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SUB-COOLED FILM BOILING ON HORIZONTAL CYLINDERS*

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Abstract—Data are presented for sub-cooled, pool, film boiling on horizontal tubes of diameters approximately 3, 6 and 13 mm, in water with surface temperatures from 540 to 880°C and in ethanol with surface temperatures from 250 to 370°C. Comments are made on the appearance of the flow pattern.

INTRODUCTION

FILM boiling occurs when a liquid comes into contact with a surface whose temperature is considerably higher than its boiling point. A layer of vapour develops between the liquid and the surface, considerably reducing the flow of heat. When the situation is that of a hot body immersed in a tank of fluid at rest, the term "pool boiling" is used. The further qualification "saturated" or "sub-cooled" may be added when the bulk temperature of the liquid is respectively at or below its boiling point.

This paper is concerned with sub-cooled, pool, film boiling. It occurs in the process of metallurgical quenching, and is of considerable interest and importance since it is a relatively slow mode of heat transfer, whereas the purpose of quenching (in general terms) is to produce rapid cooling. Much attention has accordingly been directed towards the phenomenon from a metallurgical standpoint. A great many tests have been made and standardized procedures devised, but in the main these have been concerned with the resulting metallurgical properties of the specimen in relation to its composition and size, its initial temperature, the nature and temperature of the quenching fluid, and so on; they usually afford little useful information about the heat transfer process itself. The nearest approach to a direct study of the heat-transfer aspect of quenching has taken the form of the so-called "silver ball' test [1] in which the temperature of a standard object is continuously recorded as it is quenched under the conditions of interest. This produces a "cooling curve" from which heat transfer data may be deduced. Since the temperature changes rapidly, and the film boiling regime occurs at the beginning of the test when the fluid may be still disturbed by the entry of the hot body, the resulting data are of rather limited value.

Many investigations specifically directed towards heat transfer in film boiling, as an object of interest in itself, have been reported in recent years, but the great majority have been concerned with the situation where the bulk temperature of the liquid is at (or very near to) the boiling point; a survey paper on this topic has been published by Jordan [2], and an earlier paper by Breen and Westwater [3] also includes a useful review of the literature. The comparative simplicity of the flow patterns obtained in steady pool film boiling, in contrast to, for example, the complexity of nucleate boiling, has led to a considerable interest in the phenomenon from an analytical standpoint, and a number of workers have extended their analyses to include the effect of sub-cooling [4–8]. Very few experimental studies have, however, been made on film boiling at significant degrees of sub-cooling.

The experiments now reported were designed to obtain heat transfer data for steady-state film boiling, at a substantial degree of sub-cooling, in liquids whose physical properties were reliably known for both the liquid and vapour phases. Practical considerations led to the choice of electrically heated horizontal cylinders of small diameter, immersed in water and ethanol. It was considered that tests in water at the three surface temperatures of about 880, 710 and 540°C would adequately cover the range of metallurgical interest (corresponding respectively to immersion, the start of transformation, and the "nose" of the transformation curve). The tests in ethanol were planned subsequently, with a view to comparative analysis of heat-transfer data rather than direct application to quenching, and surface temperatures of 370, 310 and 250°C were chosen to give approximately the same dimensionless parameters as in the tests in water.

EXPERIMENTAL DETAILS

In exploratory experiments, a test-piece made of a straight length of stainless steel tubing about 2·5 mm dia and 150 mm length was used. It was heated by the direct conduction of electricity, and supported in a horizontal position by the two current terminals. A thermocouple insulated with quartz-fibre sheathing was fitted inside the tube. Film boiling was established by first heating the test piece in air to above the Leidenfrost temperature, and then immersing it in a bath of water, simultaneously increasing the current, in the manner described by Kovalev [9]. With test pieces of this type it was found that operating conditions were

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limited to surface temperatures in the region of 700°C and water temperatures above about 90°C. At much higher surface temperatures the stainless steel corroded badly and the thermocouple burnt out; at much lower surface temperatures, and at water temperatures less than about 90°C, local cooling at the terminals resulted in the development of local nucleate boiling, which quickly spread over the rest of the tube. To prevent this, two ceramic collars were attached around the tube near each terminal, as recommended by Nishikawa [10]. It was then possible to obtain stable film boiling in the region between the collars at a surface temperature of 700°C in water at a bulk temperature of about 75°C.

These experiments led to the development of the test-pieces used for the remainder of the work. They were made in the shape of a wide "U" so that the terminals and short vertical lengths of tube remained above the liquid surface during the tests; this avoided the development of local nucleate boiling at the terminals. They were constructed from a nickel–chromium alloy which had much better resistance to corrosion, and thermocouples of the mineral-insulated metal-covered type were used, further insulated from the test-piece by silica-fibre sheaths. The sensing junctions of the thermocouples were positioned approximately in the middle of the horizontal section, which was at least 10 diameters long and usually longer, so that the data may reasonably be taken as applicable to horizontal cylinders of indefinite length. The thermocouples were located by means of ceramic and asbestos bushes, and were put into position before bending the tubes. It was found necessary to make the radius of the bends at least 40 mm to avoid a tendency for film boiling to break down at that point. The test pieces were held in position by clamping the ends into closely fitting grooves in the ends of the current terminals, which were made from copper and brass and were nickel-plated to prevent corrosion. Potential leads were welded to each end after it had been clamped in place in such a way that, during the test, they remained slightly above the surface of the liquid. Three sizes of tube were used: 3·17-mm O.D. with 0·25-mm wall thickness; 6·35-mm dia with 0·30-mm or 0·51-mm wall thicknesses; and 12·7-mm dia with 0·51-mm wall thickness. These will be referred to as the 3-, 6- and 13-mm cylinders respectively.

The immersion apparatus consisted of a gantry and movable cross-member to which the current terminals were fixed, and which could be raised and lowered by means of a lever. The tests with water were made in tanks of various capacities from 45 to 90 l, so that the change in the bulk temperature of the liquid in the course of a single test was insignificant. The ethanol tests were carried out in a 45-l tank; the level of ethanol was maintained at about 70 mm below the top, and gaseous carbon dioxide was fed steadily into the free space to prevent ignition.

The heating current was taken from a fixed transformer, rated at 16 V, 250 A, driven by a variable transformer which enabled the heat dissipated to be varied between zero and maximum. Much higher currents could be taken for short periods.

The heating rate was measured between the potential tappings by means of a current transformer and wattmeter. The temperature of the bulk liquid was measured by thermocouple, positioned at about the same level as the horizontal section of the test-piece, and 12 mm from it.

The liquid was brought to the temperature required and stirred thoroughly. The test-piece was heated in air to approximately the surface temperature required for the test; it was then immersed, and at the same time the heating rate was increased and adjusted with precision to give the required surface temperature. Readings were taken of the surface and bulk liquid temperatures, and the rate of heat dissipation. The simple open-tank apparatus enabled readings to be taken to within half to one degree of the boiling point of the liquid. High heat losses prevented the temperature of the liquid being maintained nearer to the boiling point. Special efforts were made to enable results to be taken very close to the boiling point for the 6-mm dia test-piece in water. These involved using two tanks, the outer one containing water which was kept boiling; the tanks were covered to reduce evaporation.

When the temperature of the bulk liquid was within about 10 K of the boiling point it was possible to take readings for all three surface temperatures from one immersion. At lower bulk temperatures it was necessary to take from each immersion a set of readings for one surface temperature only, because temperature stratification quickly developed in the liquid. Normally a set of readings could be taken within one minute of immersion.

The bulk temperature was measured just before immersion, and if there was any significant change from this value when the surface temperatures were taken the whole set was discarded. The problem was particularly acute when the liquids were cold, because a well-defined circulation would develop in a matter of seconds. To suppress this, two vertical plates were positioned parallel to the tube and about 6–12 diameters apart. They extended along the whole length of the test-piece, to about 12 mm below it, and to within 6 mm of the surface. Even so, to get a reliable set of readings in a cold liquid it was necessary to ensure that, on immersion, the surface temperature was within about 5 K of the required value, and that the rate of power generation was set to the correct value immediately. To achieve this, a few preliminary runs were usually necessary.

The method used to establish film boiling was not completely reliable at high subcooling in water. It was necessary to synchronise rather precisely the immersion of the test-piece and the increase in the heating rate, so as not to allow the surface temperature either to fall below the Leidenfrost point or to exceed the melting point of the metal. This was somewhat less critical for the test-pieces made from the thicker-walled tubing, probably because of the higher thermal capacity.

On occasion, film boiling would be replaced locally by nucleate boiling, which would then spread over the whole test-piece. This could start almost anywhere. The cause was not fully established, but it seemed beneficial to clean the tube periodically with a very mild abrasive. The speed at which nucleate boiling spread was found to increase as the temperatures of the surface and the bulk liquid were reduced; the chance of breakdown occurring also increased. The resulting thermal shock caused considerable distortion, especially in cold water. The tube became oval in section, and the horizontal and vertical parts became bent so badly that the test-piece eventually had to be discarded. The test-pieces made from the thicker-walled tubing were better able to withstand the shock.

With the 13-mm dia test-pieces, it was not possible to take readings at 540°C in water below about 65°C, because breakdown of the film occurred on the vertical sections. These were found to be considerably colder than the horizontal section.

ACCURACY

The possible error in the measured bulk liquid temperature was estimated to be $\pm\frac{1}{2}$K, arising principally from the lack of uniformity of temperature in the tank.

The measured surface temperatures were subject to uncertainty arising from the difference in temperature between the sensing junctions on the axis of the tube and the outer surface of the tube. This was estimated to be 5 K at most, and was accordingly ignored, as lying within the accuracy of the thermocouple readings.

Two thermocouples were used to measure the temperature of the hot surface. Normally their readings agreed to within ± 2 K in water and ± 1 K in ethanol, so routine readings were taken from one only, the reading of the other checked occasionally. If the differences between the two readings were consistently greater than the above values, the test-piece was discarded. It was assumed that either one of the sensing junctions had been displaced from the axis of the tube and was no longer registering the mean temperature, or one of the thermocouples had become faulty.

The uncertainty of the surface temperature measurements, from all sources, was estimated as about 1·1 per cent of the surface–liquid temperature difference in water and 1·7 per cent in ethanol.

The value of the heat flux in the horizontal section was taken as the mean value measured between the voltage tappings. The accuracy of measurement was estimated to be better than $\pm 1{\cdot}75$ per cent. The surface area was calculated, for each test temperature, from measurements of the diameter and length of the test-pieces when cold, an allowance for expansion being made. Errors in the estimation of the areas were less than ± 1 per cent. The heating rate was measured with a wattmeter and current transformer, quoted accuracies being 0·5 per cent of full scale deflection for the wattmeter and at $\pm 0{\cdot}15$ per cent for the current transformer. At 40 per cent of full scale deflection, which was the smallest used, the accuracy of the wattmeter was about $\pm 1{\cdot}25$ per cent.

The value of the heat flux in the horizontal section would be expected to differ slightly from the measured mean value because the electrical resistance of the tubing varied slightly with temperature, and the vertical sections were usually cooler than the horizontal section. Errors in the values of the heat flux arising from this source were estimated to be less than $\pm\frac{1}{2}$ per cent for ethanol and $\pm 1\frac{1}{2}$ per cent for water under usual conditions, but rather worse errors occurred in cool water, when the true value of the heat flux in the horizontal section was estimated to be up to 3 per cent higher than the mean. The surface emissivity of the various test-pieces was not directly determined but was estimated to be about 0·9.

RESULTS

The heat-transfer results are presented in Figs. 1–3 for water and 4–7 for ethanol. The total heat flux is plotted against the degree of subcooling, with the surface temperature as the third parameter. The graphs show that in all cases the heat flux increases with subcooling and with superheat. The degree of reproducibility is generally very good. Smoothed curves have been drawn through the experimental points.

(a) *Water*

Successful measurements were made at the three surface temperatures of 544, 711 and 878°C with cylinders of 3- and 6-mm dia, and at 544 and 711°C with 13-mm cylinders.

With 13-mm cylinders at 711°C, data could not be obtained at values of subcooling greater than about 65 K because of power supply limitations, and for the same reason almost no data were obtained at 878°C. At 544°C, film boiling could not be reliably maintained at a subcooling greater than about 50 K with 3-mm cylinders and 30 K with 13-mm cylinders. If film boiling was established at a higher surface temperature, and the heating rate slowly reduced, the surface temperature would fall but, before it reached 544°C, local nucleate boiling would occur and would then spread over the whole surface. Otherwise, the degree of subcooling for which results could be obtained was limited by the increasing difficulty of matching the speed of immersion with the change in the heating rate.

The heat-transfer data for the 3-mm cylinder, which were obtained first, include some for distilled, deionized water, some for ordinary tapwater, and some for tapwater that had been aerated (by bubbling air through the water for several hours), or partially deaerated (by boiling for a few minutes and allowing the water to cool). No differences could be detected, so untreated tapwater was used in all subsequent tests.

The results for the 3-mm cylinder lie close to smooth curves which are approximately parallel. The results for the 6-mm cylinder behave similarly except that with between 5 and 30 K of subcooling the curves tend to separate somewhat. The results for the 13-mm cylinders at 711°C exhibit a distinct change of slope, and for subcoolings of between 33 and 40 K the heat flux remains constant.

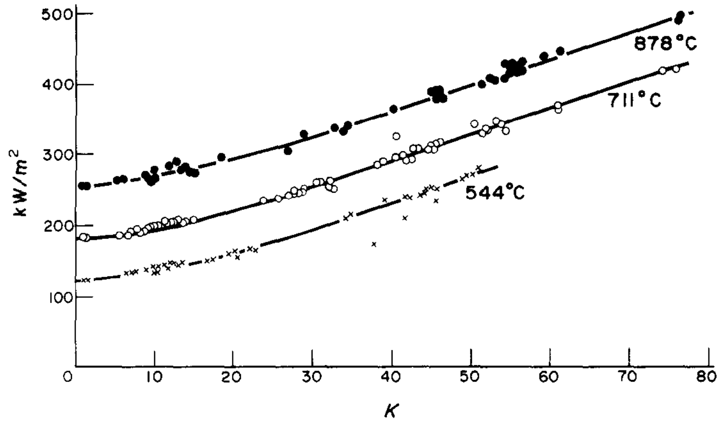

FIG. 1. Three millimetre cylinder in water.

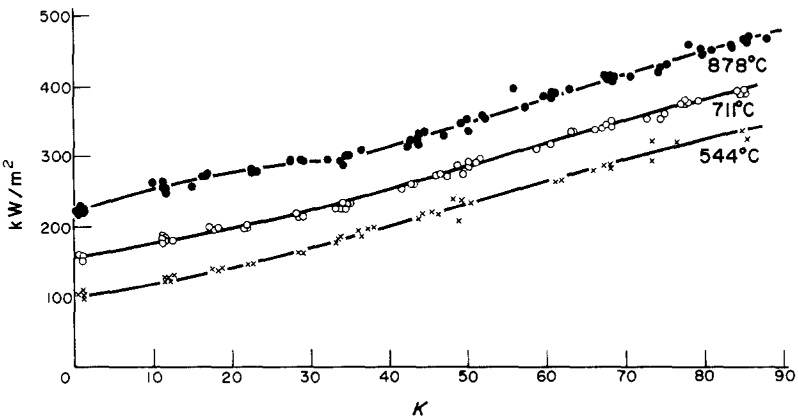

FIG. 2. Six millimetre cylinder in water.

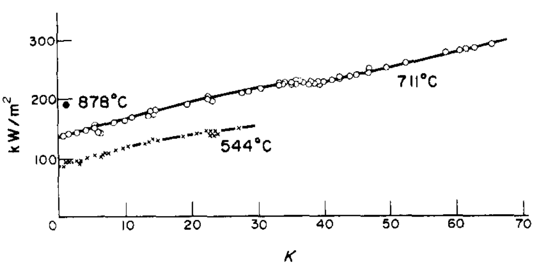

FIG. 3. Thirteen millimetre cylinder in water.

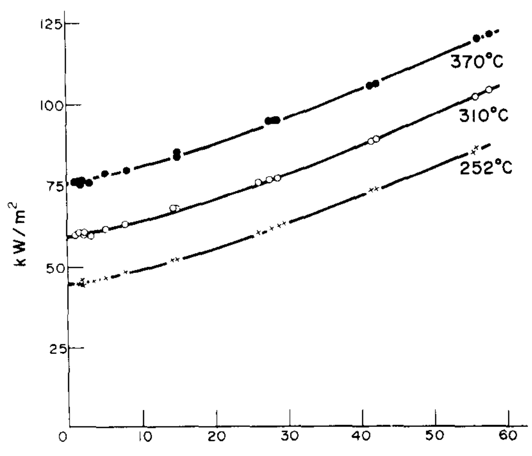

FIG. 4. Three millimetre cylinder in ethanol.

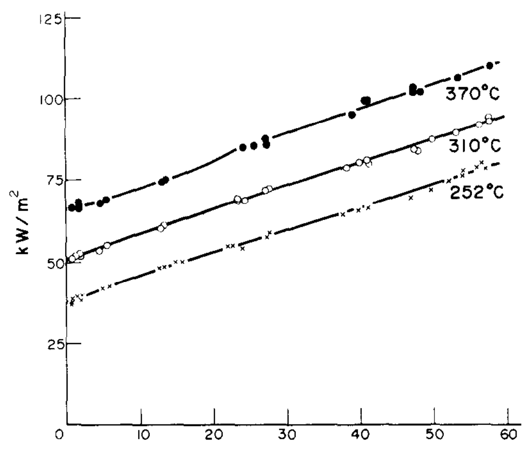

FIG. 5. Six millimetre cylinder in ethanol.

(b) *Ethanol*

Successful measurements were made at surface temperatures of 252, 310 and 370°C for the three sizes of cylinder. Data were also obtained at a surface temperature of 544°C for 6-mm cylinders (Fig. 7) to allow of a direct comparison with the results for water.

The data for the 3-mm cylinder lie close to smooth curves similar in shape to those for water. For the 6-mm cylinder, the curves are nearly straight but again

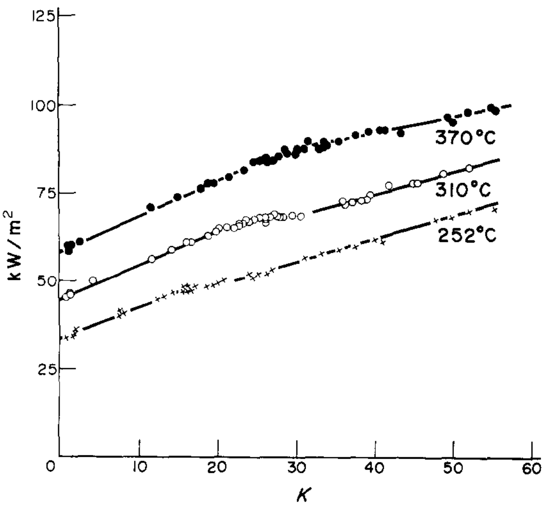

FIG. 6. Thirteen millimetre cylinder in ethanol.

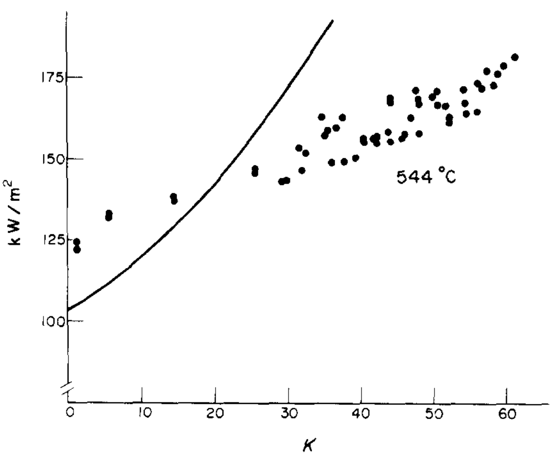

FIG. 7. Six millimetre cylinder in ethanol: the solid line represents the corresponding data for water from Fig. 2.

approximately parallel. The results for the 13-mm cylinder show kinks similar to those for water at this diameter.

The data for 544°C are more scattered than those for the other surface temperatures. The results fall into groups according to the test session during which they were obtained; the sessions were at least one day apart. Carbon was often found to have been deposited on the surface of the tube in the course of a test, and this had to be cleaned off since otherwise stable film boiling could not be maintained. The amount deposited was very sensitive to the magnitude of the heat flux; if this was less than $160\,kW/m^2$ the deposit was negligible, yet at $167\,kW/m^2$ a thick coating formed.

VISUAL STUDIES

In film boiling, all the heat transmitted from the hot body is passed through the layer of vapour to the surrounding liquid. If the bulk temperature of the liquid is already at the boiling point, it cannot be significantly increased any further, so all the heat must be absorbed in generating more vapour. The film accordingly grows thicker, until buoyancy leads to the detachment of bubbles of vapour at the top, rising to the surface in a continuous stream. Since most experimental work on film boiling has been carried out under such conditions, this picture of the process has become familiar.

When, on the other hand, the bulk temperature of the liquid is substantially less than the boiling point, local temperature variations can be produced, and heat can be transmitted by free convection in the liquid, so that the flow pattern and configuration of the film may be different. These are important factors in analytical work, and close attention was accordingly paid during these experiments to the form taken by the vapour layer. The following is a simplified account of the observations.

In saturated film boiling on a horizontal cylinder, the liquid–vapour interface around the lower half of the cylinder is smooth and apparently motionless. Proceeding towards the upper half of the cylinder, slight ripples can be detected on the interface, increasing in amplitude with increasing height. Near the top of the cylinder the interface becomes completely irregular, and streams of bubbles emerge and escape upwards.

With a small degree of sub-cooling, the violence and irregularity of the motion at the top of the film is reduced, and a regular, wavy outline develops with bubbles released in an orderly fashion from the peaks. A further increase in sub-cooling damps out the motion still more, and the rate of release of bubbles is reduced. Eventually, with a sufficient degree of sub-cooling, the release of bubbles ceases altogether, and the whole of the vapour–liquid interface becomes smooth and steady. The point at which this state is reached depends on the temperature and diameter of the cylinder and on the nature of the liquid. The hotter the body, and the larger its diameter, the greater the subcooling required to suppress the motion of the interface. It is more readily suppressed in water than ethanol; in the present tests, bubble release and comb-like profile along the trailing edge persisted in ethanol at the highest sub-cooling investigated. A detailed description, with photographs is available; the studies include other geometries [11].

It is to be presumed that these observations have a bearing on the nature of the heat transfer data, and in particular on the kinks and other peculiarities to which attention has been drawn. Caution is clearly necessary when setting up idealized models of the flow pattern for the purpose of analysis.

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EBULLITION EN FILM SOUS-REFROIDI AUTOUR DE CYLINDRES HORIZONTAUX

Résumé—Des résultats sont présentés relatifs à l'ébullition en film dans un liquide sous-refroidi immobile autour de tubes horizontaux de diamètres approximatifs de 3,6 et 13 mm, dans le cas de l'eau avec des températures de surface allant de 540 à 880°C et dans le cas de l'éthanol avec des températures de surface allant de 250 à 370°C. L'allure des contours de l'écoulement convectif est commentée.

UNTERKÜHLTES FILMSIEDEN AN HORIZONTALEN ZYLINDERN

Zusammenfassung—Es werden Werte für unterkühltes Behälter-Film-Sieden an horizontalen Rohren mit Durchmessern von ungefähr 3, 6 und 13 mm in Wasser bei Oberflächentemperaturen von 540 bis 880°C und in Äthanol mit Oberflächentemperaturen von 250 bis 370°C angegeben und das auftretende Strömungsbild erklärt.

ПЛЕНОЧНОЕ КИПЕНИЕ НА ГОРИЗОНТАЛЬНЫХ ЦИЛИНДРАХ ПРИ НЕДОГРЕВЕ

Аннотация — Представлены данные по пленочному кипению в большом объеме при недогреве в трубах диаметром приблизительно 3,6 и 13 мм. Использовалась вода при температуре поверхности от 540 до 880 °C и этанол при температуре поверхности от 250 до 370 °C. Обсуждается картина течения.