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The non-boiling vapour film

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Abstract—The stable, non-boiling, vapour film on a horizontal, confined, surface reported earlier is investigated in more detail. The film is curious in that, unlike normal film boiling, no vapour bubbles detach. New measurements have established a reproducible method of generating the film and the dependence on subcooling and linear surface dimension. The film thickness is measured. The heat transfer behaviour is very similar to that of normal film boiling but there are experimental advantages in being able to study a film free of large-scale disturbances.

INTRODUCTION

RECENTLY an apparently novel type of two-phase heat transfer was described [1]. In pool boiling of water on a horizontal, upward facing, confined surface, in the surface temperature range where film or transition boiling would be expected, instead a stable vapour film appeared (Fig. 1). This vapour film was strikingly different to that of film boiling on a horizontal surface since no vapour mushrooms appeared and no vapour bubbles detached. In fact there was no escape of vapour from the surface, and once the system had settled down, no evidence for any net generation of vapour. The existence of the vapour film was confirmed by measurement of electrical impedance across the film. Estimates of film thickness based on the measured heat flux and an assumption of heat transfer by conduction through the vapour were consistent with literature estimates for the thickness of vapour films under Leidenfrost drops.

However, a number of aspects of this novel phenomenon were unclear. For a start, no entirely consistent method of generating the film had been found. Although the stable vapour film appeared a number of times there were also runs where it did not appear. When a different research worker attempted to reproduce the results he, initially at any rate, failed. It was clear that a much more systematic study was required.

One difficulty was that it seemed that a large number of different factors might be significant. The small diameter of the confined boiling surface, comparable to the most dangerous wavelength, λ_D, for disturbance of the liquid–vapour interface, was considered important in preventing the formation of the vapour mushrooms typical of film boiling. The wavelength is given by

$$\lambda_D = 2\pi \left[\frac{3\sigma}{g(\rho_L - \rho_V)} \right]^{1/2} \quad (1)$$

where σ is the surface tension, g the acceleration due to gravity and ρ_L and ρ_V are liquid and vapour density, respectively. This formula applies strictly to small amplitude waves on an infinite surface. However, the spacing of the vapour mushrooms detaching from the interface in normal film boiling is found in practice to be close to λ_D and it is assumed that the same parameter is relevant in confined geometries [2].

Also it was noticed that once the stable vapour film formed the bulk liquid temperature slowly fell to about 15 K below saturation. However, there was no method of controlling the subcooling. It is worth noting that in very different geometries, sphere and horizontal wire, Toda and Mori [3] found that at high subcoolings vapour bubble release was suppressed. Gross fluctuations in the position of the liquid–vapour interface persisted however.

At the periphery of the vapour film (Fig. 1) the liquid–vapour interface touches the solid surface of the sealing ring. It was considered that it was important for the liquid to have a non-zero contact angle here, otherwise surface tension would tend to pull the liquid down onto the boiling surface. In the previous

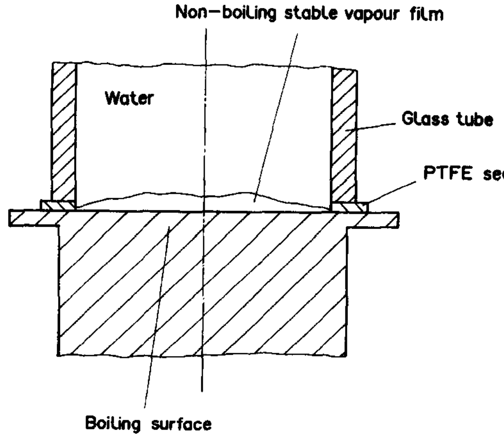

FIG. 1. The non-boiling vapour film (unevenness of film exaggerated).

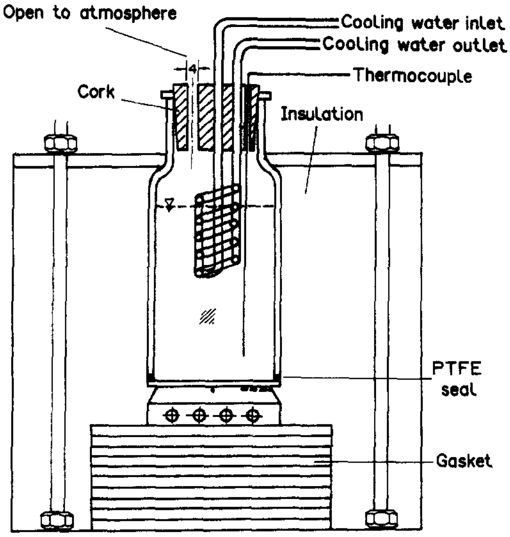

FIG. 2. Apparatus for the pool boiling tests.

measurements [1] a pre-formed PTFE seal was used. Given the requirements of large contact angle, not too high thermal conductivity (to prevent boiling on the surfaces of the seal or glass) and resistance to high temperatures there seemed to be no reason to change the material.

Consequently PTFE seals were used throughout but made in the laboratory by cutting circles (or squares, as appropriate) out of 2 mm thick sheet.

So a programme of experiments was set up in which the linear dimension of the surface ranged from 18.65 to 40 mm (λ_D for water = 27.2 mm) and the subcooling ranged from 0 to 20 K. Also measured, but not directly controlled, was the contact angle of the water on the boiling surface. In addition to the heat transfer measurements the thickness of the vapour film was measured from its electrical capacitance. Details of this are given in the next section.

Subsequently it became clear that one of the more interesting properties of the stable, non-boiling, vapour film is that its heat transfer properties are very similar to those of normal film boiling. This suggests that by this technique it is possible to isolate and study the aspect of film boiling that controls the heat transfer rate—the thin vapour film on the surface—without the complication of detaching vapour bubbles.

APPARATUS

The test surface and the glass boiling vessel are shown in Fig. 2. Subcooling is controlled by a small heat exchanger coil with variable water flow rate and variable depth of immersion. Fibre glass insulation, 10 cm thick, is used. For saturated boiling experiments a condenser is used to condense the vapour escaping from the glass boiling vessel and return it as liquid. The bulk water temperature is measured by a thermocouple, located 1.5 cm above the boiling surface.

Details of three of the test sections, made of commercially pure aluminium, are shown in Fig. 3. The circular boiling surfaces have diameters of 40, 26 and 18.65 mm (some earlier measurements were made on a 15.5 mm diameter surface without direct control of subcooling). Square test sections of boiling sides 40, 30 and 20 mm were also used. The number of Watlow cartridge heaters (each 240 V, 250 W, 38 mm effective length and 3.2 mm diameter for the larger surfaces and 150 W, 32 mm long and 6.2 mm diameter for the smaller surfaces) is sufficient to surpass the critical heat flux in the steady state since the entire boiling curve was measured (but not reported in this paper).

The controlling chromel–alumel thermocouple (Phillips type TKA) is of the sheathed type, 0.5 mm in diameter with a 0.01 s time constant, soldered to the bottom of a 1 mm diameter hole located 3 mm below the centre of the boiling surface. Other similar thermocouples are also used at the same depth (Fig. 3). To find the surface temperature all readings are averaged and allowance made for one-dimensional heat conduction to the surface. To improve thermal contact a tin–zinc solder is used (Fry's Metals No. 703) which is solid below 199°C and fully liquid above 310°C. To prevent electrical interference with the thermocouple signals both the temperature controller and test section are earthed.

The rest of the equipment is shown in Fig. 4. A Eurotherm temperature controller of the logic output type with a 0.1 s cycle time, model 820, is used. To obtain good control throughout the boiling curve it is necessary to adjust the full on power of the heaters to about twice the required average power; this is done with a variable a.c. transformer. Power consumption is measured by a standard kWh meter (GEC Measurements, type C11B2, 5 A for the smaller test surfaces and a similar 80 A meter for the larger surfaces). A comparison between results obtained with this method and an alternative method using the total on time of the heaters showed agreement to within 3% [4]. For each test section heat losses were measured as a function of temperature with the boiling surface covered with insulation.

The electrical capacity of the vapour film (when present) is measured with a universal bridge, type TF2701, from Marconi instruments, at a frequency of 1 kHz, using screened leads. One connection is made to the metal base of the test section and the other consists of a pure aluminium wire 1 mm in diameter ending in a flat spiral around 1 cm diameter held in the water 1 cm above the heat transfer surface, as shown in Fig. 4. Since the capacitance measured is small other sources of capacitance, i.e. the thermocouple and heat exchanger, are removed for the short time it takes to use the bridge. The bridge is balanced manually. Capacitance values over the range 15–45 pF were measured. The impedance of the bulk water is very low compared with the impedance of the vapour film. Film thickness d is calculated using

$$d = k\varepsilon A/C \qquad (2)$$

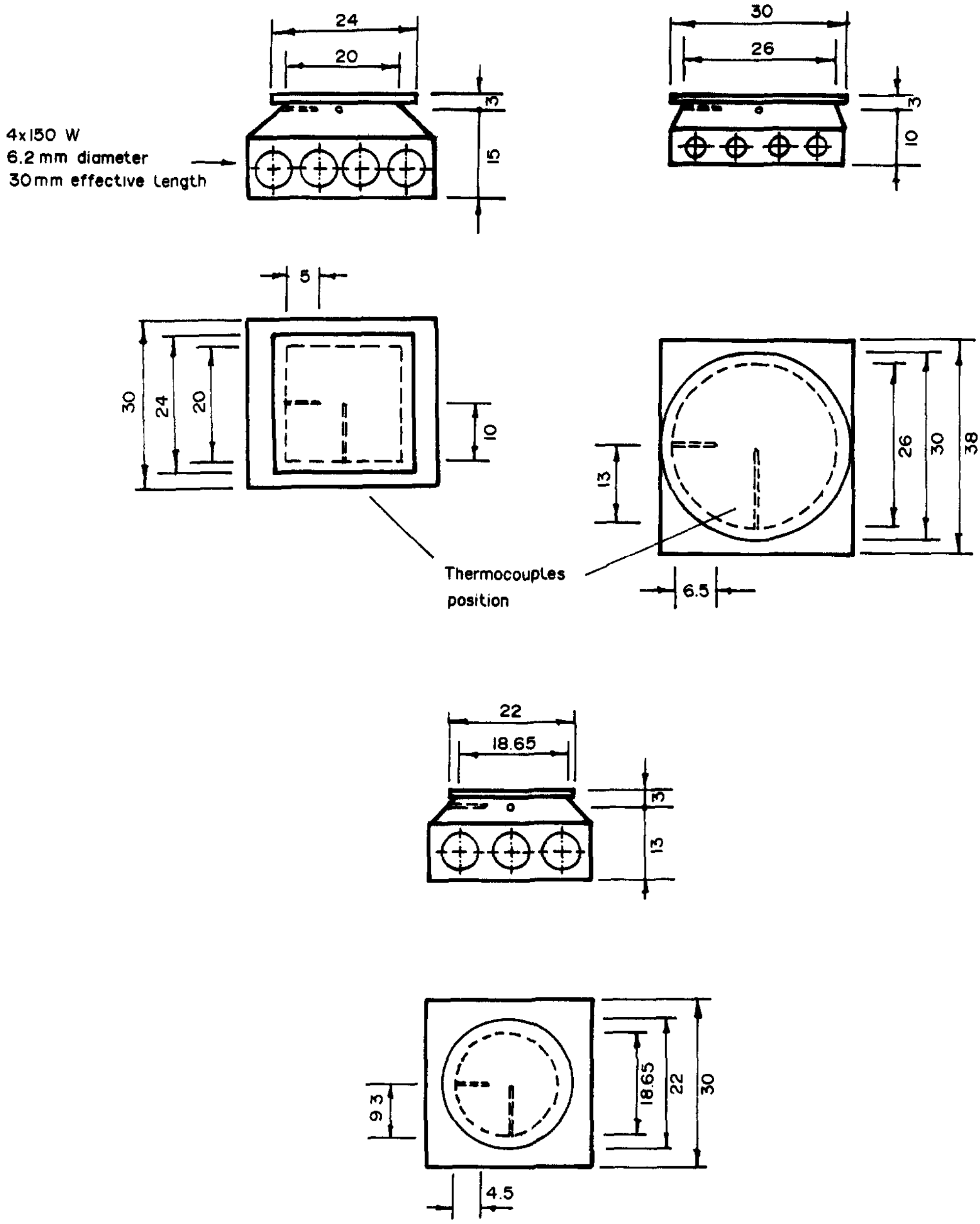

FIG. 3. Details of test section construction for the cases where the non-boiling vapour film appeared.

where $k = 1.01$ is the dielectric constant of steam [5], $\varepsilon = 8.85 \times 10^{-12}$ F m^{-1} the permittivity of free space, A the area of the boiling surface (m^2) and C the capacitance (F).

The electrical impedance technique used to detect liquid–solid contacts described in ref. [6] was also used but not shown in Fig. 4; when the stable vapour film was present liquid–solid contact was invariably zero. The technique of ref. [6], while adequate to detect the electrical current flowing into the heat transfer surface when the surface is, in part at least, in direct contact with the water, is not sufficiently sensitive to measure the very high impedance of the vapour film.

A separate set of measurements on one particular stable vapour film using a Frequency Response Analyser confirmed that the impedance of the system was dominated by the capacitative impedance of the film.

The aluminium boiling surface is prepared by polishing with emery paper grade 800, washing with acetone and then washing with deionized water. The liquid contact angle is measured at room temperature by placing water drops on at least two locations and observing the drops through a travelling microscope with a protractor eyepiece. The heat transfer experiment starts by heating in the absence of water to

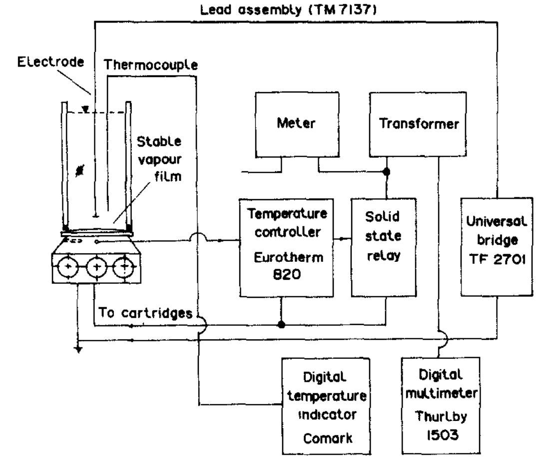

FIG. 4. Associated equipment for controlling temperature, measuring heat flux and measuring vapour film thickness.

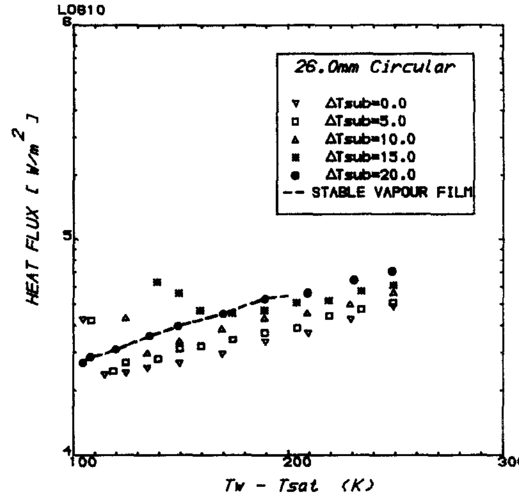

FIG. 5. Boiling curves on 26 mm round surface. The stable vapour film only appears at the highest subcooling.

350°C, keeping the temperature at that level for 5 min and then deionized water is slowly poured in. Once all the water has been added it is allowed to boil for 15 min to de-gas. Next the heat exchanger is introduced. This causes some disturbance of temperature but after about 20 min steady conditions are reached with the surface temperature returning, under controller action, to 350°C. Subcooling can now be kept constant to within about ± 1 K. A series of steady-state measurements are then made by step reductions in the set temperature on the controller.

RESULTS

In the majority of tests the stable vapour film did not appear. The difficulty of obtaining the stable vapour film on large surfaces and at zero subcooling was confirmed. With the given surface preparation and normal experimental technique the contact angle varied over the range 63°–74° before the boiling measurements and 59°–65° afterwards. When a surface (which had previously shown the stable vapour film) was aged by boiling at a surface temperature of 120°C for 8 h the contact angle fell to zero, the surface became discoloured and the stable vapour film could no longer be obtained.

Examples of the boiling curves are shown in Fig. 5 for the 26 mm round surface and in Fig. 6 for the 20 mm square surface. A curious feature of the boiling curves is that it is impossible, just by looking at trends in the film boiling region, to detect that the stable, non-boiling, vapour film is present. Observing the boiling process itself there is no difficulty—there are no vapour bubbles detaching—but relying simply on the heat flux vs surface superheat measurements the only odd feature when the stable vapour film is present is that the film boiling region seems to extend to rather low superheats and heat fluxes. In each of the figures the unusual stable vapour film only appears in the range below about 200 K surface superheat and for the highest subcooling. On the graphs the results for the stable vapour film appear as a smooth continuation of the trend, either from higher surface superheats for constant bulk subcooling, or from lower subcoolings at constant surface temperature.

For all the runs where subcooling was controlled the temperature limits of the stable vapour film were fairly constant at from around 80 K superheat to around 200 K superheat, i.e. occupying a substantial part of the region where one would expect transition boiling and some of the film boiling region. In Fig. 5 (by extrapolation from lower superheats) it seems that the upper temperature limit is close to where the minimum film boiling point would be expected. However, in Fig. 6 the stable vapour film extends well into the region where film boiling would be expected. In Fig. 7 the results of all runs are plotted on a graph of bulk subcooling vs dimensionless length, showing the boundary of the stable vapour film region. This graph includes some earlier results for a 15.5 mm diameter

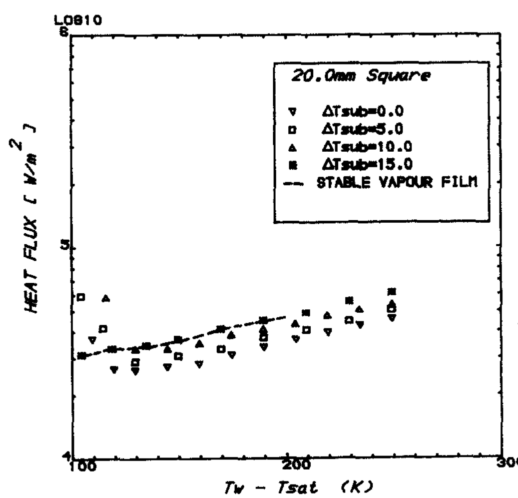

FIG. 6. Boiling curves on 20 mm square surface.

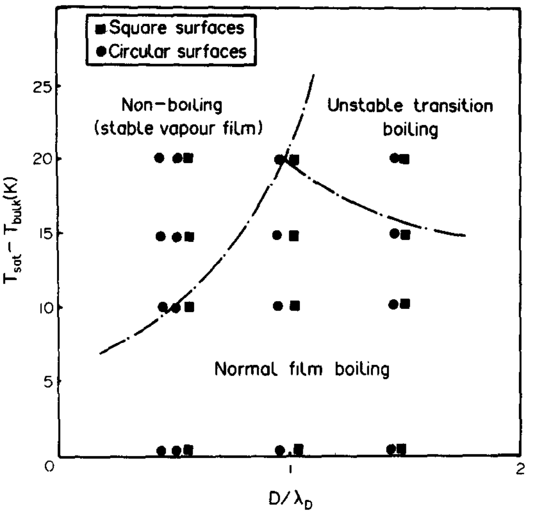

FIG. 7. Stability limits for the stable, non-boiling, vapour film.

surface (the smallest value of D/λ_D shown in the figure) where the subcooling was not controlled, i.e. varied with surface temperature, but the system nonetheless was at equilibrium for each measurement. For the 15.5 mm diameter surfaces, measurement extended to 35 K subcooling; the stable vapour film was still present. At low subcoolings the stable vapour film is replaced by normal film boiling and at high subcoolings and diameters by an unstable type of transition boiling.

As mentioned earlier the subcooling, as measured at the thermocouple position, could be kept constant to within ± 1 K. During some runs extra measurements were made by changing the vertical position of the thermocouple. The depth of water was about 10 cm. Measurements extended over the region from 0.5 cm above the solid heat transfer surface to 1 cm below the upper water surface. It was decided not to approach closer than 0.5 cm to the solid surface for fear of disturbing the vapour film.

Very little variation of temperature was found. At higher surface superheats distinct natural convection circulation could be seen in the water; the only variation of temperature was an increase of about 1 K near the heated surface of the test section. At lower surface superheats the natural convection circulation could no longer be seen; the only variation of temperature was a decrease of about 1 K near the upper water surface. In addition the stable vapour film appeared in preliminary runs where the bulk water was cooled simply by exposure to room air on the unlagged sides of the glass vessel, so the exact method of obtaining the subcooling and precise temperature distribution do not appear to be critical.

Figure 8 shows the measured vapour film thickness for all the runs where the subcooling was controlled and the stable vapour film appeared. The thickness increases with surface superheat but does not vary much with geometry or size of surface. Knowing the

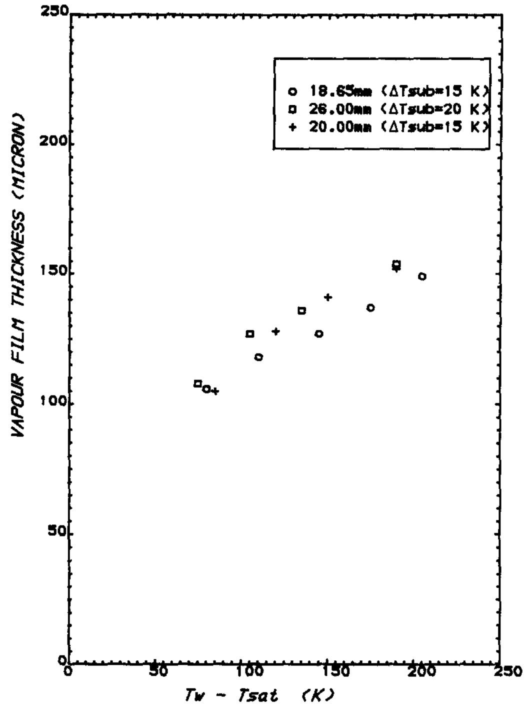

FIG. 8. Measured vapour film thickness.

thickness of the vapour film the rate of heat conduction Q_{cond} through it can be calculated from the measured solid surface temperature and assuming that the liquid–vapour interface is at saturation temperature. In Fig. 9 this is compared with the experimentally measured heat flow rate Q_{exp}. Clearly the dominant heat transfer process through the vapour film is conduction. The contribution from radiation has been calculated and, for realistic values of the emissivities, is less than 1%. So a small convective contribution appears possible, which is consistent with the observed movement of the liquid–vapour interface and of the bulk liquid. As the surface tem-

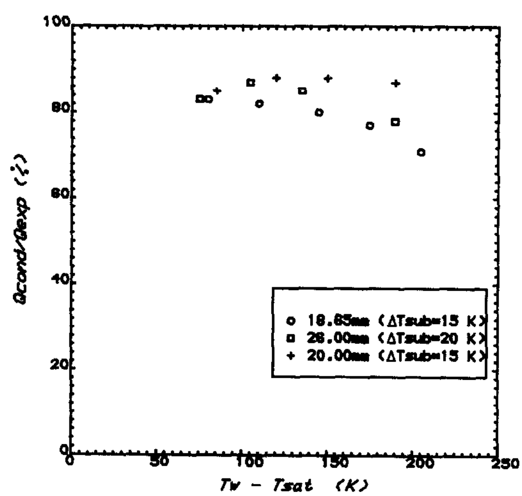

FIG. 9. Proportion of heat transferred through the stable vapour film by conduction.

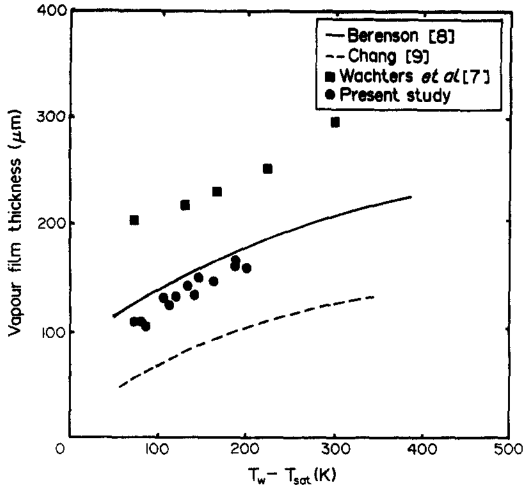

FIG. 10. Comparison of present film thickness measurements with other values in the literature.

perature increased, i.e. as the normal film boiling region was approached, a waviness was observed in the stable vapour film, consistent with an increased convective component and the trend in Fig. 9. The measurements of Toda and Mori [3] with a different geometry (wire) and different method of measuring film thickness (laser beam) generally relate to a very unstable vapour film and give Q_{cond}/Q_{exp} values of around 0.5. However, extrapolated to higher subcoolings they are consistent with Fig. 9.

DISCUSSION

In Fig. 10 the present experimental results are compared with various other experimental results [7] and with various theoretical predictions [8, 9] for normal film boiling. The experimental results [7] relate to a Leidenfrost drop (of water) on a hot, horizontal, plate. It is interesting to see that there is a degree of agreement in spite of the different geometries and the fact that in normal film boiling the vapour mushrooms grow and detach from the surface. The present measurements appear to be the only ones on extended surfaces (rather than drops or wires). Although the present measurements relate to the stable vapour film the trends in Figs. 5 and 6, mentioned earlier, show that the heat transfer behaviour is virtually the same as in normal film boiling.

Although measurements were not made over a particularly wide range of boiling surface contact angle and only a single material was tried for the sealing ring, it is now reasonably clear what the controlling factors are in the existence of the stable non-boiling vapour film. With all the factors listed it becomes clear as well why the effect has apparently not been observed before. High contact angle and low thermal conductivity are needed for the material of the sealing ring to prevent liquid being drawn down to the boiling surface and to prevent boiling occurring on the other confining surfaces. The confined geometry itself is needed to stabilize the liquid–vapour film by attachment to the solid surface at the periphery. Figure 7 suggests that subcooling of the bulk liquid is needed to suppress the growth of vapour mushrooms into the bulk and allow removal of heat from the liquid vapour interface. Also if the diameter of the boiling surface is too high then the waves in the liquid–vapour interface can grow regardless of the attachment of the liquid–vapour interface at the edges. If the contact angle the liquid exhibits on the solid surface is zero then chance contacts will allow the liquid to spread and the vapour film is disrupted (such contacts are probably inevitable when the system is being set up). If, in addition, the surface is significantly contaminated with a layer of low thermal conductivity material then the interface temperature following chance liquid–solid contact is that much lower and the area and duration of contacts increases [10, 11].

Figure 10 and, particularly, the boiling curves such as Figs. 5 and 6, suggest strongly that the heat transfer processes occurring in the stable, non-boiling vapour film are the same as those controlling the heat transfer rate in normal film boiling. However, the stable vapour film is much more convenient to study experimentally since the disturbance caused by the departure of the vapour bubbles is prevented.

Although this paper is mainly concerned with the properties of the stable, non-boiling vapour film, it is interesting to note that the results (e.g. Figs. 5 and 6), most of which relate to normal film boiling, show the expected trends of increasing heat flux and increasing surface temperature at the minimum film boiling point as the subcooling is increased (e.g. refs. [3, 12–14]).

CONCLUSIONS

The rather restrictive conditions for the existence of the stable, non-boiling, vapour film have been investigated and defined.

Thickness measurements on the film show that heat transfer through it is mainly by conduction.

The film has the useful property that it may be regarded as a model, from the heat transfer point of view, of the behaviour in normal film boiling but without the complication of regular disturbance of the film due to departing vapour bubbles.

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LE FILM DE VAPEUR SANS EBULLITION

Résumé—Le film de vapeur stable, sans ébullition sur une surface horizontale, confinèe, qui a été décrite antérieurement est étudiée plus en détail. Le film est curieux en cela qu'aucune bulle de vapeur s'en détache, contrairement à l'ébullition normale en film. De nouvelles mesures ont établi une méthode reproductible de génération du film et la dépendance entre le sous-refroidissement et la dimension linéaire de la surface. L'épaisseur du film est mesurée. Le comportement du transfert thermique est très semblable à celui du film en ébullition normale, mais avec l'avantage d'un film sans perturbation à grande échelle.

DER NICHTSIEDENDE DAMPFFILM

Zusammenfassung—Der stabile, nichtsiedende Dampffilm auf einer begrenzten horizontalen Oberfläche, über den bereits früher berichtet worden ist, wird hier genauer untersucht. Die Besonderheit dieses Films ist, daß sich keine Dampfblasen von ihm ablösen—im Gegensatz zum gewöhnlichen Filmsieden. Mit neuen Messungen wird eine reproduzierbare Methode zur Erzeugung solcher Dampffilme gefunden, außerdem die Abhängigkeit der Filmbildung von der Unterkühlung und der Abmessung der Heizfläche. Die Filmdicke wurde gemessen. Das Wärmeübergangsverhalten ist demjenigen bei gewöhnlichem Filmsieden sehr ähnlich. Es bietet aber experimentelle Vorteile, einen Dampffilm untersuchen zu können, der frei ist von größeren Störungen.

ПАРОВАЯ ПЛЕНКА ПРИ ОТСУТСТВИИ КИПЕНИЯ

Аннотация—Более детально исследуется устойчивая паровая пленка на горизонтальной поверхности в замкнутом объеме при отсутствии кипения. Характерная особенность состоит в том, что, в отличие от обычного пленочного кипения, в данном случае не происходит отделения пузырьков пара. Проведенные исследования позволили разработать воспроизводимый метод создания пленки, а также установить роль в этом процессе недогрева и линейных размеров поверхности. Измерена толщина пленки. Характер теплопереноса идентичен случаю обычного пленочного кипения, но преимуществом является то, что эксперимент позволяет проводить исследование пленки при отсутствии крупномасштабных возмущений.