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# THE BOILING CRISIS IN SATURATED AND SUBCOOLED POOL BOILING AT REDUCED PRESSURES

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**Abstract**—Values are presented of critical heat fluxes measured during the pool boiling of water at low pressures and under conditions of subcooled and saturated boiling. The fluxes are well correlated by the equation

$$\frac{q_{sub}}{q_{sat}} = 1{\cdot}06 + 1{\cdot}015\frac{\Delta t_{sub}}{p^{0{\cdot}474}}$$

for pressures of 760–100 torr. and liquid subcoolings of up to 60°C. The results confirm that existing correlations adequately predict critical heat fluxes for saturated boiling until the mechanism of boiling changes because of the effect of reduced pressure on the nucleation site activity. No equivalent comparison can be made for subcooled boiling where values have previously been reported for atmospheric pressure only.

## NOMENCLATURE

$A$, empirical constant;
$B$, empirical constant;
$g$, gravitational acceleration, $LT^{-2}$;
$k$, thermal conductivity, $MLT^{-3}\theta^{-1}$;
$K$, empirical constant;
$n$, empirical constant;
$p$, pressure (torr.), $ML^{-1}T^{-2}$;
$\frac{q}{a}$, heat flux, $MT^{-3}$;
$t$, temperature, $\theta$.

Greek symbols
$\lambda$, latent heat, $L^2T^{-2}$;
$\rho$, density, $ML^{-3}$;
$\sigma$, surface tension, $MT^{-2}$;
$\Delta$, finite difference operator.

Subscripts
$l$, liquid;
sat, saturated;
sub, subcooled;
$v$, vapour.

ACADEMIC interest in low pressure pool boiling stems from the marked changes in boiling characteristics which accompany small reductions in the system pressure. On the industrial scale interest in reduced pressure boiling is developing rapidly, particularly in the field of water desalination.

In a study of the acoustics of boiling reported by Ponter and Haigh [1] it was found necessary experimentally to determine values of the critical heat flux for water boiling on a tubular stainless steel heater under reduced pressure conditions. The purpose of the tests was to furnish data which could be used to reduce the possibility of the physical destruction of subsequent heaters by accidental excursion into film boiling. Existing data were found to be insufficient for accurate prediction of the critical heat fluxes.

It is convenient to review the published data

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separately *viz.* saturated boiling conditions and subcooled boiling conditions.

*Saturated boiling.* Cichelli [2] correlated critical heat flux data for boiling organic liquids at elevated pressures in terms of the reduced pressure $p/p_c$ and obtained a relationship approximating to an inverted parabola but having a maximum value of the critical heat flux at one third of the critical pressure $p_c$. Little data on boiling water was available for inclusion in the correlation and interpolation from the curve for water boiling at atmospheric pressure and below is inadvisable. Rohsenow [3] correlated the Cichelli data, together with the results of Addoms [4] and Braunlich [5] by the dimensional equation.

$$\frac{q/a}{\lambda . \rho_v} = 1{\cdot}21 \left[\frac{\rho_l - \rho_v}{\rho_v}\right]^{0{\cdot}6} \text{cm/s.} \tag{1}$$

Zuber [6, 7] developed a quantitative expression for the critical heat flux based on the instability of the vapour/liquid interface in boiling and confirmed the validity of the expression

$$\frac{q/a}{\lambda \rho_v} = K \left[\frac{\sigma g(\rho_l - \rho_v)}{\rho_v^2}\right]^{\frac{1}{4}} \left[\frac{\rho_l}{\rho_l + \rho_v}\right]^{-\frac{1}{2}} \tag{2}$$

using the existing data [2, 4, 8] and recommended a value of $K$ of 0·13.

*Subcooled boiling.* Data presented in references [9 to 16] relating to the critical heat flux in subcooled boiling of water at atmospheric pressure are summarised in Fig. 1. Three types of curve are apparent; linear (1–4), S-shaped (5 and 6) and concave upwards (7 and 8). The experimental procedures and the range of heater geometries used may explain in part the lack of agreement between the data of the various workers. It is also apparent that critical heat fluxes for vertical heaters may be considerably less than for horizontal heaters. Subcooled pool boiling at pressures other than atmospheric has not been studied in any detail.

Zuber [7] has extended the analysis of the boiling crisis to include the effect of the heat transferred to the liquid by convection during

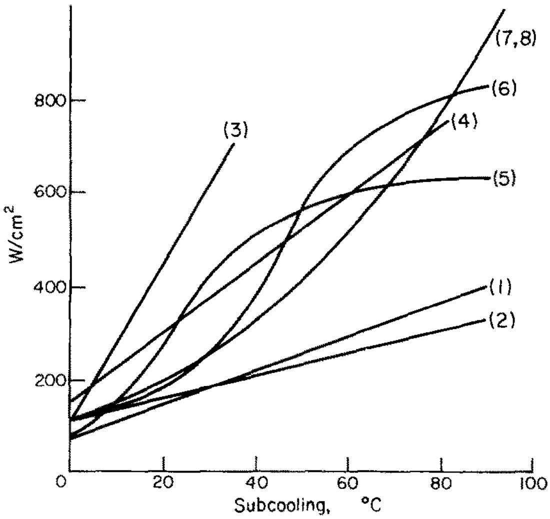


FIG. 1. Reported critical heat fluxes in subcooled pool boiling of water showing heater material and orientation.
(1) Platinum wire *V* Mosciki [9] 0·004 in dia.
(2) Stainless steel tube *V* Mirschak [10].
(3) Platinum wire *H* Nukiyama [11] 0·008 in dia.
(4) Graphite rod *H* Kutateladze [12].
(5) Platinum wire *H* van Stralen [13] 0·008 in dia.
(6) Stainless steel strip *H* Gunther [14] 0·002 in thick.
(7) Stainless steel strip *H* Ellion [15] 0·004 in thick.
(8) Stainless steel tube *H* Ivey [16] 0·064 in max. dia.

subcooled boiling. The critical heat flux in subcooled boiling was expressed relative to the critical heat flux in saturated boiling as predicted by equation (2) so that

$$\frac{q_{\text{sub}}}{q_{\text{sat}}} = 1 + \frac{5{\cdot}84}{\lambda \rho_v}(k.c.\rho_l)^{\frac{1}{2}} \left[\frac{g(\rho_l - \rho_v)}{\sigma}\right]^{\frac{1}{4}} \times \left[\frac{\sigma g(\rho_l - \rho_v)}{\rho_v^2}\right]^{-\frac{1}{8}} (t_{\text{sat}} - t_{\text{sub}}). \tag{3}$$

The experimental data of Kutateladze [12] for the subcooled pool boiling of water at one and two atmospheres pressure and ethyl alcohol at pressures up to 10 atmospheres were shown to be in agreement with values predicted from equation (3).

## EXPERIMENTAL

The apparatus is fully described in reference [17] and comprised a stainless steel cylindrical vessel containing a heater element on which the boiling could be observed through one of three optical ports. Ancillary equipment installed comprised provision for temperature control within the vessel, an overhead condenser to maintain both liquid level and system pressure, an "Edwards" vacuum unit for pressure selection and a liquid recirculation unit. A schematic diagram of the apparatus is given in Fig. 2 and general views are seen in Fig. 3. The lid assembly, seen in Fig. 4, supported the elliptical cooling coils, condenser and thermocouple containment tower.

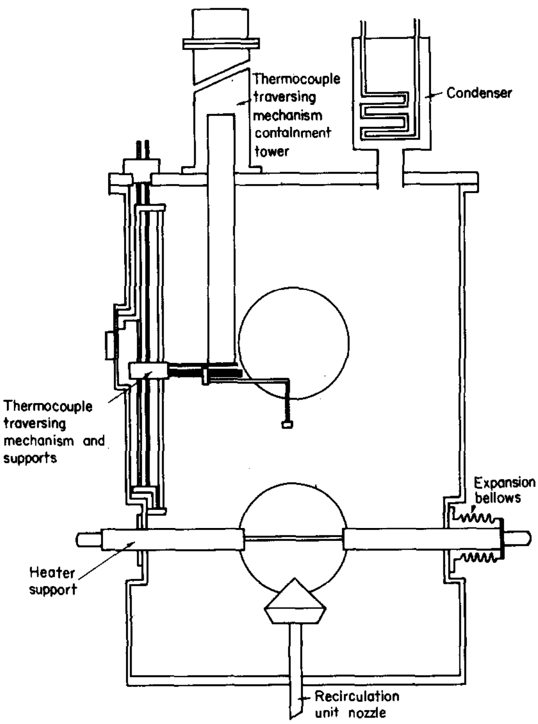


FIG. 2. Schematic representation of low pressure boiling facility. (Not shown: Heat exchangers; Recirculation unit; Vacuum connection; Potential tappings.)
Vessel dimensions: Height (base-lid) 33 in. Inside dia. $21\frac{1}{2}$ in. Heater length 6 in. Height (base-heater) $8\frac{1}{2}$ in.

The heater element was fabricated from a 6 in length of 0·23 in dia. 18 Cr/8 Ni/1 Ti stainless steel tube with a wall thickness of 0·015 in and was designed for easy replacement within the vessel in the event of total failure of the test piece. For this reason also the heater had no provision for determination of surface temperatures although later heaters were so fitted. Provision was made for thermal expansion of the heater as can be seen in Fig. 5.

Electrical power for these tests was supplied from a "Variac" controlled, three phase transformer supplying a maximum of 800 amp at 15 V, 50 Hertz a.c. The supporting members of the heater assembly acted as potential carriers and were insulated from the vessel by PTFE inserts.

A typical experimental run is now described. The vessel was evacuated to about 5 torr. pressure and demineralised water was pumped in to immersè the heater to a depth of 3 in. Pumping the water into a low pressure environment caused vigorous degassing of the water and further degassing took place as the water temperature was raised by steam condensing inside the heat exchangers. The water was boiled at 100°C for about an hour to remove residual dissolved gases.

Power was supplied to the heater at a gradually increasing rate until vigorous nucleate boiling was observed. Steam heating was continued during this period to prevent a reduction in the system pressure caused by vapour condensation. As the critical heat flux was exceeded film boiling was observed, initially on the upper surface of the heater, then spreading round the tube to form a vapour locked patch which became red hot and burnt out unless the power was reduced. Power at a reduced level was resupplied to the heater so that nucleate boiling at a heat flux below the critical value continued. The steam supply to the heat exchangers was shut off and cooling water was supplied to the condenser to prevent a pressure build-up. Care was taken to ensure that the pressure within the vessel corresponded to the vapour pressure of the water at the temperature indicated by a mercury in glass thermometer immersed in the water. The power was again increased up to the point at which film boiling appeared and was then switched off. Two or three further excursions into the film boiling region were necessary to established the precise values of the heating current and potential drop at the point at which the boiling crisis appeared. After determination of the critical heat flux for water boiling at 100°C, the water temperature was lowered by passing cooling water through the heat exchangers and the procedure was repeated for the new saturation conditions. Saturated boiling at pressures as low as 15 torr. was studied.

The procedure for subcooled boiling studies was similar to the saturated boiling studies described above but a 2 ft depth of water was used and the pressure within the vessel was controlled at the desired operating pressure rather than at the saturation pressure corresponding to the liquid temperature. Regulation of the system pressure was achieved with nitrogen, this being less soluble than both oxygen and air.

The limit of all tests, other than those in which the heater was accidentally destroyed, was set by either the minimum attainable water temperature or by the maximum power available from the transformer. At high heat fluxes, cold water was circulated through the heat exchangers to act as a heat sink for the removal of the heat supplied thereby maintaining a steady water temperature.

During the operational life of a heater continued excursion into the film boiling region caused local discolouration of the heater surface. The patches did not appear to affect the performance of the heaters and no tendency for film boiling to commence predominantly from discoloured locations was observed. Similar discolourations have been reported in comparable studies.

## RESULTS

Experimental values of the critical heat flux for the saturated pool boiling of water under reduced pressure conditions are presented in Fig. 6. The data comprise the results of a systematic series of experiments as described above and also the results obtained in a random manner during the commissioning of the appa-

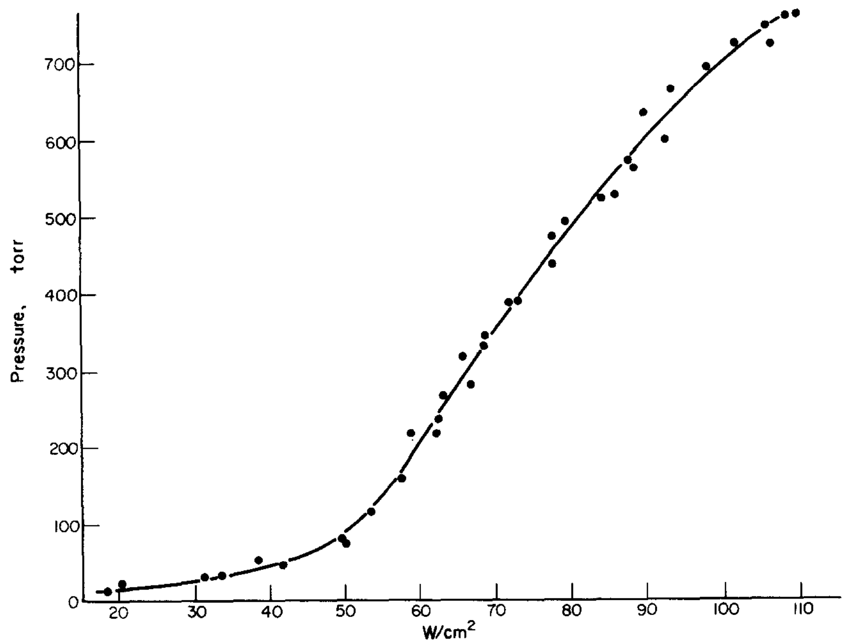


FIG. 6. Experimental values of critical heat flux in saturated low pressure pool boiling of water.

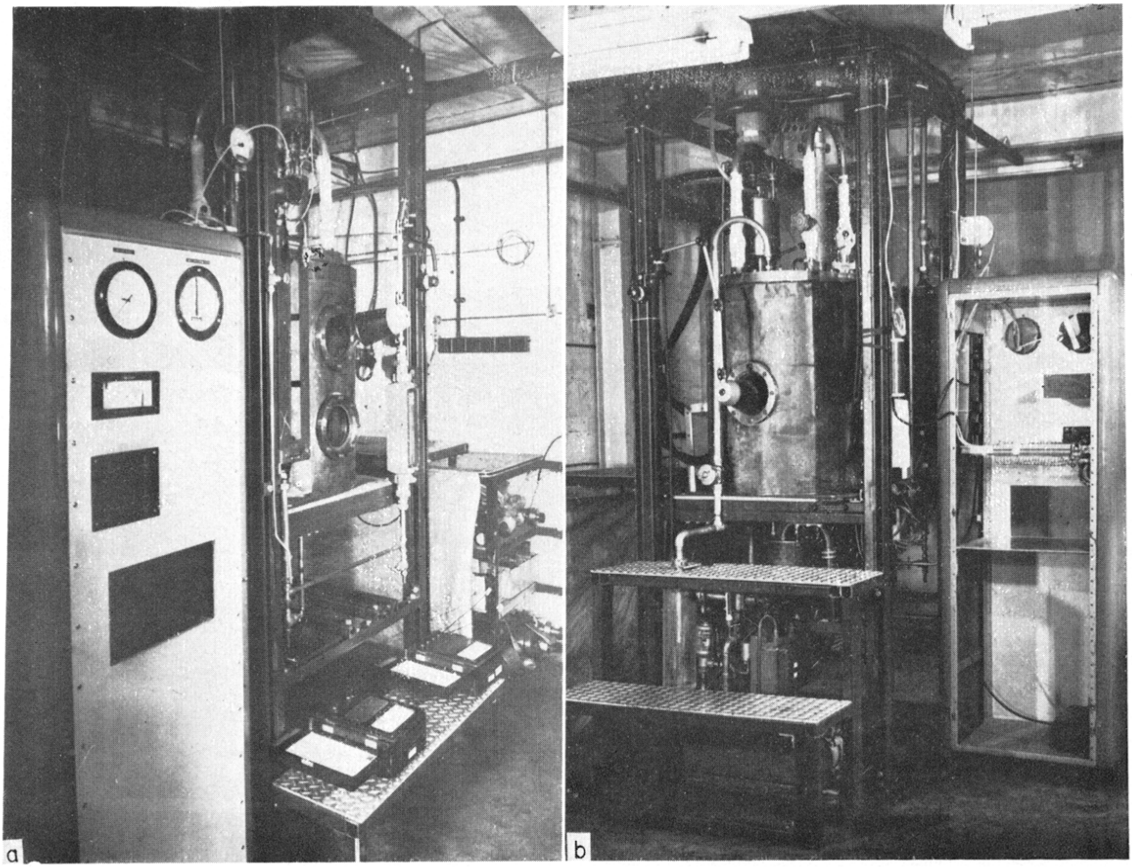

FIG. 3. General views of test facility. (a) Front, (b) Rear.

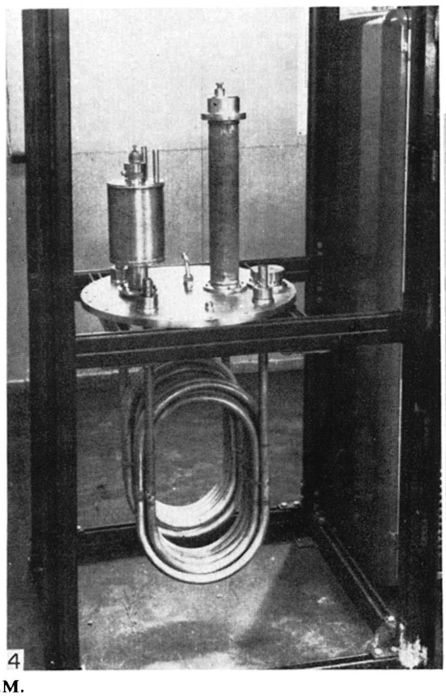

FIG. 4. Boiling vessel lid assembly.

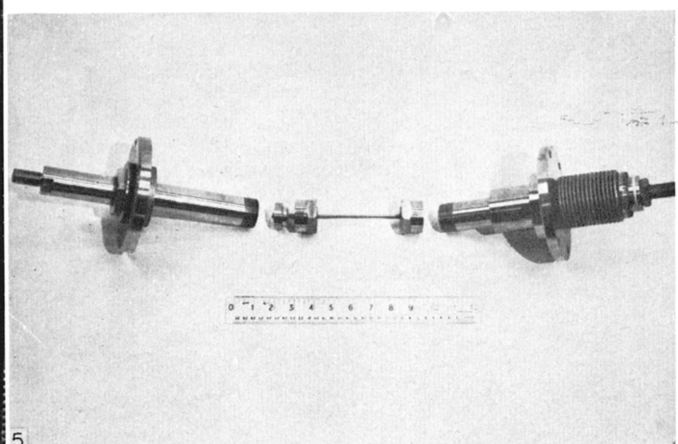

FIG. 5. Heater assembly

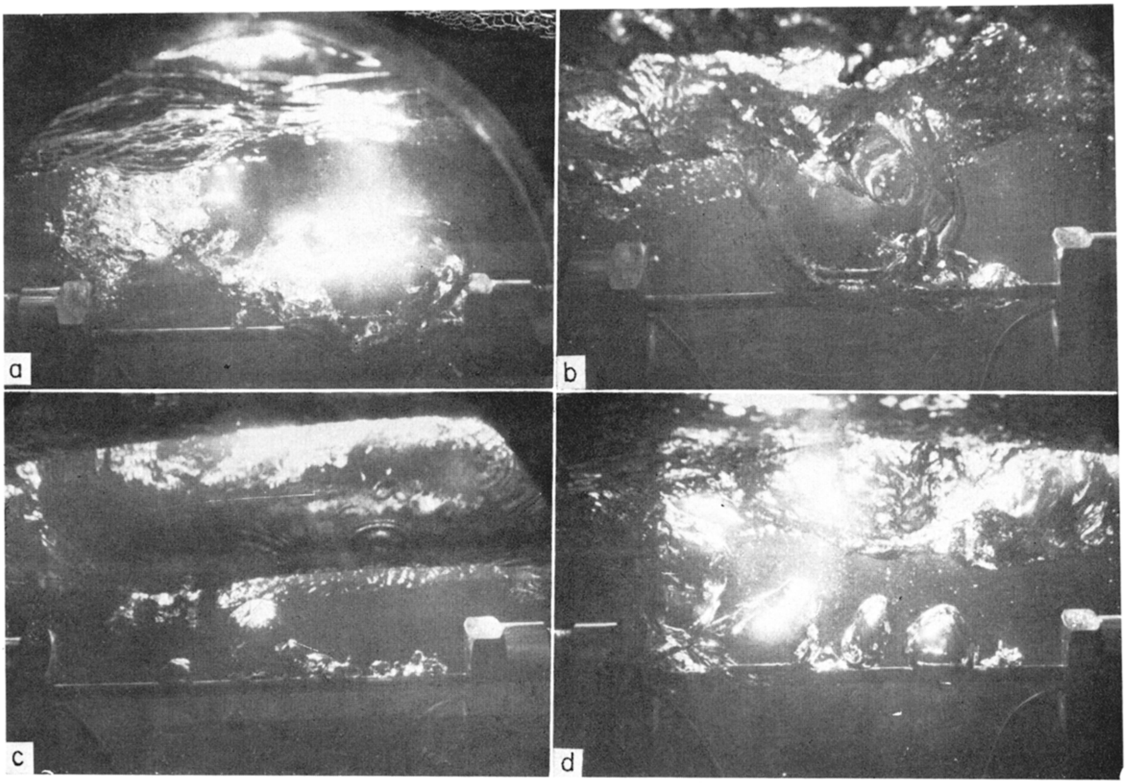


FIG. 7. Saturated boiling at 15 torr. pressure. (a) Heat flux, 15 W/cm$^2$. (b) Heat flux, 15 W/cm$^2$. (c) Heat flux, 15 W/cm$^2$. showing formation of smaller bubbles after departure of a large (6 in.) bubble. (d) Critical heat flux, 25 W/cm$^2$ showing onset of film boiling at three locations.

ratus. During the commissioning runs three heaters were destroyed and the data of Fig. 6 was therefore obtained from four different heaters. All the data may be represented by a single line which has a marked gradient change in the region of 150 torr. pressure. Visual, photographic and stroboscopic examination of the boiling at pressures lower than 150 torr. confirmed that at such pressures the bubble formation process differed from the process observed at atmospheric pressure. This change in bubble formation characteristics can be attributed to the reduction in the number of potentially active nucleation sites with reducing pressure as described in the analyses of Séméria [18] and Hsu [19] and reported by Rallis [20 and 21]. The random nature of the low pressure pool boiling process is demonstrated in the photographs of Fig. 7 which were obtained during boiling at a pressure of 15 torr.

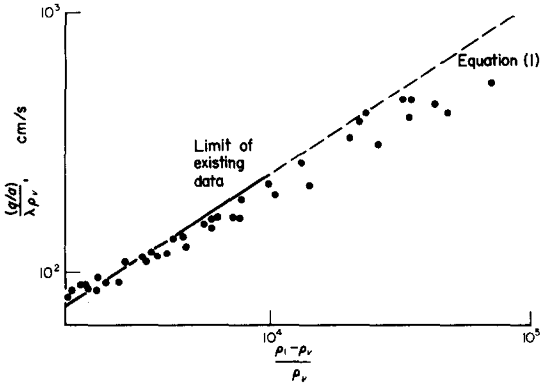


FIG. 8. Comparison of authors' experimental critical heat flux data with the Rohsenow correlation.

In Fig. 8 the data have been correlated using the Rohsenow equation (1), and it is seen that at very low pressures the values of the critical heat flux predicted by the correlation are in excess of the experimentally determined values. This is probably due to the boiling crisis not being the result of bubble coalescence as assumed in the Rohsenow analysis. The data fits the Zuber correlation equation (2), more closely and confirms the value of $K$ of 0·13 predicted by Zuber although again rather more scatter is apparent at the lower pressures in Fig. 9.

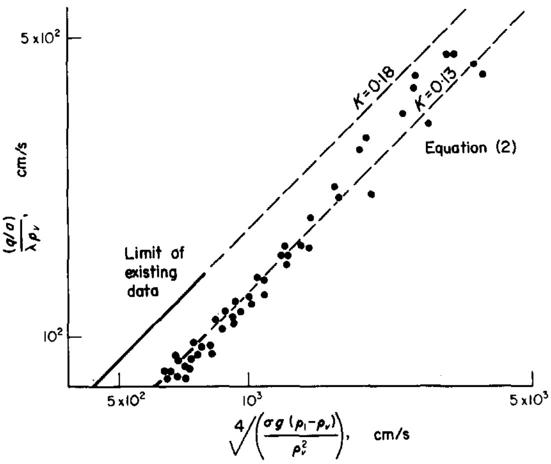


FIG. 9. Comparison of authors' experimental critical heat flux data with the Zuber correlation.

Experimental subcooled pool boiling data are presented in Fig. 10. The results for atmospheric boiling are comparable with those reported by Ivey [16], (curve 8, Fig. 1) for a similar system. Despite the observed change in the nature of the boiling crisis at low pressure, the rate of increase in the value of the critical

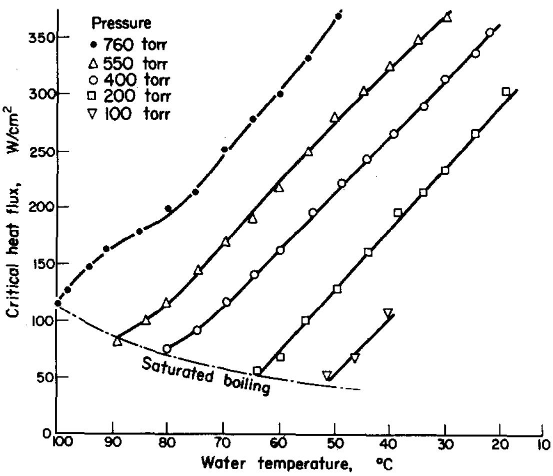


FIG. 10. Authors' experimental critical heat flux values for subcooled low pressure pool boiling.

heat flux with subcooling is remarkably constant. This observation supports the theory that the increase is due to an increase in the convective heat transfer component as assumed in the extension of the Zuber analysis. Figure 11 compares the experimental data with values predicted by the Zuber correlation, equation (3), and it is evident that although at atmospheric pressure the theoretical and experimental values lie in close agreement, as the pressure is reduced the experimental values become progressively lower than predicted by the correlation. At a pressure of 100 torr., for example, the correlation predicts values of the ratio $q_{sub}/q_{sat}$ that are up to 20 per cent in excess of the experimental values.

The experimental data were analysed by a linear regression technique and the following expressions for correlating the data were obtained,

760 torr. $q_{sub}/q_{sat} = 1{\cdot}014 + 0{\cdot}04458\,(t_{sat} - t_{sub})$,
550 torr. $q_{sub}/q_{sat} = 1{\cdot}128 + 0{\cdot}0510\,(t_{sat} - t_{sub})$,
400 torr. $q_{sub}/q_{sat} = 1{\cdot}130 + 0{\cdot}0552\,(t_{sat} - t_{sub})$,
200 torr. $q_{sub}/q_{sat} = 0{\cdot}8898 + 0{\cdot}0915\,(t_{sat} - t_{sub})$,
100 torr. $q_{sub}/q_{sat} = 1{\cdot}0190 + 0{\cdot}11225\,(t_{sat} - t_{sub})$.

Assuming a correlation of the form similar to that of Zuber for subcooled boiling

$$\frac{q_{sub}}{q_{sat}} = \mathrm{A} + \mathrm{B.p}^n\,(t_{sat} - t_{sub}) \qquad (4)$$

a regression technique was used to show that

$$B = 1{\cdot}015 \text{ and } n = -0{\cdot}474$$

when the system pressure was expressed in torr. and the temperature in °C. Thus

$$\frac{q_{sub}}{q_{sat}} = A + 1{\cdot}015\,\frac{\Delta t_{sub}}{p^{0\cdot474}}\,. \qquad (5)$$

In Fig. 12 the data have been correlated in this form and it is apparent that $A$ has a value of approximately unity as expected. Calculation of the standard deviation of the data around lines having different assumed values of the intercept $A$, showed the minimum deviation of the data to be around a line with a value of 1·06. Thus the data on critical heat fluxes in the subcooled pool boiling of water on a tubular stainless steel heater, at pressures in the range 100 to 760 torr. and with up to 60° of subcooling, are correlated by the expression

$$\frac{q_{sub}}{q_{sat}} = 1{\cdot}06 + 1{\cdot}015\,\frac{\Delta t_{sub}}{p^{0\cdot474}} \qquad (6)$$

where the value of the saturated boiling critical heat flux $q/a_{sat}$ is estimated from the authors data or from the Zuber correlation, equation (2).

## CONCLUSIONS

(1) Critical heat fluxes in the saturated pool boiling of water under reduced pressures are correlated by the Rohsenow [3] and Zuber [6] correlations until the sporadic mode of bubble formation dominates the boiling process. These correlations are based on experimental data obtained at pressures in excess of one atmosphere and their applicability for the low pressure data is evidence in support of the validity of the models used in their derivation.

(2) Critical heat flux data for the subcooled boiling of water at atmospheric pressure are comparable to the data of Ivey [16] for a similar heating system.

(3) No comparable data are available with which to compare the experimental data on critical heat fluxes in subcooled boiling at pressures other than atmospheric and the Zuber [6] correlation of critical heat fluxes in subcooled boiling does not satisfactorily correlate the data.

(4) The authors' experimental data on the critical heat fluxes in the subcooled pool boiling of water on a stainless steel tube at pressures in the range 760 to 100 torr. and with liquid subcoolings of up to 60°C are correlated by the expression

$$\frac{q_{sub}}{q_{sat}} = 1{\cdot}06 + 1{\cdot}015\,\frac{\Delta t_{sub}}{p^{0\cdot474}}$$

where the pressure $p$ is expressed in torr. and the liquid subcooling $\Delta t_{sub}$ in °C.

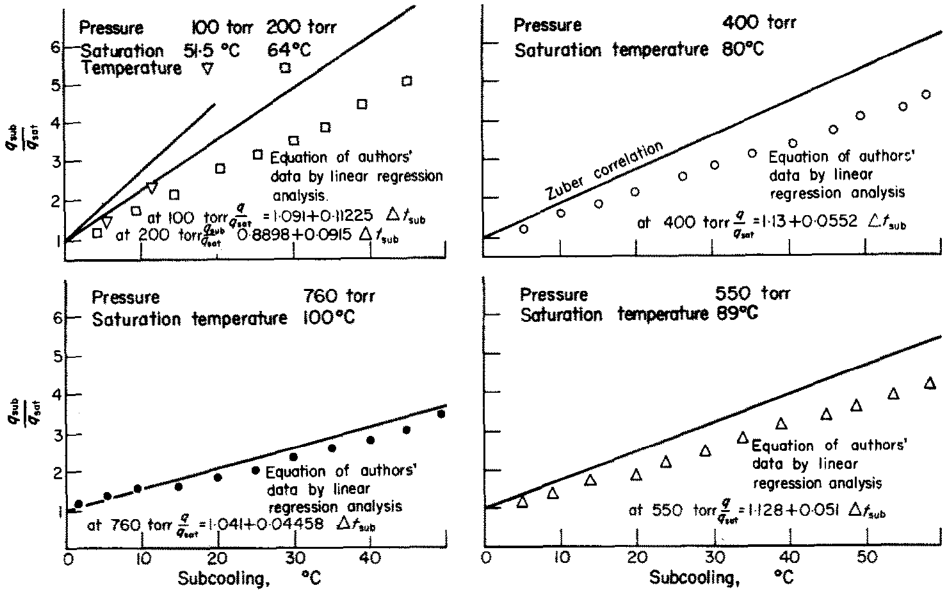


FIG. 11. Comparison of experimental heat fluxes in subcooled water with values predicted from the Zuber correlation.

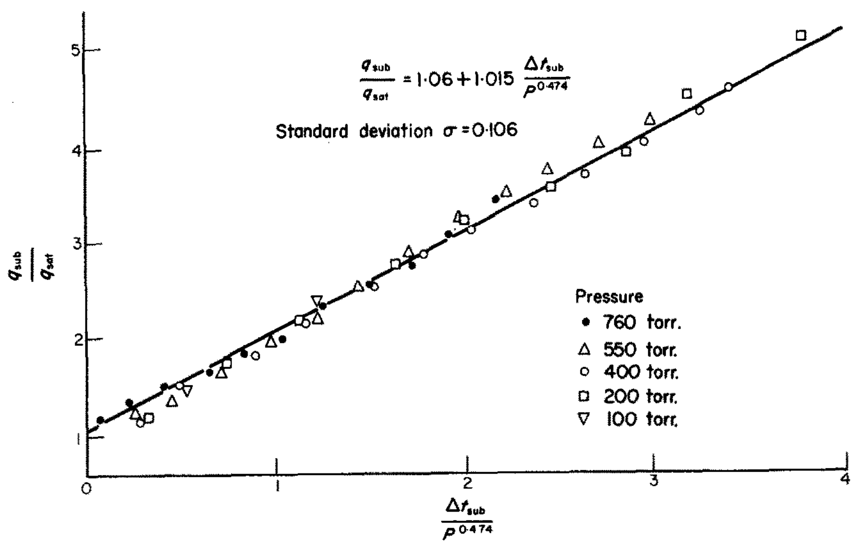


FIG. 12. Authors' correlation of experimental critical heat flux data for the low pressure subcooled boiling of water.

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**Résumé**—On présente des valeurs des flux de chaleur critiques mesurés pendant l'ébullition en réservoir de l'eau sous des faibles pressions et sous des conditions d'ébullition sous-refroidie et saturée. Les flux sont bien corrélés par l'équation:

$$\frac{q_{sub}}{q_{sat}} = 1{,}06 + 1{,}015 \frac{t_{sub}}{p^{0{,}474}}$$

pour des pressions de 760–100 torr et des sous-refroidissements du liquide allant jusqu'à 60°C. Les résultats confirment que les corrélations existantes prédisent convenablement les flux de chaleur critiques pour l'ébullition saturée jusqu'à ce que le mécanisme de l'ébullition change à cause de l'effet de la pression réduite sur l'activité des sites de nucléation. Aucune comparaison équivalente ne peut être faite pour l'ébullition sous-refroidie pour laquelle les valeurs ont été données auparavant seulement à la pression atmosphérique.

**Zusammenfassung**—Es wurden Messwerte für die kritischen Wärmestromdichten beim Behältersieden von Wasser bei kleinen Drücken bei Unterkühlung und Sättigung angegeben. Die Wärmeströme wurden durch die Gleichung

$$\frac{q_{sub}}{q_{sat}} = 1,06 + 1,015 \frac{t_{sub}}{p^{0,474}}$$

für Drücke von 760–100 Torr und Flüssigkeitsunterkühlungen bis 60 Grad gut korreliert.

Die Ergebnisse bestätigen, dass Berechnungen der kritischen Wärmestromdichten für Flüssigkeiten bei Sättigung nach bereits bestehenden Beziehungen, solange hinreichend genau sing, bis sich der Siedemechanismus wegen der Wirkung des verkleinerten Druckes auf die Keimbildung ändert.

Für unterkühltes Sieden, wo nur Werte für atmosphärische Drücke vorliegen, kann kein entsprechender Vergleich gemacht werden.

**Аннотация**—Приводятся значения критических тепловых потоков при кипении воды в большом объеме при малом давлении и в условиях недогретого и насыщенного кипения. Тепловые потоки хорошо описываются уравнением

$$\frac{q_{\text{недог}}}{q_{\text{насщ}}} = 1,06 + 1,015 \frac{t_{\text{недог}}}{p^{0,474}}$$

в диапазоне изменения давления от 760 до 100 торр и при недогреве жидкости до 60°C. Результаты подтверждают, что существующие уравнения удовлетворительно определяют критические тепловые потоки в условиях насыщенного кипения до тех пор, пока в результате влияния пониженного давления на активность образования ядер не изменяется механизм кипения. Нельзя сделать соответствующего сравнения для случая кипения недогретой жидкости, так как появившиеся ранее данные относятся только к кипению при атмосферном давлении.