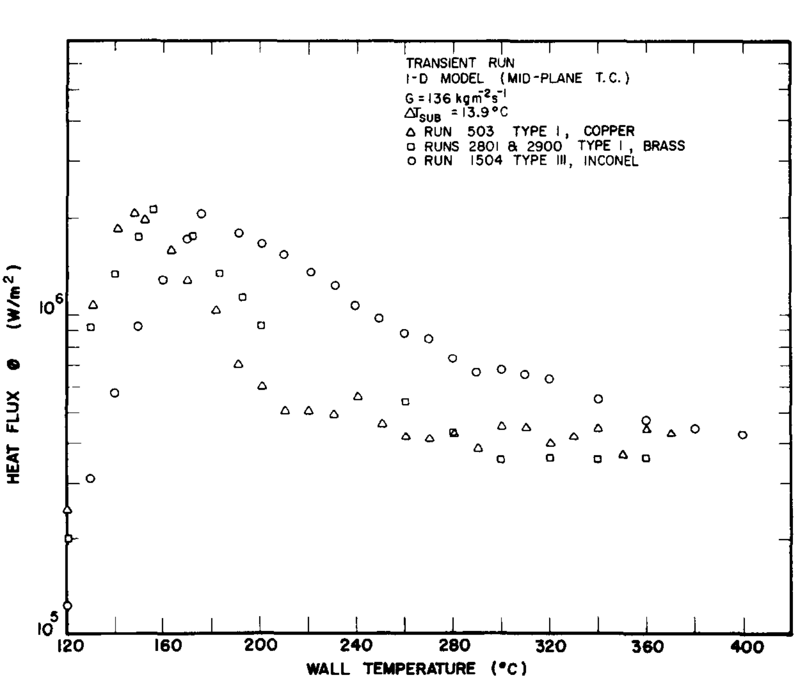

FIG. 10. Comparison of boiling curves obtained from type I and type III test sections: effect of heated surface properties.

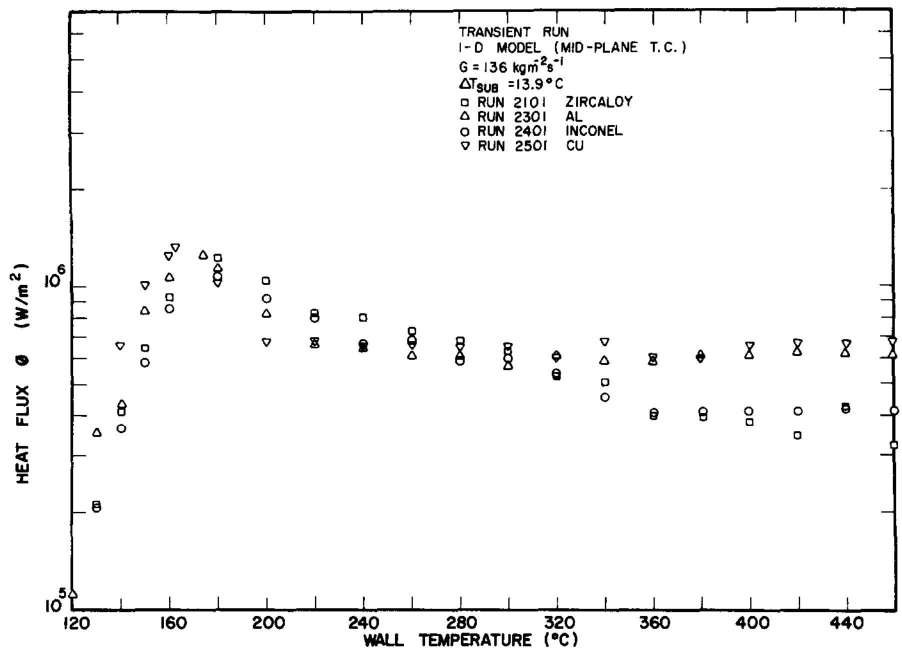

FIG. 11. Effect of flow tube material on boiling curve (type IV test section).

section, a thin silver solder layer (0.13 mm) between the copper block and the tubing material was designed to provide a low thermal resistance path for the heat flow from the copper block. The contact resistance between the tube and the copper block is expected to have some effect on resultant boiling curves. Because of good thermal properties and wetting characteristics of the silver solder, this effect was found to be very small.

Figure 10 presents the effects of k (or $k\rho c_p$) on boiling curves obtained in the type I and type III test sections using copper, brass and Inconel heated surfaces. In general, the values of CHF and minimum heat flux are about the same for all three heated surfaces. However, the rewetting occurs at higher wall superheat for heated surfaces having a lower k (or $k\rho c_p$). This is in agreement with experiments carried out elsewhere [8, 9].

Because of problems in brazing Zircaloy and aluminum tubes to copper, a liquid metal gland (Wood's metal) was used to bring the two metals thermally into contact (Fig. 2, type IV test section). In addition, copper and Inconel tubes were also used in the type IV test section. A comparison of thermocouple signals of the type III and IV test sections suggested a larger than expected contact resistance in the liquid metal gland, it is suspected that, due to the poor wetting characteristics of Wood's metal, air bubbles might have remained in contact with the copper block or flow tube outside surface.

A comparison of the boiling curves obtained for the four different flow tube materials used in the type IV test section is shown in Fig. 11 for standard test conditions: $G = 136\,\text{kg}\,\text{m}^{-2}\,\text{s}^{-1}, \Delta T_{sub} = 13.9°\text{C}$. The results show that the Inconel and Zircaloy heated surfaces produce an almost identical boiling curve.

Table 1. Type IV test section flow tube dimensions

Run series	Tubing material	Tubing dimensions
2100	Zircaloy	O.D. = 1.31 cm, $\delta = 0.0559$ cm
2300	Aluminum	O.D. = 1.40 cm, $\delta = 0.0635$ cm
2400	Inconel	O.D. = 1.27 cm, $\delta = 0.038$ cm
2500	Copper	O.D. = 1.27 cm, $\delta = 0.038$ cm

Table 2. Thermal properties of heated surfaces and solders at 20°C

Heated surface	k (W m^{-1} °C^{-1})	ρ (kg m^{-3})	c_p (J kg^{-1} °C^{-1})
Copper	379	8938	385
Inconel	17	8169	435
Zircaloy	15	6549	316
Aluminum	229	2707	896
Brass (70% Cu, 30% Zn)	144	8522	385
Solder			
Silver solder	50	8938*	385*
Wood's metal	25†	9134	145†

*Assuming the property of copper.
†Approximate value.

The copper and aluminum heated surfaces, however, produce a higher heat transfer coefficient in the film boiling region and also the transition boiling curve has a steeper negative slope for copper and aluminum as compared to Inconel and Zircaloy. The ΔT_{CHF} and ΔT_{min} are also smaller for copper and aluminum.

Caution should be exercised in using these results as: (a) the thermal resistance of the liquid metal gland may be different for each material and may not be properly modelled, (b) the wall thickness δ was not kept constant (see Table 1), (c) axial conduction heat losses were different because of large differences in thermal conductivity (see Table 2), and (d) the tubes were tested as received (except for possible reduction in outside diameters) and the finish of the inside bore was not identical. However, qualitatively the results are believed to be correct as they confirm the trends observed by the type I and III test sections (Fig. 10).

7. CONCLUSIONS AND FINAL REMARKS

(1) Mass flux and inlet subcooling are important parameters in transition boiling. Heat transfer increases with increasing mass flux and subcooling within the range of the flow parameters investigated; mass flux range 68–203 kg m^{-2} s^{-1} and subcooling range 0–28°C.

(2) Boiling curves generated from mid-plane thermocouples using the 1-D model represent the average heat flux for the test section and agreee with the steady-state data.

(3) The agreement between the steady-state and transient boiling curves suggests that the transient technique using a high thermal inertia test section is a simple and effective method of obtaining transition boiling data.

(4) Upstream history can have a strong effect on the boiling curve. The presence of a vapour blanket just upstream of a transition boiling section tends to reduce the transition boiling heat flux considerably.

(5) The heated surface properties have a strong effect on the boiling curve:

(i) an increase in k (or $k\rho c_p$) decreases the transition boiling heat transfer coefficient,

(ii) the effect of heated surface material on CHF or the minimum heat flux is small,

(iii) an increase in k (or $k\rho c_p$) decreases the wall superheat at CHF and at rewetting (this is in agreement with the experiments carried out elsewhere [8, 9]).

(6) A transition boiling correlation may be considered reliable if it reflects the parametric effects discussed in this study. Present transition boiling correlations do not reflect such effects. In addition, most correlations over predict the heat flux values of present data [6].

(7) Similar to transition boiling, the existing nucleate boiling correlations over predict the heat values of present data [6].

(8) Comparison of the measured values of CHF with present correlations shows that, the Macbeth's correlation [10] over-predicts the present data by a factor of 1, whereas both the Menegus' [11] and Zenkevich's [12] correlations under predict by a factor of 1.

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OBSERVATION DU SOUS-REFROIDISSEMENT DE L'EAU DANS L'EBULLITION DE TRANSITION AVEC CONVECTION FORCEE

Résumé—On résume les résultats d'une étude de l'ébullition de transition avec convection forcée. Des courbes d'ébullition ont été obtenues pour l'eau à une pression proche de l'atmosphère en utilisant une section d'essai à forte inertie thermique. On a étudié en détail les effets suivants sur la zone d'ébullition de transition de la courbe d'ébullition: (a) conditions d'écoulement (flux massique, sous-refroidissement), (b) méthode d'analyse (conduction 1-D et 2-D), (c) méthode opératoire (transitoire, permanente), (d) montage expérimental (disposition et construction de la section d'essai, propriétés de la surface chauffée).

BEOBACHTUNGEN BEIM ÜBERGANGSSIEDEN VON UNTERKÜHLTEM WASSER BEI ERZWUNGENER KONVEKTION

Zusammenfassung—Der Aufsatz faßt die Ergebnisse einer ausgedehnten Untersuchung des Übergangssiedens bei erzwungener Konvektion zusammen. Mittels einer Teststrecke mit hoher thermischer Trägheit wurden Siedekurven für Wasser im Bereich des Umgebungsdruckes ermittelt. Folgende Einflüsse auf den Übergangsbereich der Siedelinie wurden ausführlich untersucht: (a) Strömungsbedingungen (Massenstrom, Unterkühlung); (b) Auswertungsverfahren (ein- und zweidimensionale Leitung); (c) Versuchsverfahren (instationär, stationär); (d) experimentelle Einrichtungen (Anordnung der Teststrecke, Aufbau der Teststrecke, Heizflächeneigenschaften).

НЕСТАЦИОНАРНОЕ КИПЕНИЕ НЕДОГРЕТОЙ ВОДЫ В УСЛОВИЯХ ВЫНУЖДЕННОЙ КОНВЕКЦИИ

Аннотация — Обобщаются результаты исследования нестационарного кипения при вынужденной конвекции. Кривые кипения получены для воды при давлении, близком к атмосферному, на участке с большой тепловой инерцией. Подробно исследовано влияние на процесс нестационарного кипения (а) режима течения (массовый поток, недогрев), (б) метода анализа, (в) режима работы (нестационарный, стационарный) и (г) параметров экспериментальной установки (конструкция экспериментального участка, характеристики нагретой поверхности).