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Experimental studies of heat transfer and vapour formation in fast transient boiling

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Abstract—This paper presents the results of fast transient boiling tests using rapidly heated platinum wires immersed in water. Very fast heating resulted in spontaneous nucleation on the wire surface and exceptionally high rates of heat transfer. Vapour blanketing of the wire did not occur under the investigated transient conditions for periods lasting several tens of microseconds and exceeding by two orders of magnitude the associated bubble growth time.

1. INTRODUCTION

THE EXPERIMENTAL studies on fast transient boiling were undertaken as a part of a programme of research on thermal explosions with potential application to the safety of nuclear reactors. The aim of this work was to obtain measurements and to acquire a better understanding of the physical mechanisms of heat transfer under highly transient conditions, similar to those occurring during the vapour film collapse stage of a thermal explosion.

In a number of previously published works transient boiling effects were studied using a variety of techniques. Hall and Harrison [1] and Yesin [2] experimented with metallic ribbons heated electrically so as to give exponentially rising power input. This technique was also used by Sakurai and Shiotsu [3] in their studies of boiling on wires immersed in water. A different method of heating was chosen by Board *et al.* [4] who investigated very fast transient processes of heat transfer and vapour formation using a thin nickel foil target heated by a laser beam.

In the present work a fine platinum wire immersed in water was heated by a surge of electric current. The study has revealed some unexpected characteristics of transient boiling heat transfer, particularly when the rate of heating was very high. As a result of fast temperature rise the liquid became highly superheated for short times during which the thickness of the thermal layer adjacent to the wire surface was insufficient to support heterogeneous nucleation. As it was demonstrated by Skripov [5] and by Simpson and Walls [6], it is possible to superheat the liquid in such a manner to its homogeneous nucleation temperature where the molecular energy fluctuations become the dominant mechanism for vapour nucleation. In contrast, the slower transients [7] showed different characteristics attributable to heterogeneous nucleation.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental method adopted in the present work was to rapidly heat a platinum wire (0.025-mm diam. and approx. 10-mm long), immersed in water, by a single square-wave pulse of electric current. The temperature of the wire was determined using the principles of resistance thermometry. The heat transfer rates were inferred from the power input to the wire and the rate of change of its temperature. The apparatus used in the experiments is shown in Fig. 1.

The changes of the wire resistance, R_w, were detected by a resistance bridge and recorded, together with the bridge supply voltage, by a storage oscilloscope. The response of the bridge was calibrated for each new wire

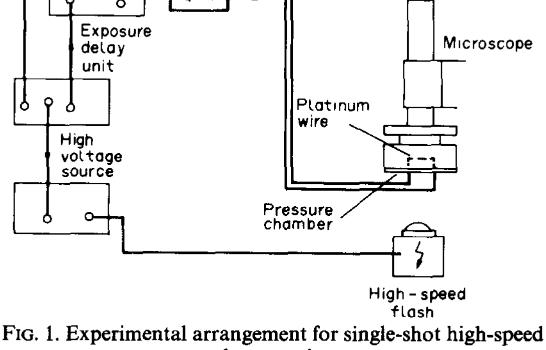

FIG. 1. Experimental arrangement for single-shot high-speed photography.

by placing the wire in a fluid at a range of temperatures and noting the value of R_4 required to balance the bridge.

The bridge was fed by a power supply producing a single square-wave pulse of current of variable amplitude and duration. Very fast heating transients could thus be imposed on the wire resulting in rates of temperature rise up to 10^7 K s^{-1}.

A simple technique was devised to minimise the changes of the power input into the wire during the heating pulse. It can be shown that by selecting the value of the resistor R_2 to be equal to $\sqrt{2}\,R''_w$ (where R''_w is the resistance of the platinum wire at ambient temperature) it is possible to keep the power input constant to within 4%.

The burn-out of the wire was prevented by controlling the duration of the heating pulse.

The cumulative error in the transient temperature measurement was estimated to be not more than 5%. This arises primarily from the effect of cold ends and temperature variations across the heated wire, as well as inaccuracies in the calibration procedure and stray capacitance and inductance of the bridge.

A photographic record of the nucleation phenomena was obtained using a single-exposure spark photography technique. Various stages of the boiling transients were studied by triggering the high-speed flash at a pre-determined stage during the wire heating period, but only one exposure was possible for each heating pulse.

The platinum wire, immersed in a small volume of degassed distilled water, was contained in the pressure chamber shown in Fig. 2. This design included a bellows to facilitate focusing of a standard laboratory microscope having its objective lens housed in the pressure chamber. The liquid was pressurised by a hand-operated water pump.

3. EXPERIMENTAL RESULTS

The experimental results shown in Figs. 3 and 4 consist of traces of wire temperature against time for

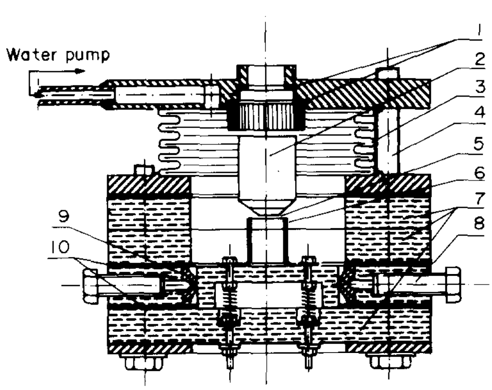

FIG. 2. Pressure chamber. 1, Rubber seals; 2, microscope objective lens; 3, stainless-steel bellows; 4, focusing screws; 5, platinum wire; 6, wire supports; 7, perspex windows; 8, wire positioning device; 9, rubber gasket; 10, rubber sealing rings.

different heating rates and ambient water pressures. The rates of heat transfer into the water, as well as the heat gereration rate, $\dot{q}$, are also shown in these figures as a function of time. To aid comparison both the heat flux and the heat generation rate are expressed in the same units.

The photographs in Figs. 5–8 illustrate the nucleation and boiling effects on the wire recorded by spark photography. The points marked with arrows on the corresponding temperature–time plots indicate the exposure time of the associated photographs. The complete photographic record was obtained from a number of tests repeated under the same conditions within a short space of time. Only one exposure was possible in each run.

3.1. *Slow transient boiling tests*

The boiling transients at relatively low heating rates are shown, for a range of liquid pressures, in Fig. 3. During the pre-nucleation stage of the transients all the traces follow the same curve which was found to conform to the theoretical solution for transient conduction into the liquid. The points of divergence from this curve indicate onset of nucleation for each transient and shift to higher temperatures when liquid pressure is increased. All traces show a certain amount of temperature overshoot followed by a prolonged period of equilibrium boiling.

The boiling effects for such relatively slow transients at atmospheric pressure were described in detail in ref. [7]. Only a few heterogeneous nucleation sites were active and led to rapid growth and spreading of vapour bubbles along the thermal boundary layer. As a result large cylindrical bubbles momentarily enveloping large portions of the wire were formed. The collapse of this brief stage of film boiling was followed by nucleate boiling.

At higher pressures heterogeneous nucleation led directly to nucleate boiling as shown in Fig, 5. The heat flux into the liquid at this stage was 36 MW m^{-2} which is an order of magnitude greater than the critical heat flux in steady-state nucleate boiling for the same degree of subcooling. Despite this the nucleate boiling stage of the transient test persisted sometimes for a considerable length of time (up to a few milliseconds) without causing the wire to burn out.

3.2. *Fast transient boiling tests*

The results obtained at higher heating rates (Fig. 4) are very different in character from those discussed above. The traces for various water pressures diverge from their common curve (representing single-phase conduction) at almost the same point. The value of the wire temperature at that point is about 20°C below the predicted homogeneous nucleation temperature [5] and it appears to be relatively insensitive to changes of the liquid pressure. Also considering that the value of this temperature was very repeatable for different wires and remained unchanged if the rate of heating was increased further, the observed effects have been

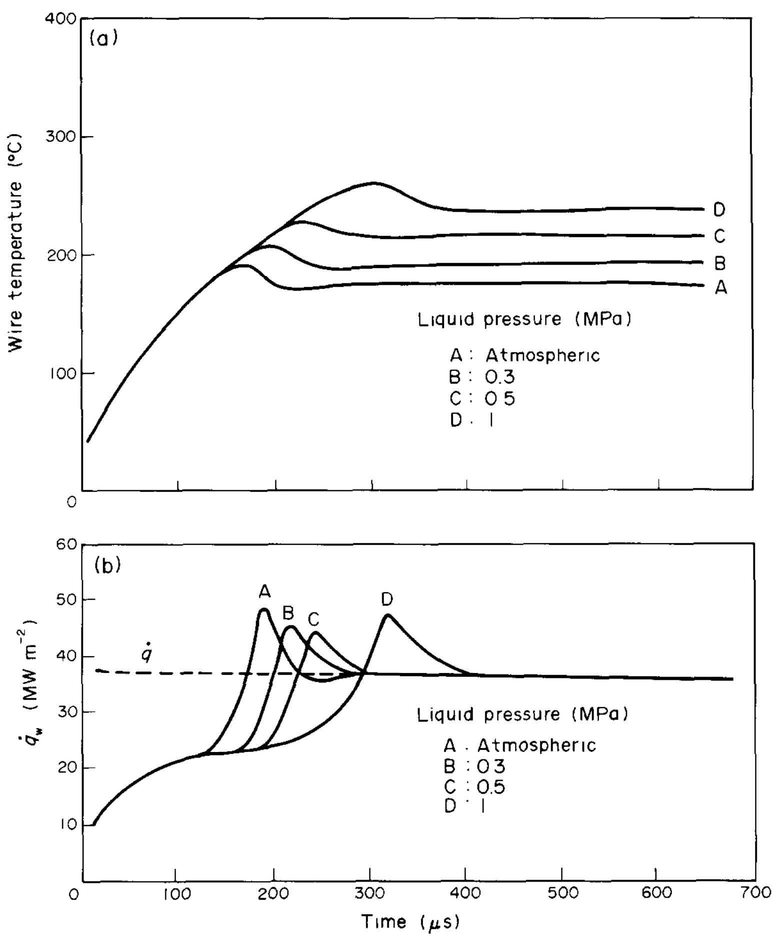

FIG. 3. Experimental results from relatively slow transient boiling tests. (a) Wire temperature as a function of time for a range of liquid pressures. (b) Heat flux at the wire surface ($\dot{q}$—rate of heat generation in the wire).

attributed to the onset of spontaneous nucleation, i.e. nucleation occurring on a poorly wetted wire surface as a result of random fluctuations of molecular energy of the fluid. The slope of the traces subsequently decreases with increasing liquid pressure which indicates an improvement in heat transfer into the liquid. For pressures above 0.5 MPa the wire temperature remains almost constant during the post-nucleation stage for up to several tens of microseconds. The heat flux during this period is as high as 125 MW m^{-2} (Fig. 4b) which is more than double that at atmospheric pressure. In all cases at the high heating rate the wire would eventually burn out if the heating was continued for another 200–300 μs.

The nucleation and boiling responsible for the effects described above can be seen on the photographs in Figs. 6–8. At atmospheric pressure (Fig. 6) the heterogeneous nucleation leads to formation and growth of large vapour bubbles which spread along the wire and coalesce forming areas of unstable film boiling. Incoherent collapse and regrowth of the vapour film can be seen during later stages of the transient.

At high pressure a certain amount of incipient heterogeneous nucleation can be observed in the early part of the transient. The arrows shown in Fig. 8 illustrate the repeatability of the nucleation at active sites in successive tests. During the post-nucleation period the boiling process resembles intense nucleate boiling despite the wire temperature approaching the spontaneous nucleation temperature. This process can persist for several tens of microseconds, which exceeds by two orders of magnitude the associated bubble growth time.

At intermediate pressures (Fig. 7) the boiling process exhibited a combination of effects observed in two fast transients described above. A certain amount of heterogeneous nucleation was present leading to formation of local zones of unstable vapour film, which periodically collapsed and reformed. The areas of tightly packed, separate bubbles similar to those observed at higher pressures can also be seen.

4. DISCUSSION

Under extreme transient conditions the temperature at which a liquid boils may approach its homogeneous

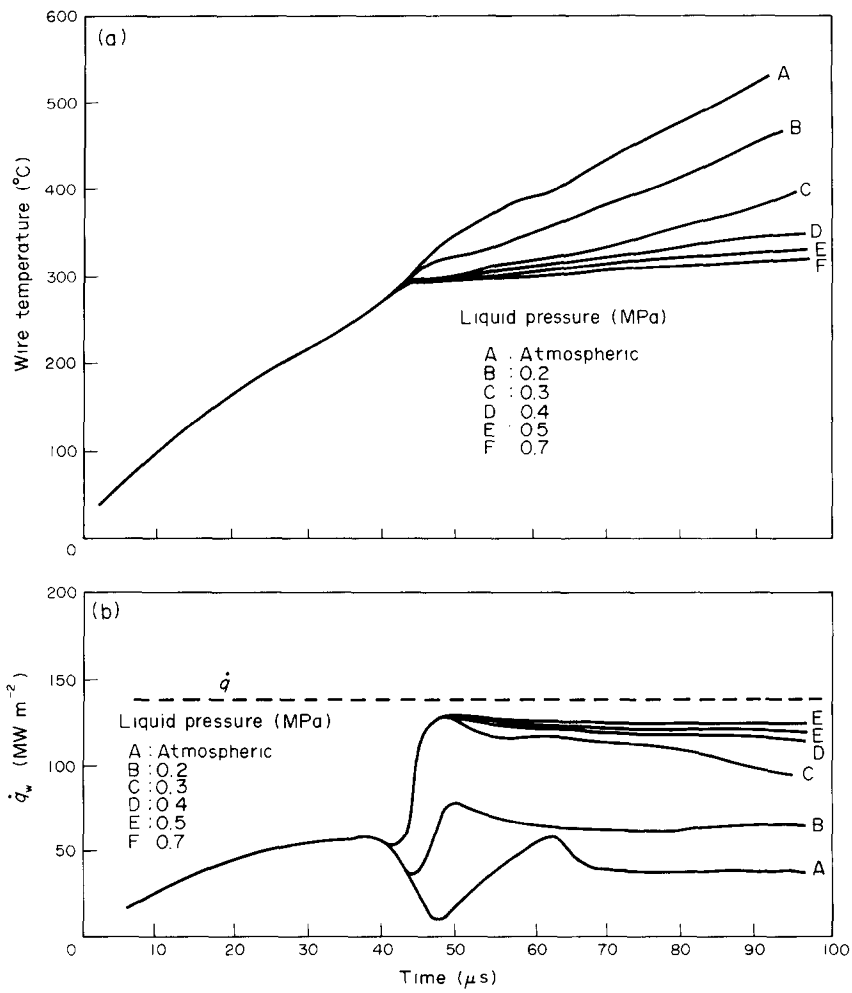

FIG. 4. Results of fast transient boiling test for a range of liquid pressures. (a) Wire temperature as a function of time. (b) Heat flux at the wire surface ($\dot{q}$—rate of heat generation in the wire).

nucleation temperature before a significant amount of vapour is produced at the existing nucleation sites. The nucleation results predominantly from molecular energy fluctuations at a rate expressed by the Boltzman factor, $\exp(-W_c/kT)$, where W_c is the work of formation of a critical size nucleus. The rate of nucleation increases rapidly with temperature (roughly by a factor of 100–1000 for each 1 K increase in temperature). If the liquid is heated at a rate of 5–10 K μs^{-1} it would seem reasonable to expect that nucleation would occur in an avalanche-like manner and the liquid in the vicinity of the wire surface would be promptly filled with tightly packed vapour bubbles growing and coalescing in times of the order of a fraction of a microsecond.

However a theoretical analysis (described in detail in refs. [9] and [10]) suggested a rather low bubble population of about 10^{10} m^{-2} thus the average distance between the nuclei would be about 10 μm [which is about 300 times greater than the radius of a critical nucleus (3×10^{-9} m)]. The analysis is based on the assumption that nucleation occurs in a thin layer of liquid surrounding the wire at a rate governed by the Doring–Volmer equation [8]. The subsequent growth of bubbles increases the liquid pressure and the vapour produced replaces some of the hot liquid adjacent to the wire surface in which nucleation can occur. Both these effects act in opposition to the increase in nucleation rate caused by rising temperature and eventually limit the number of nuclei formed. It is interesting to note that the bubble population observed in Fig. 8 corresponds quite closely to the prediction of the analysis.

Garnett [11] introduced a modification to this theory which accounted for the presence of a very steep temperature gradient in the liquid adjacent to the wire surface. As the bubbles grow they begin to experience the effect of the cold liquid which slows the rate of growth and limits the size of the bubbles. At low pressure the bubble inertia is sufficient to allow for bubble expansion well into the cold liquid from which it rapidly contracts. Large amplitude oscillations and

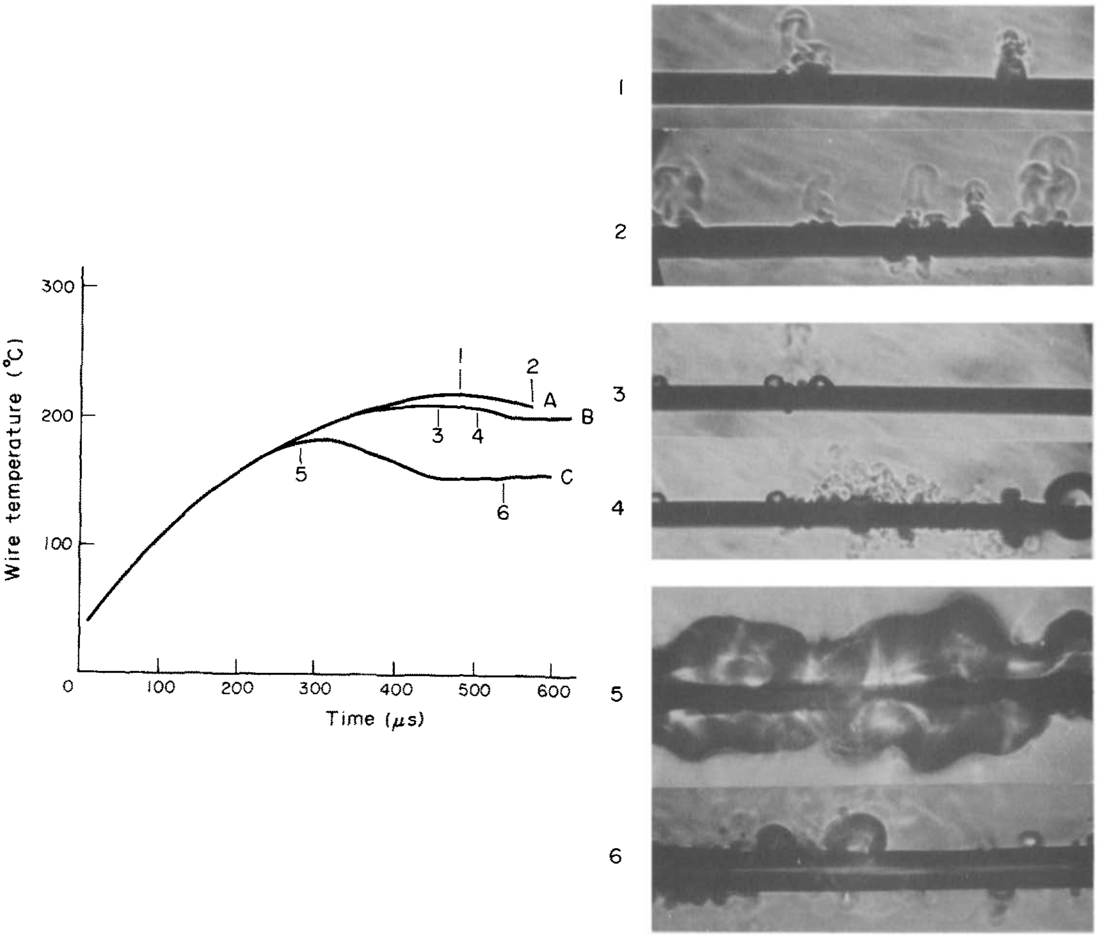

FIG. 5. Photographic record of a relatively slow boiling transient at elevated liquid pressure; A : $p = 0.4$ MPa, B : $p = 0.2$ MPa, C : p = atmospheric.

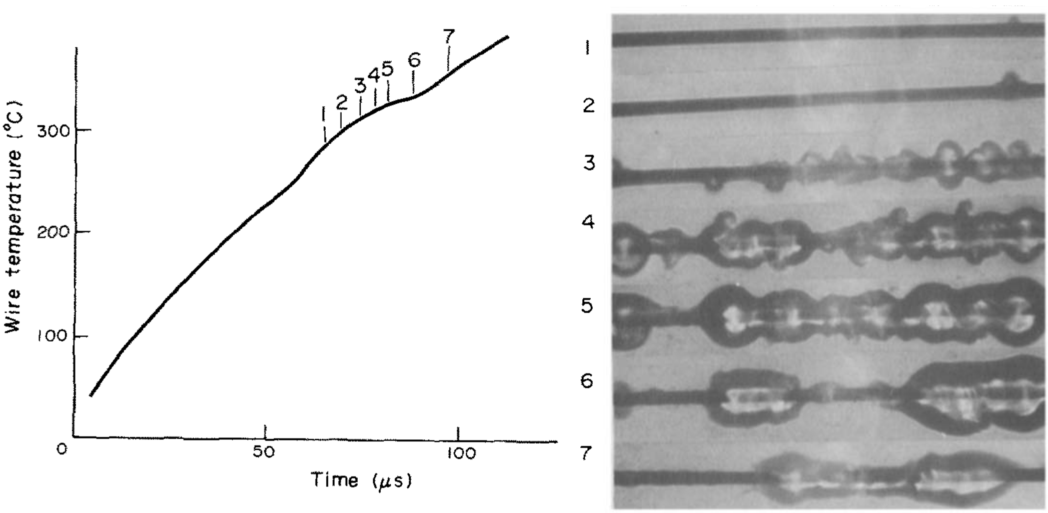

FIG. 6. Photographic record of fast transient boiling at atmospheric pressure.

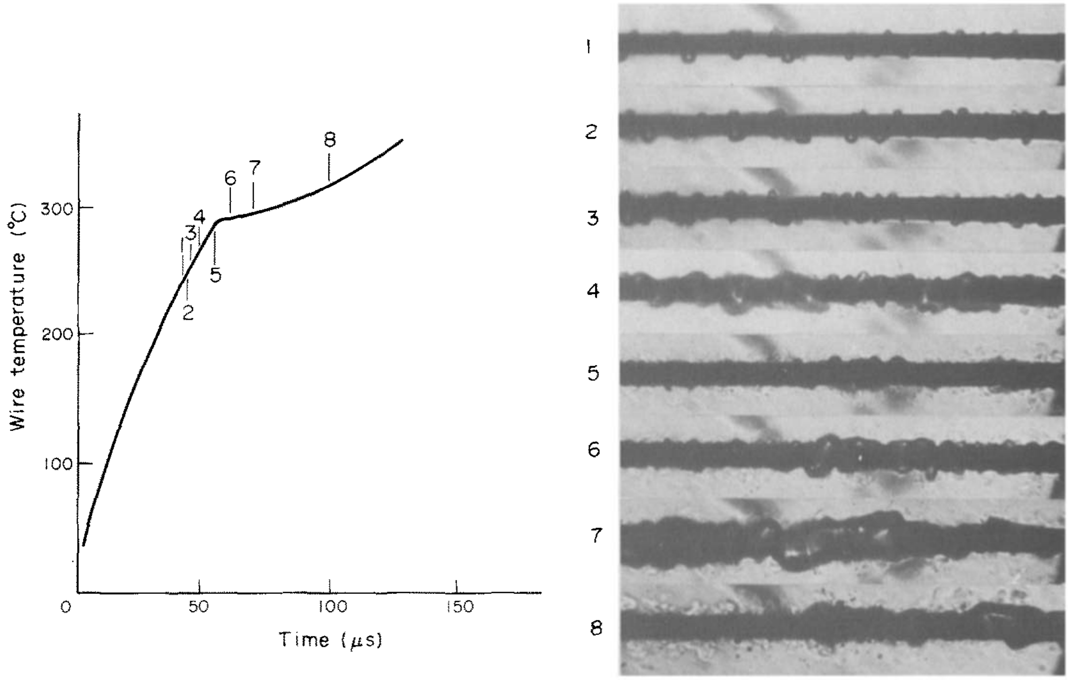

FIG. 7. Photographic record of fast transient boiling at $p = 0.035$ MPa.

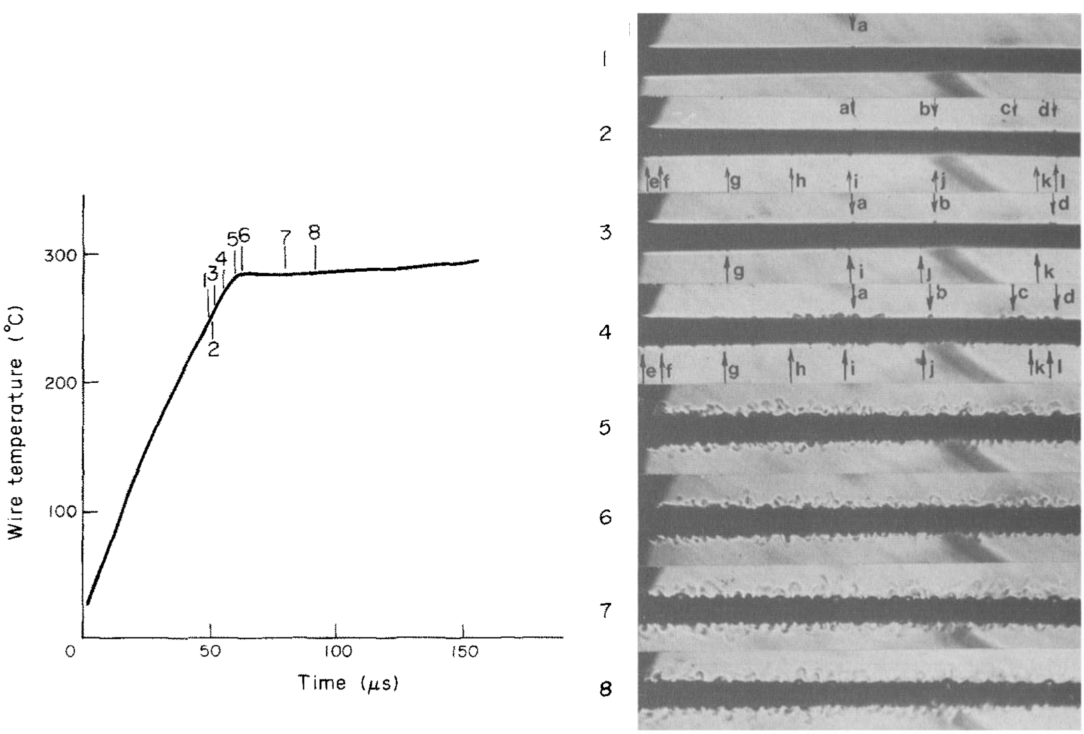

FIG. 8. Photographic record of fast transient boiling at $p = 0.61$ MPa.

even total bubble collapse can be expected. At liquid pressure increased to 0.8 MPa, Garnett's calculations predicted damped oscillations of frequency of the order of 4 MHz before the bubble found a position of equilibrium. At even higher pressures the oscillations disappeared and the bubbles were found to grow slowly to their maximum size without any inertial overshoot. The theory thus indicated that changing liquid pressure within the range from atmospheric to 1.0 MPa changed the pattern of growth of the vapour phase from unstable and oscillatory, possibly leading to momentary film boiling, to damped and overdamped vibrations at intermediate and higher pressures. Similar effects can be observed clearly in the presented photographs (Figs. 6–8).

Assessing the heat transfer rates for such a process is difficult due to a number of combined effects involved. At low pressure the predominant effect may be that of periodical insulation of the wire surface by patches of unstable vapour film. At intermediate pressures high-frequency oscillations of the vapour bubbles could induce a flow from the cold bulk liquid to the thermal layer which cools the wire and recirculates back into the bulk liquid. Gould [12] demonstrated experimentally that resonant vibrations of the bubbles present on the solid wall could increase the heat transfer rates across the solid–liquid interface by a factor of 10 over the values obtained in a similar case but without bubble oscillations.

Significant heat flux can also be attributed to forced convection process induced by thermocapillary flow even when there is little liquid agitation due to bubble dynamics. Vapour bubbles present on the wire surface experience a steeply varying liquid temperature from 300°C at the surface to 20°C approx. 3 μm away from it. The surface tension varies over the bubble surface which causes variations in the shear stress thus inducing liquid circulation. This circulation removes the hot liquid in the vicinity of the wire and replaces it with much cooler liquid drawn from some distance away from the wire surface. A rigorous theoretical solution for this case was obtained by Gaddis [13]. A simplified treatment of the thermocapillary flow around vapour bubbles based on a suggestion by Gaddis can also be found in ref. [11].

It was shown in these calculations that volumetric flow rates as high as $\dot{V} = 0.3$ m^3 s^{-1} per unit area occupied by vapour bubbles can be expected. If the entire heat flux from the wire was due to thermocapillary convection, its magnitude could be estimated by $\dot{q}' = \dot{V}\rho_w c_p \Delta T$ where ΔT is the temperature difference between the cold stream approaching the surface and the hot stream moving away from it. Considering the typical heat flux of 120 MW m^{-2} observed in the present experiment the required value of ΔT is approx. 120 K, which constitutes only about 40% of the available temperature difference between the wire and the bulk of the liquid.

The thermocapillary flow circulates within a layer of fluid adjacent to the wall of thickness comparable to the wire diameter (see Fig. 8) requiring a period of 20–30 μs to complete a cycle. After a few cycles a significant amount of heat will be deposited in the fluid resulting in gradual loss of subcooling thus leading to reduction in heat transfer. In this aspect the postulated model is consistent with the results of the experiments at high pressure, which revealed the existence of a relatively long period of equilibrium followed by a gradual and relatively slow rise of the wire temperature.

The effect of raising the liquid pressure would be that of reducing the temperature variations over the bubble surface since the saturation temperature is a much stronger function of pressure than the spontaneous nucleation temperature. This should clearly result in reduction of the thermocapillary flow rate and consequently the heat transfer rate. Thus in this respect the thermocapillary flow as a postulated heat transfer mechanism is not consistent with the experimental findings.

5. CONCLUSIONS

The most interesting outcome of the presented work is a rather low observed value for spontaneous nucleation density in water under the conditions of fast transient boiling. Previously it had always been assumed that a very large number of bubbles would be formed, typically 10^{14}–10^{15} m^{-2}. The theoretical considerations as well as the experimental results of the present work suggest a much lower population of bubbles (in the range 10^9–10^{10} m^{-2}). This population appeared unchanged for periods up to several tens of microseconds despite the wire temperature exceeding the spontaneous nucleation temperature. As a result the heat fluxes as high as 120 MW m^{-2} were measured in some of the transients which exceeds by two orders of magnitude the critical nucleate boiling heat flux for the same degree of liquid sub-cooling. The characteristics of the complex heat transfer processes involved in fast transient boiling have so far defied complete explanation. Some speculative possibilities have been indicated in the previous section.

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ETUDE EXPERIMENTALE DU TRANSFERT THERMIQUE ET DE LA FORMATION DE VAPEUR PENDANT L'EBULLITION RAPIDEMENT VARIABLE

Résumé—On présente les résultats d'essais d'ébullition rapidement variable à partir de fils de platine chauffés en immersion dans l'eau. De très rapides chauffages provoquent une nucléation spontanée à la surface du fil et des flux de chaleur exceptionnellement élevés. Le recouvrement du fil par la vapeur ne se produit pas dans les conditions étudiées, pour des périodes de plusieurs dizaines de microsecondes et excédant de deux ordres de grandeurs le temps associé à la croissance des bulles.

EXPERIMENTELLE UNTERSUCHUNGEN DES WÄRMEÜBERGANGS UND DER DAMPFBILDUNG BEI STARK-INSTATIONÄREM SIEDEN

Zusammenfassung—Es werden Ergebnisse von stark-instationären Siedevorgängen an schnell in Wasser aufgeheizten Platindrähten dargestellt. Die sehr schnelle Aufheizung verursacht eine spontane Blasenbildung an der Drahtoberfläche und außergewöhnlich große Wärmeübergangskoeffizienten. Eine Dampffilmbedeckung des Drahtes erfolgte bei den untersuchten instationären Bedingungen nicht. Die Perioden dauerten einige 10 ms und überschritten um zwei Größenordnungen die damit verbundene Blasenwachstumszeit.

ЭКСПЕРИМЕНТАЛЬНОЕ ИЗУЧЕНИЕ ТЕПЛОПЕРЕНОСА И ПАРООБРАЗОВАНИЯ ПРИ БЫСТРОМ ПЕРЕХОДНОМ РЕЖИМЕ КИПЕНИЯ

Аннотация—В работе представлены результаты опытов по быстрому переходному кипению при скоростном нагреве платиновых проволочек, погруженных в воду. В результате очень быстрого нагрева на поверхности проволоки мгновенно образуются пузырьки и теплообмен происходит при исключительно больших скоростях. В исследованных переходных режимах за времена в несколько десятков микросекунд (на два порядка выше времени роста пузыря) обволакивания проволоки паром не происходило.