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TRANSIENT FILM AND TRANSITION BOILING FROM A SPHERE

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Abstract—The nature of transition boiling from $\frac{3}{4}$ in. dia. copper sphere moving through subcooled distilled water was experimentally investigated. High-speed photographs show that transition occurs as a rapidly pulsating vapor film on the forward portion of the sphere. The behavior of the vapor wake is highly dependent upon the manner in which vapor is being formed on the forward portion of the sphere. Instantaneous heat transfer rates calculated from experimental temperature-time measurements indicate that film and transition boiling are as effective as nucleate boiling over the velocity range, 9·6–20·0 fps, in highly subcooled water. That is, there is no significant change in the heat transfer rate at transition as observed for free convection quenching of spheres.

NOMENCLATURE

A,	area of sphere, including support nipple [ft^2];
C_p,	specific heat [Btu/lbm F];
q'',	heat transfer rate [Btu/h ft^2];
T,	temperature [F];
θ,	time;
ρ,	density [lbm/ft^3];
V,	volume of sphere, including support nipple [ft^3].

Subscripts

i,	initial;
s,	sphere;
sat,	saturation.

INTRODUCTION

THE TRANSITION boiling regime is an unstable phenomenon, and is difficult to study with most steady-state systems. An experimental study of this regime requires different techniques. High-speed photography has proved to be a particularly effective method for this type of study.

This paper reports an experimental investigation of the film and transition boiling regimes for a sphere moving with a uniform velocity in subcooled water. The primary objective of this study was to describe the nature of the transition from film to nucleate boiling around a sphere.

A better understanding of the transition phenomena for a hot solid spherical particle being quenched in a liquid should be useful in understanding related problems. For example, this information might be useful in predicting the behavior of liquid surrounding a moving molten metal particle. Fragmentation and vapor explosions apparently caused by rapid heat transfer from molten materials have been observed both in industry and by other investigators [1, 2]. The causes of these phenomena seem to be closely related to the sequence-of-events that accompanies transition boiling. The unpredictibility and destructive nature of these events is of particular concern in assessing the potential hazards associated with the operation of nuclear reactors.

EXPERIMENTAL APPARATUS

The experimental apparatus used in this study employs a transient quenching technique that involves the passing of a heated $\frac{3}{4}$-in. dia., silver-plated copper sphere through a pool of subcooled, distilled water. This equipment is similar in concept and design to that described by Witte [3].

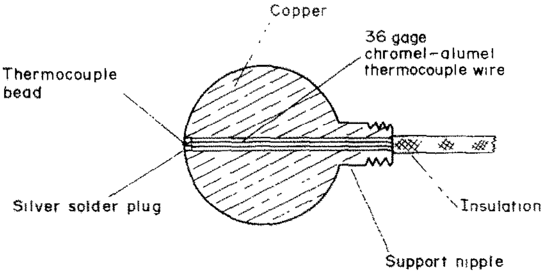


FIG. 1. Schematic drawing of sphere-thermocouple assembly.

The sphere, as shown schematically in Fig. 1, was machined from pure copper; copper was selected because of its high thermal conductivity. A 36-gage chromel–alumel thermocouple was inserted through a 0·040-in. dia. hole and the thermocouple bead positioned at the sphere surface as shown in Fig. 1. The bead was silver-soldered in place and the front surface re-machined to a spherical configuration. The sphere assembly was then plated with silver to retard oxidation. The plating thickness averaged from 0·001 to 0·002 in.

The sphere, mounted on a hollow support tube, was attached orthogonally to the drive shaft of a printed-circuit d.c. motor. The motor shaft was mounted transversely above a semicircular plexiglas tank, as shown in Fig. 2. The tank is 4 in. wide with a 12-in. radius. An electric resistance furnace, mounted on a pair of vertical rails, could be lowered over the sphere to obtain the desired initial temperature. The sphere heating furnace is shown in Fig. 2 in its raised position.

The position and velocity of the test sphere were monitored by a tracking system composed of a timing disk and a photo-electric cell. The timing disk, with accurately-spaced reflective strips glued to its edge, was driven by the d.c. motor shaft. Thus, the movement of the timing disk reflected the travel of the test sphere. As the disk rotated, the photocell detected the change in reflected intensity as a reflective strip passed beneath it. In this way, both the position and velocity of the test sphere could be accurately determined as the shaft made one revolution.

An experiment involved having the heated sphere make one pass through the plexiglas tank. The first 180-degrees of travel for the sphere was in the area above the tank as can be seen in Fig. 2. During this travel, the heated sphere would reach its terminal velocity prior to entering the pool of distilled water.

The output of the sphere thermocouple and the photocell were recorded simultaneously on a Tektronix Model 565 dual-beam oscilloscope. As the sphere passed through the pool of distilled water, high-speed motion pictures were taken through the side of the plexiglas tank with a Fastax Model WF3 16mm camera.

Tests were conducted with 75 and 140 F distilled water. The velocity of the sphere was varied from 9·6 to 20·0 fps. The range of sphere initial surface temperatures was 300–475 F.

Further details of the experimental apparatus and the test procedure may be found in [4].

PRESENTATION OF RESULTS

The nature of transition

A point of primary concern in this study was a determination of the nature of the transition from film boiling to nucleate boiling for a spherical particle moving through a subcooled liquid. A cross-correlation of the high-speed movie data with the time-temperature information provided the following description of this phenomenon.

As the heated sphere enters the subcooled liquid, if its surface temperature is sufficiently high, a thin film of vapor will be established at all points on the sphere surface. When the sphere has lost a sufficient amount of energy, it will no longer be capable of supporting a stable vapor film at its surface and transition begins. The onset of transition is characterized by a pulsation of the vapor film. These pulsations may be uniform about the sphere surface or, as was observed in some tests, they may be irregular.

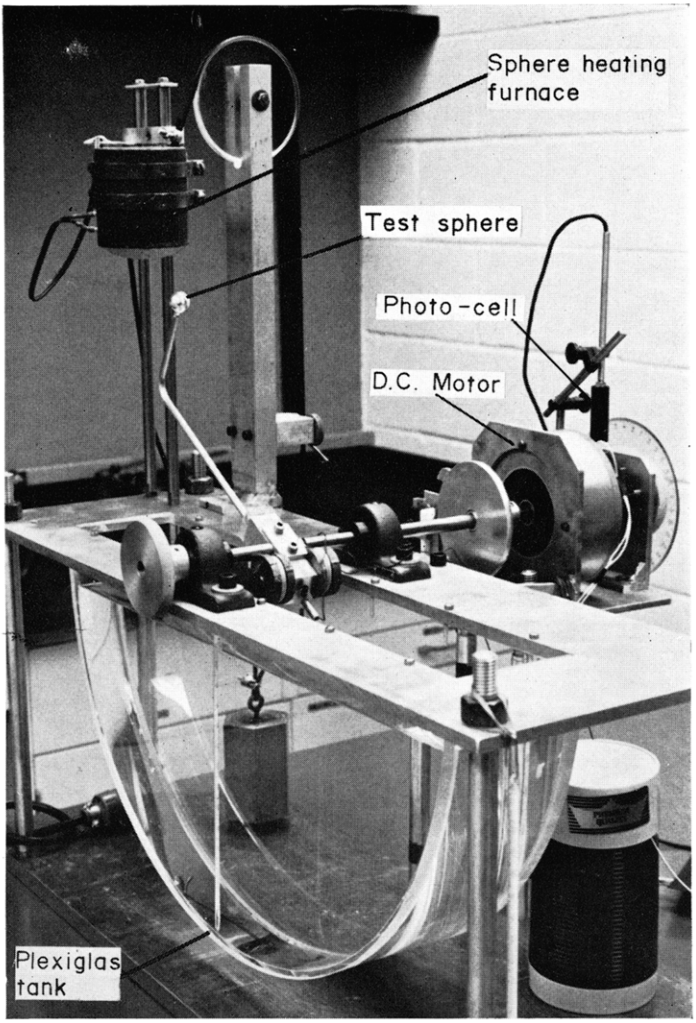
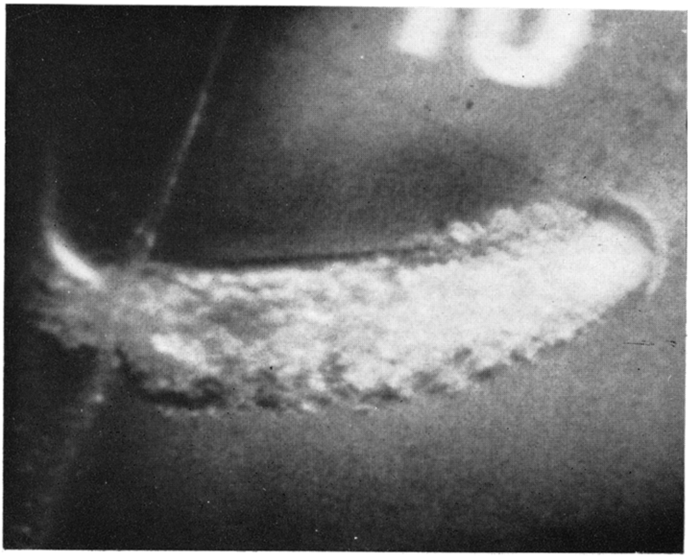
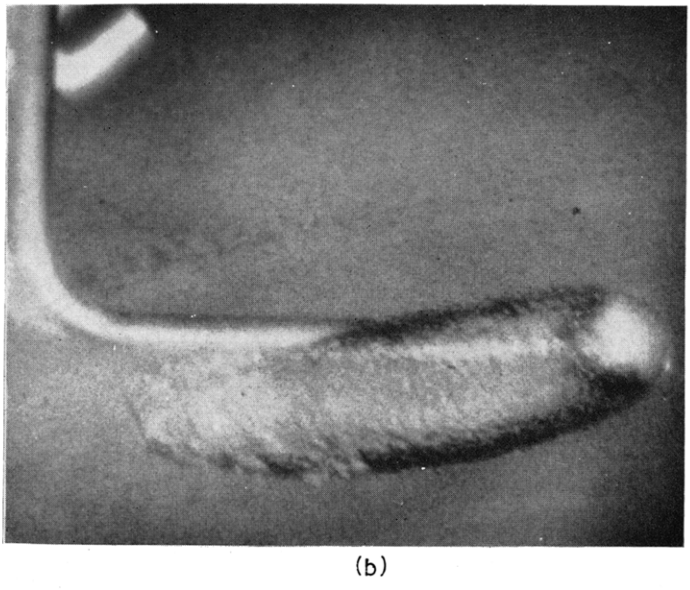


FIG. 2. Forced convection boiling apparatus.



(a)

Pulsating vapor film



(b)

Nucleate boiling

FIG. 3. Selected frames from high-speed motion pictures.

That is, the vapor film may be growing on a portion of the sphere while it collapses at some other point. The frequency of the pulsations of the vapor film is not constant. They begin at a low frequency and then increase in frequency as transition proceeds. Accompanying this frequency increase is a decrease in the maximum thickness to which the vapor film will grow between pulsations. The scope of our study did not allow a determination of the frequency range during transition.

Walford [5] in a photographic study of transient quenching of a $\frac{1}{4}$-in. dia. nickel sphere noted similar behavior. He observed for certain conditions an "explosive cavity" forming intermittently. His experiments were performed in 172 and 203 F water and at low sphere velocities; the cavity grew quite large. Apparently, Walford's "explosive cavity" formation corresponds to what we describe as the pulsations of the vapor film during transition. The experiments reported herein were done in cooler water and at higher velocities, causing the vapor cavity not to grow so large.

The end-of-transition comes when the sphere has cooled to the point that liquid may contact the surface and no longer be flashed into vapor. Then nucleate boiling takes place as small bubbles grow at specific sites and are swept by the flow pattern into the wake region. The behavior of the wake region during film and transition boiling is greatly influenced by the events taking place at the surface of the sphere. Two distinct types of wakes were observed.

Wake behavior

Whenever the condition at the sphere surface was one of the stable film boiling or a pulsating vapor film, the wake region was a mixture of fluid and vapor with a complex, irregular flow pattern. Individual pulsations of the vapor film were swept into the wake region causing large amplitude waves in the liquid–vapor interface. The appearance of these waves in the wake was one of the best indicators that transition had begun.

As the end of transition approached, the size and intensity of the waves in the wake decreased. With the last pulsation of the vapor film at the sphere surface, which was observed to occur quite rapidly, there was a distinct change in the appearance of the wake. A smooth liquid–vapor interface, which began at approximately the 90-degree point on the sphere, swept the wake region clean of any remaining liquid thus establishing a well-defined wake. Small amplitude laminar waves could be seen moving along the interface. Vapor condensed at the tail of the wake, leaving a trail of small, frothy air bubbles as the sphere moved through the pool. Walford also observed that the wake behavior was influenced greatly by the vapor production mechanism on the front portion of the sphere.

Figure 3 illustrates the condition of a pulsating vapor film during transition and nucleate boiling after the end of transition, with the associated wake characteristics described above. The photographs in this figure are individual frames of 16 mm film, taken from the same test. Figure 3(a) shows the vapor film undergoing pulsations at the sphere surface. The irregular vapor wake trailing behind the sphere is a good example of wakes that characterize transitional pulsations of the vapor film. The waves on the liquid–vapor interface in Fig. 3(a) are the result of previous pulsations at the sphere surface.

In Fig. 3(b), the same sphere is seen after transition has been completed. The wake region is now well-defined with the smooth interface broken only by the small laminar waves mentioned earlier.

The effect of velocity and surface temperature on transition

For each test in which the initial temperature of the sphere was high enough to cause a vapor film to be established upon entering the tank, the transition temperature, i.e. the temperature at which the transition from stable film boiling began, was obtained. A cross-correlation of high speed movie data with the Polaroid time-temperature record was required to establish the transition temperature for each experiment· The correlation procedure was accomplished by viewing the film from a test run on a stop-action projector. The particular frame at which the first pulsation of the vapor film was observed, was located and flagged. Utilizing the timing marks that were included along the edge of the film, the elapsed time from entrance into the pool to the onset of transition could be established. With this information the transition temperature could then be determined from the Polaroid time–temperature record

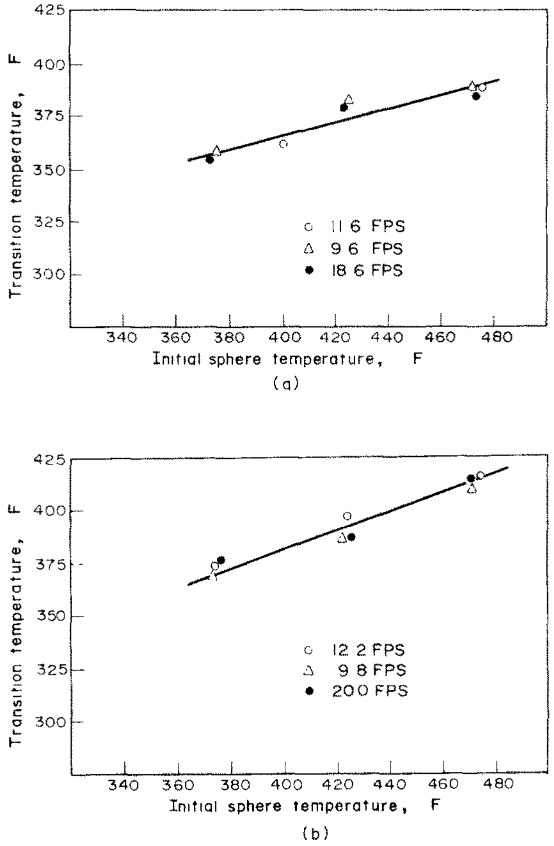


FIG. 4. The effect of initial sphere temperature.
a. 75 F water.
b. 140 F water.

Figure 4 presents the effect of velocity and initial sphere temperature on the transition temperature. These results are for two water temperatures, 75 and 140 F. The results indicate that velocity has virtually no effect on the temperature at which the transition from film to nucleate boiling begins for the velocity range studied in these tests. The scatter of the data is minimal and felt to be well within the range of experimental error.

The trend of increasing transition temperature with increasing initial sphere temperature is well-defined, as shown in Fig. 4. Intuitively one might expect that the transition temperature should be relatively constant and that, with all other system parameters held constant, increasing the initial sphere temperature would only result in a time lag before transition began. However, such was not the case for these experiments. In all cases the trend of Fig. 4 was found to exist. A careful study of the possible sources and magnitudes of measurement errors was conducted [6] and it is our opinion that this trend does exist and cannot be attributed to error in the measurement system.

One other interesting, though likewise contradictory observation, from the results presented in Fig. 4 is the effect of subcooling on the transition temperature. One might expect that as the degree of subcooling is decreased, the transition temperature would likewise decrease. This effect has been observed in free convection quenching. The reasoning here is straightforward: in hotter water the production of vapor to sustain the vapor film should be more effective, thus allowing the sphere to cool to a lower temperature before the vapor film collapses. The present results indicate just the opposite effect. By comparing Fig. 4(a) to Fig. 4(b) it can be seen that as the degree of subcooling is decreased, the transition temperature increases.

Heat transfer

Instantaneous and overall heat transfer data were obtained from the experimental temperature–time traces. The instantaneous heat-transfer rates were computed by considering the sphere as a lumped-parameter system; i.e. that the sphere cooled uniformly. The determination of the heat-transfer rate then hinges upon an accurate determination of the slope of the temperature–time curve since.

$$q'' = \frac{\rho V}{A} C_p \frac{\mathrm{d}T}{\mathrm{d}\theta}.$$

The assumption of an isothermal sphere is not considered to be a serious source of heat flux error. The computation of the heat flux is based on the slope of the temperature–time curve, rather than the sphere temperature at a specific time. Calibration tests and other procedures [4] were undertaken to establish that the test spheres used in these experiments had satisfactory response characteristics.

The overall heat transfer rates were computed on the basis of the total temperature drop of the sphere during its travel through the tank. Figure 5 presents the overall heat-transfer rates from the sphere to 75 F water at three different velocities. The temperature used in presenting these results was taken as the initial temperature of the sphere upon entering the pool, T_i. As can be seen in Fig. 5, as the sphere velocity was increased, the overall heat-transfer rate likewise increased.

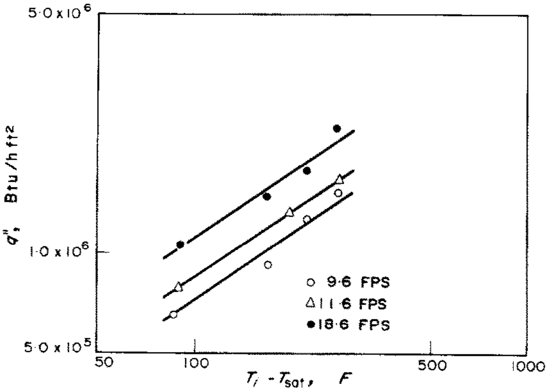


FIG. 5. Overall heat transfer rates to 75 F water.

A typical temperature (emf)–time oscilloscope record is shown in Fig. 6. The striking feature of the record is that the slope is continuously decreasing as the sphere cools. However, for the data presented in Fig. 6, the sphere entered the pool in the film boiling regime and underwent transition shortly thereafer. This was observed in the high-speed motion picture sequence for this experiment. Normally, the heat-transfer rates in film boiling are lower than that in transition or nucleate boiling. All the data indicate otherwise for the subcooled forced-convection quenching case; i.e. all of the temperature–time traces are similar to Fig. 6 in shape.

Figure 7 shows typical instantaneous heat-transfer data obtained from the temperature–time histories. The T_s values plotted in Fig. 7

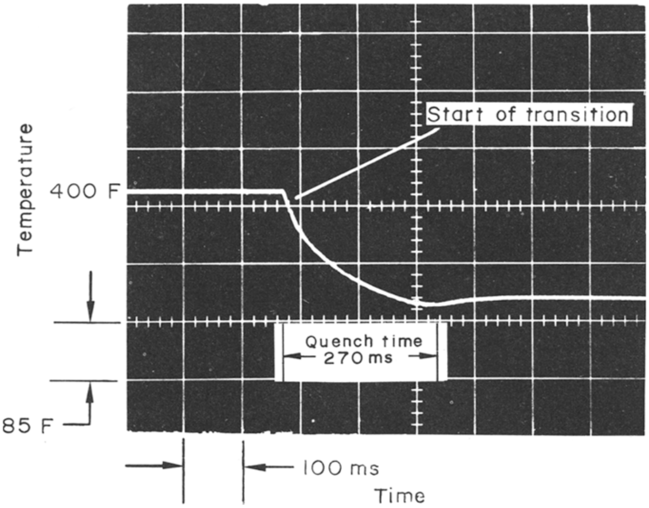


FIG. 6. Temperature history for ¾-in. dia. copper sphere in 75°F water, V = 11·6 fps, quench time ≅ 270 ms.

are instantaneous values and are estimated to be accurate to within 10 F. Note that there is no reduction in heat-transfer rates at temperature differences representative of film and transition boiling.

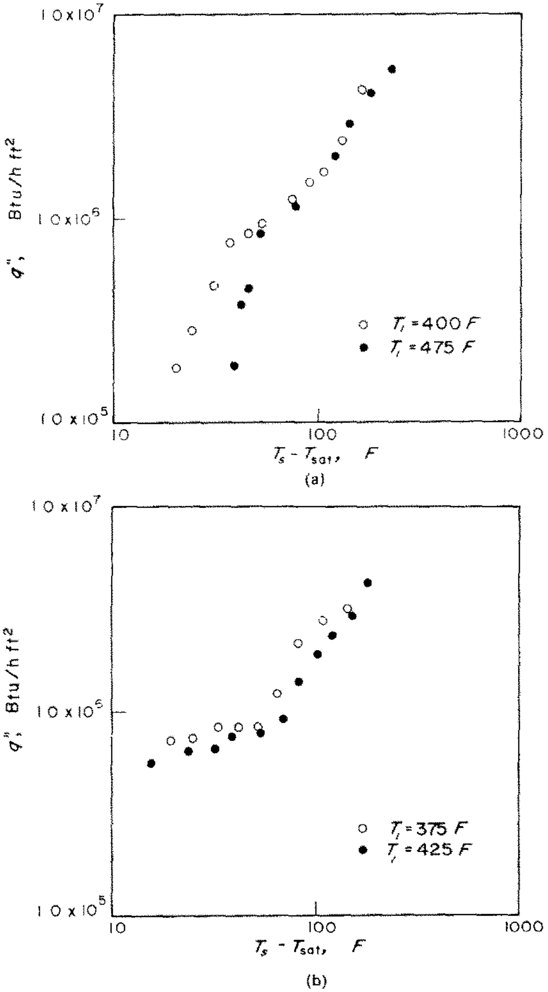


FIG. 7. Instantaneous heat transfer rates to 75 F water.
a. $V = 11{\cdot}6$ fps.
b. $V = 9{\cdot}6$ fps.

As a check on the validity of the temperature–time data for forced-convection, the following experiments were performed. The sphere–thermocouple assemblies used in this study were subjected to free-convection quenching tests; i.e. the heated spheres were plunged into a pool of water and brought to rest. Under this type of cooling, the behavior was classical; i.e. there was a definite film boiling regime, indicated by a low cooling rate, followed by a transition to nucleate boiling, in which the cooling rate increased considerably. This was taken as evidence that the sphere–thermocouple calorimeter was responding properly to its surroundings.

The point of interest here is the effect of forced convection on the heat-transfer rate during film boiling. Although a vapor film definitely exists, heat-transfer rates are higher in the film boiling regime than for nucleate boiling. Walford noted similar behavior for lower sphere velocities. Witte [9] also observed similar behavior for forced convection from high-temperature spheres in liquid sodium. He estimated that film thicknesses on the order of 10^{-6} in. would be required to achieve the measured energy fluxes from the sphere to the liquid–vapor interface. Witte noted no evidence of a transition regime during the cooling process, although the sphere was on occasion 2000 F hotter than the sodium saturation temperature. For temperature differences of that magnitude, film boiling should definitely occur. Witte found that his data could be correlated by assuming there was no vapor film present. However, the study described herein along with recent studies by Jacobson and Shair [10] and Walford [5] indicate that the assumption of no vapor film is probably erroneous.

It appears that forced convection quenching of spheres in subcooled water and liquid sodium may be similar. Film thicknesses on the order of 10^{-5} in. are estimated for the transfer of the measured energy from the $\frac{3}{4}$-in. copper sphere to subcooled water. This estimate compares well with the value of 15 μm ($\sim 6 \times 10^{-4}$ in.) given by Walford for film thicknesses on the front of the $\frac{1}{4}$-in. nickel sphere in hotter water. It appears that extremely thin films may be maintained next to a very hot surface even though the surface may be relatively rough. Conclusive evidence for this premise is given by the photographic sequences obtained in this investigation, i.e. a pulsation of the vapor film indicating transition is definitely observed, and yet the instantaneous heat-transfer rate does not change significantly at this transition point.

SUMMARY

From this study, insight into the nature of transition boiling around a sphere moving through a liquid has been obtained. Over the range of variables that was investigated, the following sequence-of-events was observed.

1. A sufficiently hot sphere will support a stable vapor film during forced convection. A vapor film is established and maintained at all points on the surface of sphere. The wake region exhibits a complex, irregular flow pattern containing both liquid and vapor.
2. Transition from a condition of film boiling to one of nucleate boiling begins with a slow pulsation of the vapor film at the sphere surface. The frequency of the vapor pulsations increases while the maximum thickness to which the vapor layer grows decreases. During the period of these vapor pulsations, the vapor wake is characterized by a complex flow situation with large amplitude waves in the wake. These waves are the direct result of pulsations of the vapor film at the sphere surface.
3. Transition is completed when fluid remains in contact with the front surface of the sphere. Nucleate boiling takes place on the front hemisphere with the bubbles being swept into a well-defined teardrop-shaped vapor wake. The liquid–vapor interface of this wake is basically smooth and disturbed only by small amplitude waves.

The velocity of the sphere has virtually no effect upon the temperature at which transition begins. Apparently, the transition temperature is lowered as the water is made cooler. This result, along with the unexplained effect of initial sphere temperature, seems contrary to intuition and will require further experimentation for a plausible explanation.

The heat-transfer characteristics of forced-convection quenching of spheres in highly-subcooled water are significantly different than free-convection quenching. Although there is definitely a vapor film surrounding the sphere, the heat-transfer rates in the film boiling regime are higher than those in the nucleate regime. The reason for this may be two-fold:

1. The vapor film may be "thinned" by the motion of the liquid and the subcooling of the liquid to such an extent that conduction across the film is highly effective, and/or,
2. The wake region in the film boiling regime may contain enough liquid to effect significant cooling of the rear portion of the sphere because of impingement and subsequent vaporization of small liquid droplets. (MacGinnis and Holman [11], for example, have observed extremely high heat-transfer rates for liquid droplets "splattering" on a hot surface.)

These heat-transfer data indicate that forced convection quenching of spheres in liquid sodium may not be significantly different than in water. Verification of this premise will depend upon a method of experimentally detecting extremely thin films near relatively hot surfaces.

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FILM TRANSITOIRE ET ÉBULLITION DE TRANSITION AUTOUR D'UNE SPHÈRE

Résumé—On a étudié expérimentalement la nature de l'ébullition de transition autour d'une sphère de cuivre, de diamètre égal à 1,9 cm se mouvant dans une eau distillée sous-refroidie. Des photographies à grande vitesse montrent que la transition apparaît comme un film de vapeur rapidement pulsé sur la portion avant de la sphère. Le comportement du sillage de vapeur dépend fortement de la manière dont la vapeur est formée sur la portion avant de la sphère. Les taux de transfert thermique instantané, calculé à partir de mesures expérimentales de température en fonction du temps, indiquent que le film et l'ébullition de transition sont aussi efficaces que l'ébullition nucléе dans la gamme de vitesse de 2,9 à 6,1 m/s, dans de l'eau fortement sous-refroidie. Ainsi, il n'y a pas de changement significatif dans le taux de transfert thermique de transition comparé à ce qui est observé pour une convection naturelle autour de sphères.

INSTATIONÄRES FILM- UND ÜBERGANGSSIEDEN AN EINER KUGEL

Zusammenfassung—Die Erscheinungen des Übergangssiedens bei der Bewegung einer Kupferkugel von 19 mm Durchmesser in unterkühltem destilliertem Wasser sind experimentell untersucht worden. Hochgeschwindigkeitsaufnahmen zeigen, dass beim Übergang ein sehr schnell pulsierender Dampffilm an der Vorderseite der Kugel auftritt. Das Verhalten des Dampfwirbels ist sehr stark von der Art der Dampfbildung an der Vorderseite der Kugel abhängig. Instationäre Wärmeübergangsraten, berechnet aus experimentellen Temperatur-Zeit-Messungen, ergeben, dass Film und Übergangssieden für den Geschwindigkeitsbereich von 292·6 bis 610 cm/s in stark unterkühltem Wasser ebenso wirkungsvoll wie das Blasensieden ist. Wie für das Abschrecken von Kugeln in freier Konvektion, ergibt sich auch hier beim Übergangssieden keine bedeutende Änderung der Wärmeübergangsrate.

НЕСТАЦИОНАРНОЕ ПЛЕНОЧНОЕ И ПЕРЕХОДНОЕ КИПЕНИЕ НА ШАРЕ

Аннотация—Экспериментально исследовалась природа переходного кипения на медном шаре диаметром 3/4 дюйма, движущемся через переохлажденную дистиллированную воду. Снимки, сделанные скоростной киносъемкой, показывают, что переход происходит в виде быстро пульсирующей пленки пара на передней части шара. Мгновенные скорости теплопереноса, подсчитанные с помощью экспериментальной зависимости температуры от времени, показывают, что пленочное и переходное кипение является таким же эффективным, как и пузырьковое кипение в диапазоне скоростей от 9,6 до 20,0 фут/сек в переохлажденной воде. То-есть, при переходе не происходит существенных изменений в скорости теплопереноса, как наблюдалось в случае затухания свободной конвекции у шара.