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Heat transfer across vapour film without ebullition

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Abstract—Measurements of the boiling curve for steady state pool boiling of water are described. Frequently when the surface temperature is such that transition boiling would be expected a stable vapour film forms instead. The vapour film is unlike that of film boiling in that no vapour bubbles detach. The existence of the vapour film is confirmed using a technique for measuring liquid–solid contact.

INTRODUCTION

THIS paper describes an unusual type of two-phase heat transfer process, that we have not previously come across. On a number of occasions, during pool boiling of water on an upward facing horizontal surface, a stable vapour layer has formed in contact with the surface. The phenomenon is quite unlike film boiling in that the surface temperatures are too low and no vapour bubbles detach from the film. In fact, it may be inappropriate to describe this phenomenon as boiling since no vapour bubbles form and there is little evidence for any net generation of vapour.

Since the phenomenon to be described bears some resemblence to the Leidenfrost effect it is of interest to review some of the information available. A Leidenfrost drop is supported above a hot horizontal surface by a layer of vapour. Heat conduction and radiation through the vapour layer cause liquid to evaporate. Viscous flow of vapour creates a raised pressure below the drop. This raised pressure supports the weight of the drop. Models based on these ideas show reasonable agreement with observed drop evaporation rates (e.g. ref. [1] where spherical drops are assumed and ref. [2] where the drops are flattened at the base).

The Leidenfrost temperature is defined as the plate temperature at which the drop evaporation time is a maximum, i.e. the minimum temperature for film boiling. The values of the Leidenfrost temperature vary greatly from one experiment to another, particularly, it seems, for water. Values of various workers reported in ref. [3] range from 161 to 320°C for water; in ref. [2], by using very smooth surfaces and avoiding vibration, values down to only a few degrees above the boiling point were obtained in a saturated atmosphere and values below the boiling point obtained in dry air.

Direct measurements of the thickness of the vapour film seem rather rare. In ref. [4] the thickness was measured at 0.06 mm but the drop was still attached to a pipette. In ref. [1] the calculated minimum vapour layer thickness was less than 0.02 mm. In ref. [2] for a large drop at a surface temperature of 400°C the calculated thickness was 0.29 mm in the centre and 0.04 mm near the edge; for smaller drops and lower surface temperatures the thickness is much less.

For larger drops, up to 10 ml [3], the boiling process starts to resemble the film boiling that occurs with extensive volumes of liquid, with vapour mushrooms breaking through the drop. The condition for breakthrough not to occur appears to be that the drop dimension parallel to the hot surface be less than the most dangerous, i.e. most rapidly growing, wavelength of interfacial waves given [5] by

$$\lambda_D = 2\pi\left[\frac{3\sigma}{g(\rho_l-\rho_v)}\right]^{0.5}.$$

It could be argued that the liquid–vapour interface on the bottom of the drop should become unstable once the linear dimension exceeded the critical wavelength $\lambda_c(=\lambda_D/\sqrt{3})$ but the curved edges of the drop have the effect that the two statements: flat base of drop equals λ_c, and overall dimension equals λ_D, are equivalent. Certainly the experimental results, for three liquids [3], agree well with the λ_D criterion.

Typical results for an extended surface 203 mm square were reported by Hosler and Westwater [6]. Film boiling of both water and Freon 11 were characterized by vapour mushrooms breaking away from the film with the average spacing between bubbles being close to λ_D. The minimum observed spacing was λ_c. The minimum film boiling heat fluxes were in reasonable agreement with some equations derived by Zuber [7]. The minimum film boiling temperature for water was 258°C.

APPARATUS

The pool boiling test section is shown in Fig. 1. For steady-state tests that include the transition boiling region it is necessary to have a short distance between the cartridge heaters and the boiling surface. Temperature control was maintained with a Eurotherm Controller (model 820, of the logic output type with a 0.1 s cycle time). The controlling thermocouple, type K, was of the bare junction type with 0.19 mm wires

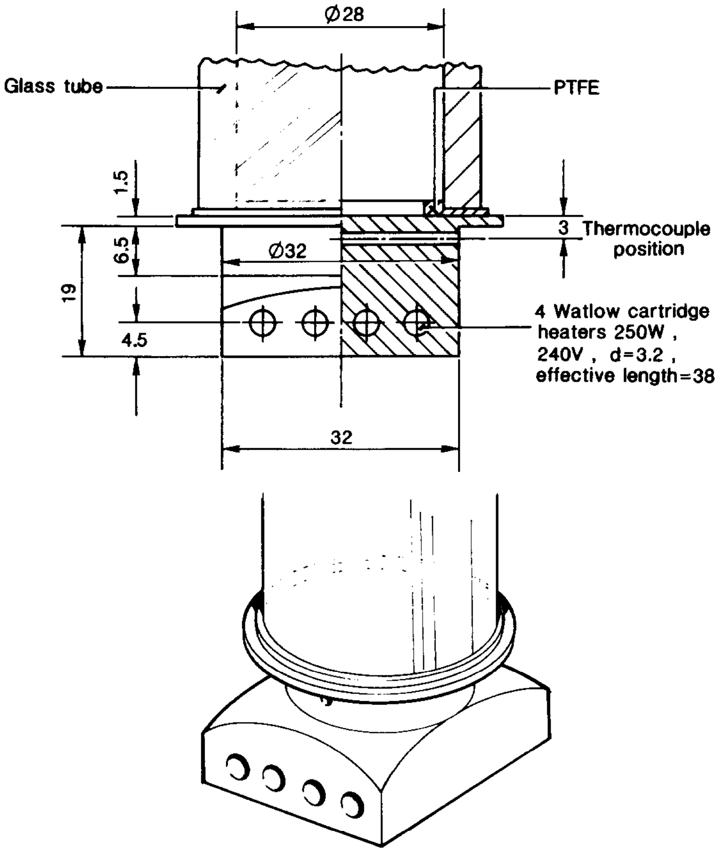


Fig. 1. Test section used for the steady-state boiling measurements. Front view and section (above), and general appearance (below). Dimensions in millimetres.

soldered to the bottom of a 1.6 mm diameter hole located 3 mm below the centre of the boiling surface. Heat flux was calculated from the electricity consumption measured by a standard meter, with correction for heat losses measured in a separate test as a function of temperature. For most of the normal boiling curve these losses amounted to less than 20%. Based on repeat measurements the accuracy of the final, corrected, heat flux values is considered to be 3% or better. This does not apply to the very low heat flux 'non-boiling' results to be described later. For these the heat losses were comparable with the heat transferred to the liquid so the error in determining the heat losses (around 2 or 3%) becomes significant in addition to the 10% scatter shown later in Fig. 2.

The measurement of liquid–solid contact followed the technique described in ref. [8]. This involves anodizing the aluminium surface. Prior to anodizing the surface was polished with emery paper 320, degreased with acetone and then washed with water. The electrolyte used for the anodizing is a solution of 3% by weight ammonium tartrate in distilled water with sufficient tartaric acid added to bring the pH to 5–5.5. Anodizing takes 4 h with the applied voltage across the cell increasing automatically to 140 V as the cell impedance rises. Electrical contact with the bulk liquid was through a flat spiral electrode held parallel about 5 mm from the boiling surface. A minor improvement on the basic technique of ref. [8] was that the detailed investigation of the properties of the oxide layer using the Frequency Response Analyser was performed at the saturation temperature rather than room temperature. This confirmed that the dominant impedance was due to the oxide layer rather than the bulk liquid. This is important because it is assumed that the vapour does not conduct electricity, so the current can only pass through the oxide layer in the areas that are wetted by liquid, i.e. impedance is inversely proportional to wetted area.

RESULTS

The anomalous heat transfer behaviour has been observed a number of times now, with marginal variations in the procedure. A common feature is that the surface is first heated up to beyond the critical heat flux, with measurements of heat flux and surface contact being made at a number of temperatures. Figure 2 shows the results of one heating run, where the critical heat flux occurred at 115.3°C (corrected surface temperature, not set temperature) and good control of temperature in transition boiling was obtained up to 127°C. Over this small range of 12°C there is a distinct drop in both heat flux and the extent of liquid–solid contact, but both are still quite high. On raising the set temperature by 1.5°C control was lost and the

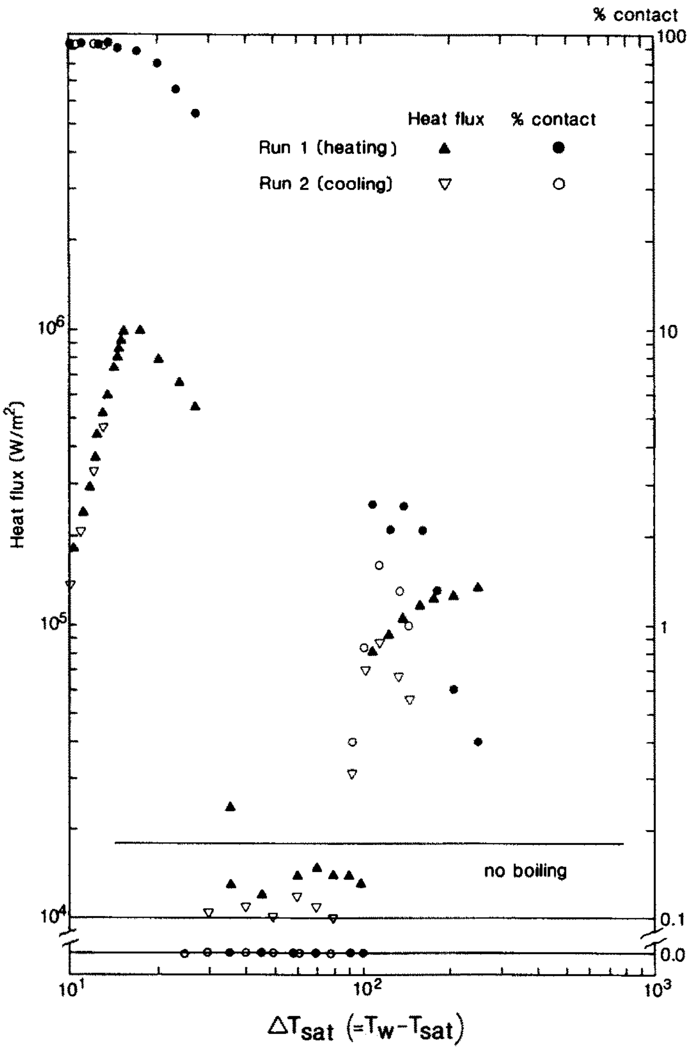


FIG. 2. Steady-state boiling curves (triangles) and the corresponding liquid–solid contact measurements (circles) for two runs where the stable, non-boiling, vapour film appeared. Note that a number of the surface contact readings were zero and so strictly cannot be shown on a log graph.

temperature rose temporarily to 150°C. On returning to the set temperature (under controller action), over a period of around 12–15 s, a totally different behaviour appeared.

Boiling, in the sense of the evolution of vapour bubbles, stopped. The heat flux fell to a very low value. Surface contact, to the accuracy of the measurement technique, became zero. When the condenser above the glass tube, and the electrode used to make contact with the bulk water, were removed, and a light shone directly down onto the boiling surface, it became clear that there was a continuous vapour film present over the surface. Also, by observing a couple of dust particles in the liquid–vapour interface, that the film was in vigorous motion. Convective currents in the bulk liquid could also be seen but the velocities were much lower. When a thermocouple was inserted into the bulk liquid, the temperature was measured at 83°C.

The temperature of the surface was then increased in a number of steps. The vapour film remained stable right up to 210°C when boiling started, with a character resembling transition boiling. This persisted up to 350°C. At 210°C transition boiling would normally be expected so from this point of view contact is not surprising. However, we were not aware of any disturbance that might account for the change in behaviour (other than the increase in temperature).

The second run, shown in Fig. 2, is a cooling run. Starting at 245°C and coming down to 216°C transition boiling was observed. On further decreasing the surface temperature, the heat flux fell and at 180°C evolution of bubbles stopped. The surface contact readings were entirely consistent, becoming zero at 180°C. This behaviour persisted down to 125°C. When the set temperature was reduced a further 5°C, normal nucleate boiling appeared.

At the end of the series of tests, the apparatus was dismantled and the liquid contact angle on the aluminium surface measured at 26–27°. The contact angle was not measured before the boiling runs but an identically prepared fresh surface before any boiling measurements, gave a contact angle of around 45°.

At constant surface temperature and without disturbance the unusual vapour film was stable. Towards the bottom of the temperature range examined, disturbances, such as removing the condenser and the bulk liquid electrode, frequently resulted in the reappearance of boiling and vapour bubbles. This boiling tended to be very bumpy in character and frequently the stable vapour film re-established after a minute or so. At higher surface temperatures, the vapour film was even more stable. In one cooling run, it persisted at a surface temperature of 150°C for over 15 min, during which time the condenser and electrode were removed and replaced twice. Only when the vapour film and the boiling surface were touched with a soft brush did bubbles appear and boiling restart.

Immediately the stable vapour film appears, the bulk water temperature is close to saturation but after a few minutes it settles down. In various runs, bulk water temperatures ranging from 82 to 86°C were measured.

Initially there was some doubt as to whether this low bulk temperature could be consistent with a liquid–vapour interface at 100°C (although bulk temperatures in Leidenfrost drops as low as 10°C below saturation are mentioned in ref. [9]). Accordingly a subsidiary experiment was performed where the metal surface temperature was controlled at 100°C (i.e. no boiling or vapour layer present). The steady-state bulk temperature was 77°C. Given that an interface that is free to move (and was observed to be moving) will provide better heat transfer than a solid metal surface the measurement is quite consistent with a 100°C liquid–vapour interface.

Since the heat flux through the vapour film was measured it is possible to estimate the thickness of the film. The contribution from natural convection can be estimated from work on two solid horizontal surfaces separated by a gap [12]. For Grashof numbers, based on gap width, of less than 1700 the effect of natural convection is negligible. The Grashof numbers for the vapour film were 0.05 or less. The amount of radiant heat transfer was calculated from the temperature of the solid surface and the liquid–vapour interface, and subtracted from the measured heat flux. The contribution of radiation was never more than 10%.

Since no information was available (other than viewing the vapour film with the naked eye) as to the uniformity or otherwise of the thickness the remaining heat transfer was assumed to be due to conduction across a uniform film. The calculated film thickness ranged from about 0.067 mm at low temperatures (30 K wall superheat) to about 0.24 mm at high temperatures (100 K superheat). These values are of the same order as the estimates of thickness mentioned in the introduction.

Measurements of temperature at several radial positions 3 mm below the boiling surface showed a maximum temperature difference of about 4 K during high heat flux nucleate boiling. Therefore, it is reasonable to assume one-dimensional heat flow in the calculation of the surface temperature of the aluminium block.

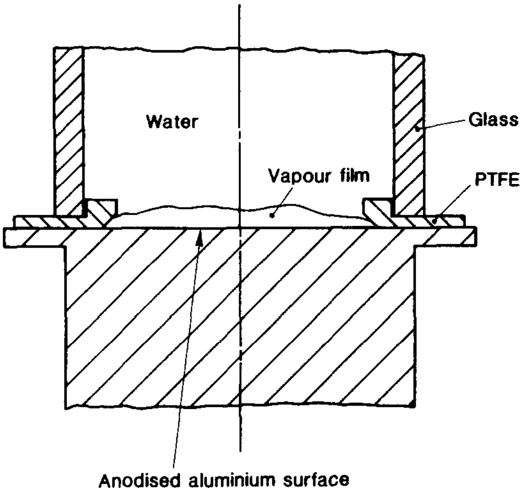
DISCUSSION

This effect, that is the appearance of a stable vapour film covering the heat transfer surface without vapour bubbles detaching, has still only been observed a few times and it is not clear what conditions are required to establish the film. Certainly a large number of tests have been conducted where the geometry of the boiling surface was very similar, the liquid the same (water) and the metal substrate the same (aluminium) and yet there was no sign of this unusual vapour film. These tests covered both anodized and polished surfaces, large and small contact angles, and steady-state and transient heat transfer. Also, a few tests have been conducted where the procedure was, as far as possible, identical to that described in the main body of this paper and the unusual vapour film did not appear. When methanol is used as the test liquid, the effect has never appeared. Also, with a very similar boiling geometry and a copper surface, the effect has never appeared.

It does seem to be necessary to heat the surface up to a temperature above the critical heat flux temperature, i.e. to somewhere in the transition boiling region, before the stable vapour film appears. The apparatus was designed to give good temperature control in the transition region during steady-state tests and does, in fact, perform rather better than previous equipment. It is possible that this is significant, i.e. the larger temperature fluctuations present in the transition region previously prevented the early stages of formation of the stable vapour film.

The diameter of the boiling surface itself is 25.8 mm but the smallest diameter of the PTFE ring is 22.9 mm (see Fig. 3). These dimensions are less than the most dangerous wavelength for the development of interfacial waves ($\lambda_D = 27.2$ mm for saturated water at 1 atm). It seems likely that on a much more extensive surface these waves would be able to grow unhindered and this unusual stable vapour film would be impossible. This would explain why the effect is not observed with methanol ($\lambda_D \simeq 17.2$ mm). These results are consistent with Patel and Bell's [3] observation of break through in Leidenfrost drops, though the present results are quite different in that there is no escape of vapour from beneath the liquid. Discussion of the stability of Leidenfrost drops [10, 11] seems to relate to vibrations at high temperatures rather than collapse at low temperatures.

The stable vapour film obviously bears considerable resemblance to the vapour film in film boiling but with the differences that it is observed at lower temperatures and there are no vapour mushrooms that detach from the film. A possible explanation of the nature of the film is that it is stabilized by attachment



ıG. 3. Possible explanation of stability of the vapour film. It is attached at its periphery by a line of three-phase contact.

at its circumference to the solid surface, as shown in Fig. 3. The dimensions of the surface are too small for interfacial waves to develop into the vapour mushrooms typical of film boiling. The stability of the film over very long periods of time suggests that an equilibrium situation with constant film thickness is reached. If the liquid comes too close to the heat transfer surface, contact is prevented by rapid vapour generation. In regions where the gap is larger, vapour condenses on the subcooled liquid, so there is no net vapour generation. This explanation requires a large temperature drop between the boiling heat transfer surface and the stabilizing line of three-phase contact, i.e. the solid material confining the boiling region should be a fairly poor thermal conductor. Also, probably, a non-zero contact angle is needed to prevent liquid spreading over the sealing material and thus reaching the boiling surface.

It might seem, assuming that this interpretation is correct, that the effect is no more than an oddity. However, the subjects of film boiling, transition boiling and film boiling collapse are of considerable interest, with their implications for various quenching phenomena including vapour explosions. If this stable, non-boiling, vapour film could be set up in a reproducible way, then its stability could be studied. For example, the size of pressure pulse needed to collapse it could be measured. This could well improve basic understanding of these phenomena.

CONCLUSION

An apparently novel type of two-phase heat transfer, where pool boiling on a horizontal upward facing surface stops and is replaced by a stable vapour film, is described.

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TRANSFERT THERMIQUE A TRAVERS UN FILM DE VAPEUR SANS EBULLITION

Résumé—On décrit des mesures sur la courbe d'ébullition stationnaire de l'eau. Fréquemment quand la température est telle que l'ébullition de transition est possible, un film stable de vapeur se forme à la place. Ce film de vapeur est différent de celui de l'ébullition en film car aucune bulle de vapeur s'en détache. L'existence du film de vapeur est confirmée en utilisant une technique qui mesure le contact liquide–solide.

WÄRMEDURCHGANG IN EINEM DAMPF-FILM OHNE BLASENABLÖSUNG

Zusammenfassung—Die Dampfdruck-Kurve von Wasser wird für stationäres Behältersieden vermessen. Bei Oberflächentemperaturen, die eigentlich Übergangs-Sieden erwarten lassen, bildet sich stattdessen häufig ein stabiler Dampffilm. Aus dem Dampffilm lösen sich—anders als bein Filmsieden—keine Dampf-Blasen ab. Das Vorhandensein des Dampffilmes wird durch Messung des Kontaktes von Feststoff und Flüssigkeit nachgewiesen.

ПЕРЕНОС ТЕПЛА ЧЕРЕЗ ПАРОВУЮ ПРОСЛОЙКУ ПРИ БЕСПУЗЫРЬКОВОМ КИПЕНИИ

Аннотация—Описываются измерения при установившемся кипении воды в большом объеме. В определенных условиях, когда температура поверхности соответствует режиму переходного кипения, на ней образуется устойчивая паровая прослойка, которая отличается от пленки при пленочном кипении отсутствием отрыва пузырьков. Существование паровой прослойки подтверждается измерениями по методу контакта жидкость–твердое тело.