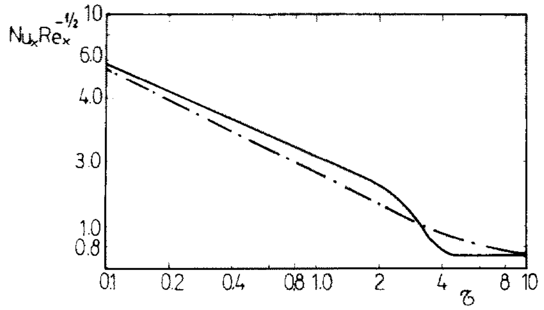

FIG. 1.

taken into account in our analysis neither the time to reach steady nor the form of the curve are properly predicted.

It should finally be mentioned that curves presented by Watkins [1] for the friction factor, are fairly well reproduced by or simple expression (20), when $n \geqslant 0$.

It can be concluded that our simple analysis is able to predict rates of heat and momentum transfer which are in fair agreement with estimates presented by Watkins [1] obtained with a rather difficult numerical technique.

However the more important achievement of this contribution is related with future works since by usual superposition techniques it is possible to analyze other situations where wall temperature is some prescribed time function or either to find wall temperature profile when the flux is prescribed.

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REFERENCES

1. C. B. Watkins, Jr., Unsteady heat transfer in impulsive Falkner–Skan flows, *Int. J. Heat Mass Transfer* **19**, 395 (1975).
2. E. M. Sparrow and J. L. Gregg, Prandtl number effects on unsteady forced convection heat transfer, NACA TN 4311 (1958).
3. R. D. Cess and E. M. Sparrow, Unsteady heat transfer from a rotating disk and at a stagnation point, in *International Development in Heat Transfer* 1961/62, p. 468. Am. Soc. Mech. Engrs, New York (1962).
4. R. D. Cess, Heat transfer to laminar flow across a flat plate with nonsteady surface temperature, *J. Heat Transfer* **83C**, 274 (1961).
5. J. C. Gottifredi and O. D. Quiroga, Unsteady heat transfer in laminar boundary layers with low Prandtl numbers, *Latin-American J. Heat Mass Transfer*. To be published.

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A METHOD OF OBTAINING FLOW FILM BOILING DATA FOR SUBCOOLED WATER

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NOMENCLATURE

G,	mass flux [kg/m^2 s];
P,	pressure [MPa];
T_{sat},	saturation temperature [K];
T_w,	heated surface temperature [K];
X_{in},	inlet quality;
ΔT_{in},	inlet subcooling [K];
ϕ,	surface heat flux [W/m^2].

THE OBJECTIVE of this paper is to describe a simple experimental method to be used for measuring flow film boiling data at low qualities and subcooled conditions.

The most widely used system in forced convective boiling studies is a heat flux controlled system where the heat output of an electrically heated element is increased gradually. Such a system however does not permit the measurement of flow film boiling data for subcooled water since the high CHF values would result in heated surface temperatures in excess of the melting point of most metals. Instead, a variety of temperature controlled systems could be used in film boiling studies. A review of experimental techniques, utilized in post-CHF studies, has been made by Groeneveld [1]. Despite the complexity of some of the techniques used none of these studies has produced fully developed flow film boiling data suitable for deriving a correlation or verifying existing correlations.

The technique used in our study was first discovered accidentally at Chalk River in the late sixties. The technique, as originally used by Groeneveld [2], employed a high thermal inertia hot patch, heated independently and attached to a directly heated tube cooled by Freon (Fig. 1). The hot patch's original purpose was to study the effect of flux spikes on the CHF. However, when the hot patch power was raised such that dryout occurred, the downstream dryout behavior was changed drastically.

The high thermal inertia of the hot patch clamp enabled the experimenter to limit the temperature rise at dryout by reducing the hot patch power. When steady film boiling temperatures were reached at the hot patch the test section power was raised slowly. At power levels well below the dryout power for uniform heating a phenomenon illustrated in Fig. 1 occurred: the dry patch started to spread from the hot patch in the downstream direction. During two runs dry patch spreading was observed visually using an i.r. camera focused on the bare test section tube; the hot region was seen to propagate slowly from the hot patch at an apparently constant rate.

The effect of a hot patch on the downstream thermal behavior of an otherwise uniformly heated tube is shown graphically in Fig. 2. The solid lines represent the boiling curves for uniform heating at constant inlet conditions while the broken lines illustrate the effect of an upstream hot patch in extending the film boiling temperature and heat flux range to lower values. Dryout at the hot patch does not seem to affect the film boiling temperatures as both symbols in Fig. 2 fall along a single curve.

It was realized immediately that this technique of producing film boiling data at heat flux levels well below the CHF could be very advantageous in water at subcooled conditions as here heater failures frequently occurred when the CHF was exceeded accidentally. Initially a similar setup for water was constructed. Because of expected failures of cartridge heaters, the copper hot patch clamp (O.D. 2.5 cm; length 4 cm) was heated by two oxygen-acetylene torches. Although dryout at the hot patch clamp did occur, especially when the flow was reduced, no spreading of the dry patch along the directly

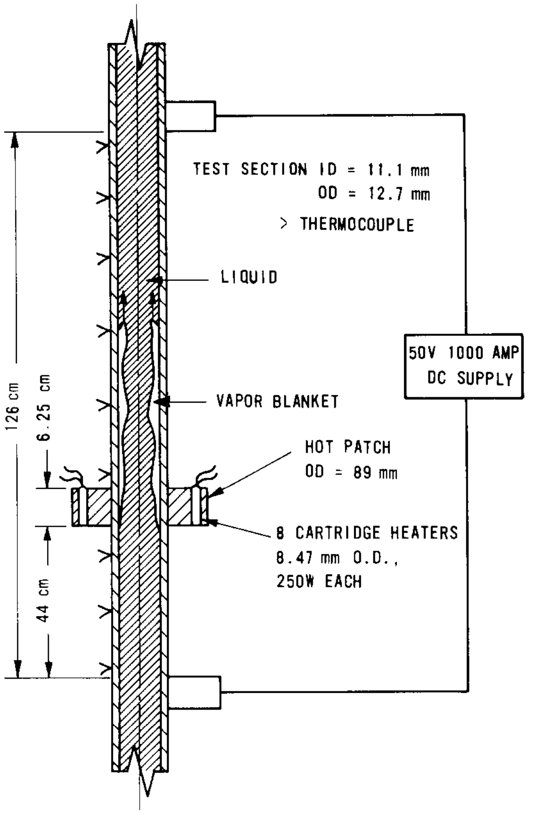

Fig. 1. Schematic of test section.

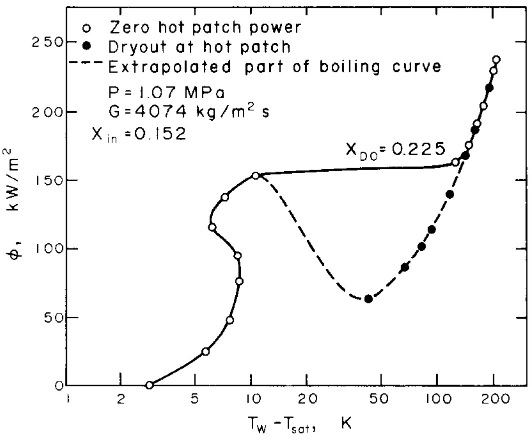

Fig. 2. Boiling curve obtained in freon-12 on test section equipped with hot patch.

heated test section was observed. After several test section failures due to overheating, this experimental approach was abandoned.

A second experimental setup in water used a much larger copper hot patch clamp (O.D. 8.9 cm; length 6.25 cm) equipped with eight 250 W cartridge heaters (Fig. 1). The hot patch clamp was silver soldered to the directly heated test section. Extra support for the hot patch clamp was required as the silver solder was liquid at the hot patch operating temperatures (≈ 800°C). The original purpose of the hot patch was to provide a dry patch location from which the vapor blanket could propagate downstream along the directly heated test section where steady-state heat-transfer measurements could then be made. It was found, however, that the spreading process was very slow in water and that excessive axial temperature variations occurred if the hot patch was employed in this manner. Subsequently a simpler method was employed where the hot patch and the test section were initially heated to approximately 800°C before introducing the coolant to the test section. After coolant injection the test section upstream of the hot patch quenched gradually, but the high thermal inertia hot patch (whose power supply was separate from the test section power supply) proved effective in preventing the quench front from propagating further downstream. As a result the downstream portion of the test section continued to experience film boiling at heat flux levels well below the CHF for uniform heating thus permitting the measurement of steady-state film boiling temperatures.

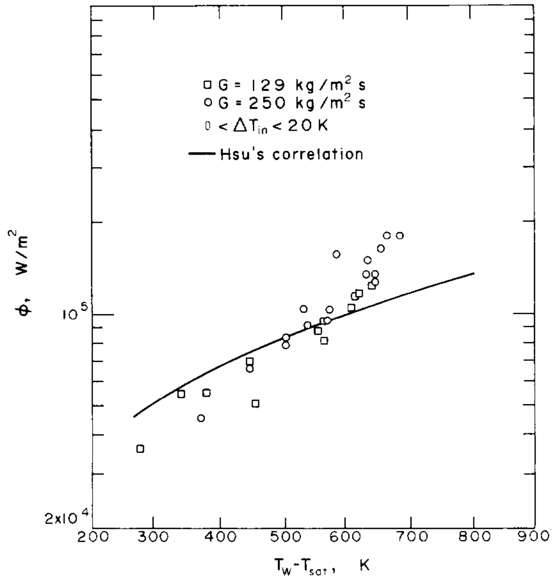

Fig. 3. Effect of mass flux on low quality and subcooled film boiling in water.

Figure 3 shows some of the initial film boiling data taken for two mass flows. No attempt has yet been made to separate the radiative heat flux component from the convective component. Also shown are the trends of the correlation proposed by Hsu [3]. The present steady-state data exhibit a slight dependence on wall superheat, mass flow, subcooling and axial location. It approaches the trends predicted by Hsu's correlation which is a slight modification of Bromley's [4] classical film boiling analysis.

REFERENCES

1. D. C. Groeneveld and K. K. Fung, Forced convective transition boiling; review of literature and comparison of prediction methods, Atomic Energy of Canada Limited report AECL-5543 (1976).
2. D. C. Groeneveld, Effect of a heat flux spike on the downstream dryout behavior, *J. Heat Transfer* **96C**, 121–125 (1974).
3. Y. Y. Hsu, Tentative correlation of reflood heat transfer, Paper presented at Third Water Reactor Safety Information Meeting, USNRC, Germantown (1975).
4. L. A. Bromley, N. R. LeRoy and J. A. Robbers, Heat transfer in forced convection film boiling, *Ind. Engng Chem.* **45**, 2639–2646 (1953).