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LIQUID METAL SUPERHEAT IN FORCED CONVECTION

R. H. S. WINTERTON
Department of Mechanical Engineering, The University of Birmingham,
P.O. Box 363, Birmingham B15 2TT, England

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Abstract—Analysis of inert gas mass transfer in systems used for the experimental measurement of superheat shows that the flow is likely to contain gas bubbles that have come out of solution, and the number of bubbles will increase rapidly if the velocity in the cold pipework, where the bubbles are precipitated, is raised. The paper examines the effect these bubbles could have on superheat measurements. Depending on the way in which the experiment is conducted, there can be an apparent effect of increasing superheat as the heat flux or temperature ramp is increased, or decreasing superheat as the flow velocity is increased.

NOMENCLATURE

A,	flow cross-sectional area;
c,	specific heat;
k,	$= 1/\log(1-p)$;
l,	heated length of test section;
m,	mass flow rate;
N,	number of repeated measurements;
n,	superheat (number of 1°C rises);
p,	probability of bubble traversing superheated region per 1°C temperature rise;
Q,	heat input to pre-heater;
q,	heat flux in test section;
R,	temperature ramp, rate of temperature rise (°C s^{-1});
r,	bubble radius;
s,	heated perimeter of test section;
T_i,	bulk inlet temperature of flow;
T_o,	bulk outlet temperature of flow;
T_s,	saturation temperature;
ΔT,	superheat, $T_o - T_s$;
t, t_b,	time to wait for bubble to arrive in superheated region;
t_h,	time to heat flow from saturation to its final level;
v,	flow velocity.

Greek symbols

λ,	disturbed mass flow in test section;
ν,	disturbed mass flow in pre-heater;
ρ,	density.

INTRODUCTION

A NUMBER of measurements of the superheat required to initiate boiling of liquid metals in forced convection have been reported in the last 5 years. The reason for this interest is the possibility of the sodium coolant in a fast nuclear reactor boiling under accident conditions. Most of the experimental work has been done with sodium. There are three main trends apparent in the results: an increase of incipient boiling superheat with heat flux; an increase with temperature ramp, i.e. the rate at which the temperature rises; and a decrease with flow velocity.

The simplest nucleation mechanism is the passage of a gas bubble through the superheated region, and in this paper it is assumed that this is the only mechanism of any importance in flowing systems. A bubble circulating with the liquid metal with a radius greater than about 10 μm will nucleate boiling at any superheat greater than a couple of degrees [1]. The measured superheat depends on how much superheat can build up before the bubble comes along.

Nearly all the experimental loops used in making these measurements have an expansion tank after the boiling test section and here the hot sodium will pick up dissolved argon from the cover gas. Since the solubility of inert gases in liquid metals increases with temperature the sodium will be supersaturated with dissolved argon once it reaches the cold portion of the loop and bubbles of argon will form on the walls of the pipes, grow to a critical size and be swept off into the flow. The main part of this paper is concerned with the effects these bubbles have on the different superheat experiments, but first we briefly consider the mass-transfer processes involved in the production of the bubbles.

Inert gas mass transfer

First we note that under typical conditions, 1 m/s flow velocity in a 1 cm radius pipe, the argon bubbles will be swept off into the flow when they reach about 100 μm radius [2]. The time it takes a bubble to grow is about 1 h. Assuming reasonable values for a typical experimental loop, and using the mass-transfer equations given in [2], the time taken to reach a steady state is found to be several hours. The number of bubbles produced once equilibrium is reached is about 10 per second.

However, 1 m/s may be rather high for the sodium velocity in the cold pipework. 1 m/s is a typical test section velocity but in a number of cases this has been achieved by having a reduced flow cross-section. Also it is unlikely, in view of the long timescales involved, that the loops are normally operated under conditions of equilibrium in the inert gas mass transfer. Isothermal operation between experimental runs seems likely. Both these factors will reduce the number of bubbles produced, and one bubble a second is probably more reasonable as an order of magnitude estimate under "typical" conditions. With rates of temperature rise in different superheat experiments ranging from less than one to some tens of degrees centigrade per second the presence of around one bubble a second in the flow is likely to be crucial.

Effect of varying velocity

There are a number of possibilities, depending on the extent to which the system manages to get to its new equilibrium state after the velocity is changed. To get some feel for what might happen we assume that sufficient time is allowed for a new crop of bubbles to grow, but that the time is not enough for the dissolved argon content to change appreciably. In these circumstances the number of bubbles produced per second {[2] equation (24)}, is proportional to $r^{-3/2}\mathbf{v}^{1/2}$, where r is the bubble radius and $\mathbf{v}$ the sodium velocity. r itself is a strong function of flow velocity and assuming the departure from typical conditions is not too great, equations (19) and (20) of [2] will still apply. The net result is that, depending on whether the sodium contact angle on the surface is zero or finite, the number of bubbles will be proportional to $\mathbf{v}^{1\cdot 82}$ or $\mathbf{v}^{3\cdot 86}$ respectively. So it is reasonable to expect a rapid increase in the number of bubbles produced per second as the velocity increases.

EFFECT OF BUBBLES ON SUPERHEAT

The superheat that can build up before a gas bubble comes along and nucleates boiling depends not only on the average time interval between bubbles but just as much on the way in which the experiment is conducted. Let t_b be the time to wait for a bubble after the test section first becomes superheated and t_h be the time taken to heat up the test section to its final (maximum) temperature. The type of experimental result obtained depends on the values of these two quantities.

Heat balance line

Under steady state conditions the inlet and outlet bulk temperatures of the sodium flowing through the test section are related by

$$T_o - T_i = \frac{slq}{A\mathbf{v}\rho c}$$

where q is the heat flux into the test section and $\mathbf{v}$ the velocity. If the saturation temperature is T_s then the bulk superheat at outlet is given by

$$\Delta T = T_o - T_s = T_i - T_s + \frac{slq}{A\mathbf{v}\rho c}. \qquad (1)$$

The superheat at the instant of boiling nucleation must obey this equation, provided steady state conditions prevail. This will be so if either:

(a) the test section heater is suddenly switched on and a new steady state achieved before nucleation occurs, i.e. before the first gas bubble comes along ($t_h < t_b$) or

(b) the rate of change of heater power is steady and sufficiently slow for the system to always be close to a steady state.

The first heat flux effect ($t_h < t_b$)

If superheat measurements are performed at fixed velocity by suddenly switching on the test section heater at a pre-set heat flux q, and provided $t_h < t_b$, then equation (1) will apply. On a ΔT vs q graph the results will lie on a straight line, slope $sl/A\mathbf{v}\rho c$ and negative ΔT intercept equal to the inlet subcooling. Experimental results obtained in this way follow the heat balance line very closely [3]. Schleisiek [4] used a slightly different experimental procedure, the power to the heater was increased in a series of steps over a period of 5–10 seconds. However, if we assume $t_h < t_b$ the exact procedure for reaching the new steady state is irrelevant. The results show an increase of superheat with heat flux consistent with equation (1) but since the experimental points are not differentiated according to the inlet subcooling there is an apparent scatter on the ΔT vs q graph.

Under these conditions the result of an individual superheat measurement can be predicted in advance using equation (1), but only in the trivial sense that the equation determines the maximum superheat the system is capable of, and this maximum value is reached before the first bubble comes along.

The first velocity effect ($t_h < t_b$)

If q is held fixed and $T_i \sim T_s$ then measurements of superheat as a function of $\mathbf{v}$ should follow a $1/\mathbf{v}$ law [equation (1)]. Figure 1 shows the results of Chen [5],

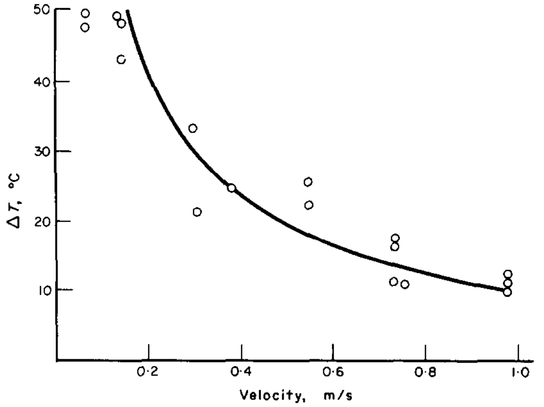

FIG. 1. Experimental results of Chen for superheat as a function of flow velocity [5]. The theoretical line is the prediction of equation (1).

together with a theoretical 1/**v** line fitted through the experimental points. The agreement is good, bearing in mind the statement in the paper that the condition $T_i = T_s$ was only approximately met. The procedure was to establish **v**, then q, and then increase T_i slowly using the preheater. Evidently q was established in a time less than t_b, probably just by switching on the test section heater at the final power level, and T_i increased until the first bubble came along. These random variations of T_i account for the scatter in the figure. Other very similar results have been obtained [6], also some that show a more rapid decrease of superheat with velocity, consistent however with equation (1) for the high inlet subcoolings used [4].

As before the result of an individual measurement is predictable using equation (1). Note however that we have used the terms "heat flux effect" and "velocity effect" only because of their previous use in the literature. Any attempt to correlate the results of different investigators using just heat flux and velocity would fail because of the different values of the other parameters in equation (1). Clearly the determining parameters are total heat input, mass flow rate and inlet subcooling.

Statistical theory for $t_h \sim t_b$

If the heating is continued until the first bubble arrives the measured superheat will show a large scatter, depending as it does on the random probability of a bubble traversing the superheated region. In this case t_h necessarily equals t_b for each individual nucleation. Suppose that the temperature is rising at a constant rate, and the probability of a bubble coming along per degree centigrade temperature rise is p. The probability of a bubble not coming along in the first 1°C temperature rise above saturation is $1-p$, and the probability of no bubble appearing for n successive 1°C temperature rises is $(1-p)^n$.

The likelihood of a bubble then coming for the first time in the next interval is $p(1-p)^n$. In other words the probability of a superheat measurement in the range n to $n+1$ deg C is

$$p(1-p)^n. \tag{2}$$

This is a particularly simple example of the negative binomial distribution and it follows from a standard result that the average superheat will be $1/p$.

The probability of a superheat greater than n is $(1-p)^n$. Suppose N measurements are to be made under a given set of experimental conditions, and we require the probability of a superheat greater than n to be $1/N$, i.e.

$$(1-p)^n = \frac{1}{N} \quad \text{or} \quad n = \frac{\log(1/N)}{\log(1-p)} = k\log(1/N).$$

So on average one of the N measurements will result in a value greater than $k\log(1/N)$. Similarly one will give a value between $k\log(2/N)$ and $k\log(1/N)$ and so on.

So we can simulate the expected experimental results by putting one point in each of these intervals. The obvious place to put it is at the point where there is an equal probability that the actual value will be higher or lower than the value we have chosen. Consequently the N simulated experimental results are

$$\Delta T = k\log[(j+\tfrac{1}{2})/N] \quad \text{with} \quad j = 0 \text{ to } N-1. \tag{3}$$

Second heat flux effect ($t_h \sim t_b$)

Here the velocity is set and the heat flux uniformly increased until nucleation occurs. Since there are no sudden changes in heat flux the system is always close to a steady state and equation (1) is obeyed. Figure 2 shows that under these conditions the experimental points do indeed fall along the heat balance lines [7]. The appearance of the ΔT vs q graph is in fact exactly the same as is obtained in the first heat flux effect. The distinction between the two effects lies in the predictability of individual experimental results. In the second effect, for a given inlet subcooling, one can only predict that the measured superheat will lie somewhere along the heat balance line. There is no way of telling exactly where.

The reason for this of course is that the arrival of the nucleating gas bubble is a random event, and it is only possible to make statistical predictions about the results of large numbers of measurements. The results of Logan *et al.* (Fig. 2) were obtained by uniformly increasing the heat flux, so the rate of rise of temperature was constant, and the probability of a superheat of a certain value should be given by equation (2).

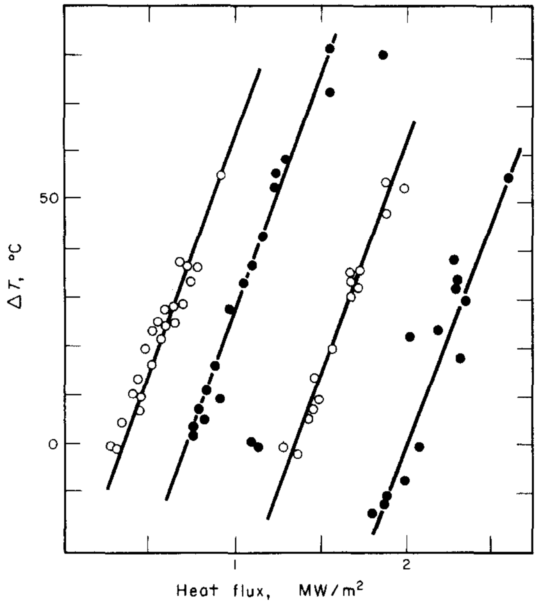

FIG. 2. Experimental results falling along the heat balance lines for different degrees of inlet subcooling [7]. $v = 1 \text{ m s}^{-1}$.

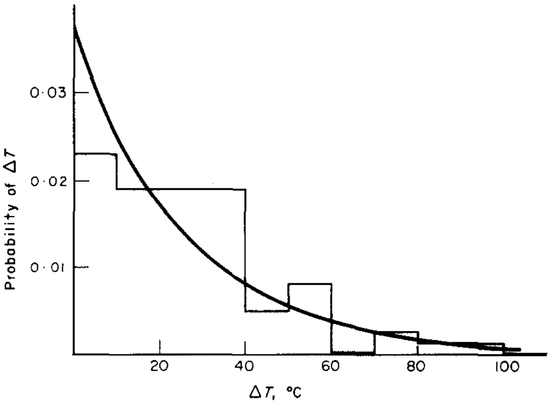

FIG. 3. Experimental results of Fig. 2 replotted as histogram of probability of measuring a certain superheat per °C interval against superheat. The smooth curve is the theoretical prediction of equation (2).

The value of p comes from the fact that the average superheat is $1/p$. In this way the theoretical line for the probability of measuring a given superheat is drawn on Fig. 3.

In order to have a reasonably large number of data points to compare with the theoretical prediction, all the points in Fig. 2 were used, since inspection of Fig. 2 does not show any obvious dependence of nucleation probability on inlet subcooling. (Changing the inlet temperature alters temperatures in the preheater, but not in the cold pipework where the bubbles are precipitated.) In this way the histogram of the experimentally measured superheat probability in Fig. 3 was constructed. One problem was what to do with the negative superheat values. In developing the statistical theory it was tacitly assumed that there was no radial variation of superheat in the test section, and so regardless of the radial position of the path of the bubble it would encounter the same maximum superheat. This obviously is not true, and for a bulk superheat of only a few degrees it is quite possible for the bubble to traverse a subcooled region and fail to nucleate boiling. This results in a greatly reduced probability of nucleation at low superheats. Also the opposite can happen, when the bulk liquid is subcooled the bubble can traverse a superheated region close to the heating surface and nucleate boiling. This accounts for the negative superheats found. If we assume that bubbles are equally likely to occur in any position in the channel, and a study of the forces involved suggests that to a first approximation this will be true [1], then every bubble that nucleates boiling at negative bulk superheat will be balanced by one that fails to nucleate at positive bulk superheat. Consequently the negative superheat points were included, but regarded as positive values. The agreement between theory and experiment is as good as can be expected, given the very small number of experimental points.

Second velocity effect ($t_h \sim t_b$)

Again we assume a uniform rate of rise of temperature, so the simple statistical theory derived above applies, and we consider the effect of doing a number of experiments at different flow velocities. The number of experimental values available is too small to attempt a proper statistical analysis, so instead we will compare the actual results with the simulated experimental results generated by equation (3). The number of bubbles going through the test section per second is likely to increase rapidly with flow velocity (see above), and so the probability that a bubble will come along per deg C temperature rise, p, will increase rapidly with velocity. To obtain a good fit for the example we assume $p = 0{\cdot}125\, v^2$, which is within the range estimated earlier.

In Fig. 4 the simulated experimental results are plotted as a function of velocity (5 measurements made at each velocity). Also shown are the actual experimental results of Pinchera *et al.* [8]. Unfortunately no details were given of the experimental procedure used, but the resemblance of the two sets of results suggests that this explanation is basically correct. Similar results have been obtained by other workers [7]. The main features of the second velocity effect which distinguish it from the first are a more rapid decrease of superheat with velocity and a large scatter in the points with the density of points increasing towards zero superheat.

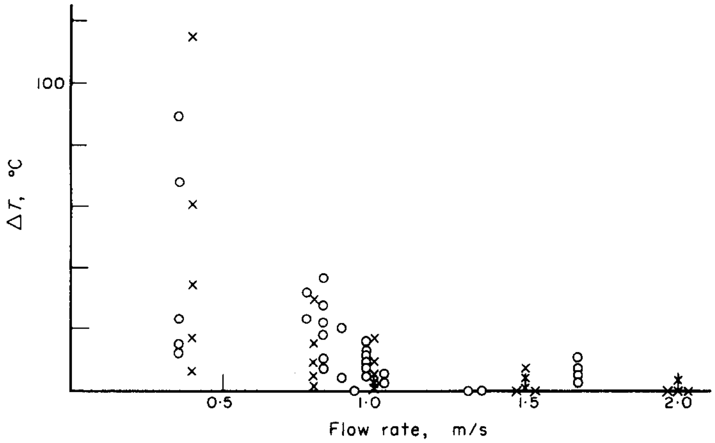

FIG. 4. The crosses represent the kind of experimental results that would be expected if nucleation occurred by the random passage of a gas bubble through the superheated region, with the probability of a bubble coming along increasing rapidly with velocity. The circles are the actual experimental results of [8].

Temperature ramp effect

Another method of bringing the liquid metal to boiling point is to fix v and q and steadily increase T_i, the temperature at inlet to the test section, by using a pre-heater. The number of bubbles passing through the test section per second will be constant, given the very long timescales required to alter the inert gas mass-transfer processes, but the probability of a bubble coming along per deg C temperature rise, p, is inversely proportional to the rate of increase of temperature, or temperature ramp, R. So the average superheat, $1/p$, will be proportional to R, and the distribution of individual results can be predicted by the statistical theory.

This experimental procedure was used by Dwyer *et al.* [9], and the main effect they observed was indeed an increase of superheat with temperature ramp (see Fig. 5). However, in a number of details the results do not fit the theory. The superheat does not tend to zero as R tends to zero, the scatter of the points is insufficient and the increase of superheat with heat flux is not predicted. All this is a consequence of the rather unusual choice of flow velocity. At 0·24 m/s in the test section and less still in the cold pipework where the argon bubbles precipitate it is appreciably lower than that used by other investigators. Under these conditions one would expect extremely large gas bubbles to form, and the passage of one of these through the test section would disturb the flow. Since the development of further theory is required detailed consideration of this experiment is left to later in the paper.

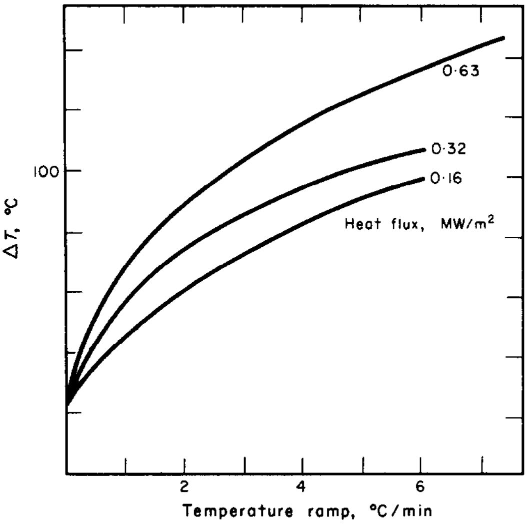

FIG. 5. Curves drawn through experimental points for superheat against temperature ramp, from [9].

High bubble concentrations

If the bubble concentration is so high that a bubble is bound to come along before the liquid metal can be heated appreciably above its saturation temperature then obviously zero superheat will result. The rapid increase of the number of bubbles with velocity means that loop experiments with velocities of a few metres a second or more are most unlikely to exhibit superheat. For example, in one experiment with test section velocities in the range 1–5 m/s essentially zero superheat was found under all conditions [10]. The range 1–2 m/s seems to be intermediate. In this case and reference [8] the superheat was low, other authors have found larger values.

The temperature ramp results of Dwyer et al.

It is stated in [3] that the cold portion of the experimental loop was made of nominal $2\frac{1}{2}$ in pipe, so the sodium velocity through the cold pipework where the argon bubbles precipitate can be estimated. Using the theoretical approach developed in [11] the radius of the bubbles on detachment was estimated to be of the order of a few mm, depending on the contact angles assumed and the orientation of the pipe. The rise velocity of bubbles of this size in a stagnant pool is over 1 m/s [2], so in rising through a vertical test section where the nominal flow velocity is only 0·24 m/s and the clearance 5·5 mm it is reasonable to expect a significant disturbance of the flow, lasting for the time it takes the bubble to rise through the test section, i.e. one or two seconds. Of course the rise velocity will be reduced by the presence of the tube walls, but even for bubbles filling the tube the velocity will be half that in an infinite pool [12].

The liquid in contact with the bubble will be cooler than under single phase conditions since the mass flow is increased. Thus the bubble may not be able to cause nucleation even though the test section was previously superheated. A heat balance across both test section and pre-heater gives, when there are no bubbles present, a superheat

$$\Delta T = T_i - T_s + \frac{slq}{mc} + \frac{Q}{mc} \tag{4}$$

where m is the undisturbed mass flow rate, Q the total heat input to the pre-heater and T_i is now the inlet temperature to the pre-heater.

With a bubble present in the flow

$$\Delta T = T_i - T_s + \frac{slq}{\lambda c} + \frac{Q}{vc} \tag{5}$$

where λ and v are the effective mass flow rates as the bubble goes through the test section and pre-heater respectively.

The minimum condition for nucleation is that the superheat in contact with the bubble, given by (5), should be zero. So,

$$0 = T_i - T_s + \frac{slq}{\lambda c} + \frac{Q}{vc}. \tag{6}$$

And the superheat measured before the bubble appeared [equation (4)], which is the value recorded, is

$$\Delta T = (T_s - T_i)\left(\frac{v}{m} - 1\right) + \frac{slq}{mc}\left(1 - \frac{v}{\lambda}\right) \tag{7}$$

(Q has been eliminated using equation (6)). This is the minimum superheat that can be measured. If in addition, after this minimum level is reached, there is a delay t before the first bubble comes along, the measured superheat at nucleation will be

$$\Delta T = (T_s - T_i)\left(\frac{v}{m} - 1\right) + \frac{slq}{mc}\left(1 - \frac{v}{\lambda}\right) + Rt \tag{8}$$

where R is the temperature ramp.

As it stands this explains the main experimental results, ΔT increasing with R and q and tending to a finite value as R tends to zero. However, to get detailed agreement with the experimental results we have to consider the effect of a distribution of bubble sizes. At very low values of R the system will not nucleate until one of the smallest bubbles in the distribution comes along. Larger bubbles cause a greater increase in mass flow rate as they rise through the test section, and hence reduce the outlet temperature below saturation. At very high values of R the superheat will have built up sufficiently by the time the first bubble comes along to ensure that the first bubble will nucleate regardless of size.

So on average a given value of R will be associated with a particular size of bubble. Now λ, v and t are all functions of the bubble size, so fixed R implies fixed λ, v and t. For example, at very high values of R, λ and v will be the average values for all bubbles in the distribution, and t will be the time to wait for any size of bubble to come along.

Inspection of equation (8) shows that with R and the other quantities fixed the superheat should be a linear function of heat flux q. Also the slope of the straight lines and the intercept on the superheat axis should change with R. These predictions are confirmed by the experimental results in Fig. 6 [9].

If on the other hand superheat is plotted as a function of temperature ramp R at fixed heat flux q then to a first approximation equation (8) predicts straight lines of slope t, which is almost what was observed experimentally (Fig. 5). However, as R increases t gets shorter. As explained above, as R tends to zero nucleation will be caused by one of the smallest bubbles in the distribution and t is the time to wait for one of these bubbles to appear. As R gets larger, bigger and bigger bubbles will also be effective in nucleating boiling, and so on average the time to wait for a suitable bubble gets less and less. Consequently the slope of the lines in Fig. 5 decreases with R.

Interestingly there was fairly direct evidence for the passage of these large bubbles through the test section, though it was misinterpreted by the authors. Figure 1 of reference [9] shows the temperature trace from one of the test section thermocouples, illustrating the occurrence of a low temperature spike. This lasted 2 s

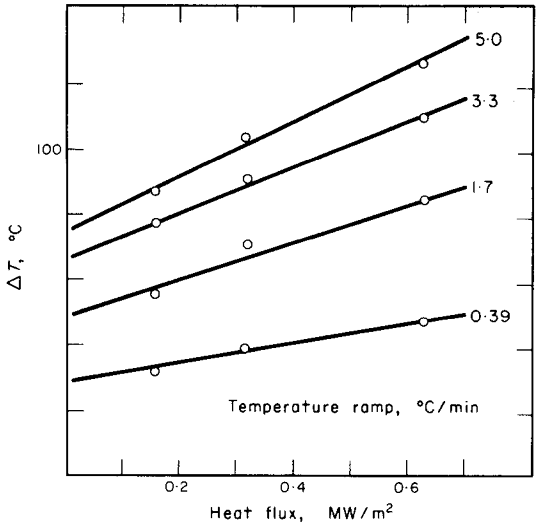

FIG. 6. Experimental results for superheat as a function of heat flux (circles), from [9]. As predicted they lie on straight lines, the slope and intercept varying with the temperature ramp.

in total, and at its peak represented a reduction in test section temperature of some 27°C. The 2 s is consistent with the estimate above of the time the flow would be disturbed, and the 27°C temperature reduction for this particular bubble is consistent with the fact that the lowest superheat observed was about 20°C.

DISCUSSION

All the main effects in incipient boiling superheat of liquid metals in forced convection have been explained. In most cases it is not possible to calculate the number of bubbles required to explain the experimental results because the rate of rise of temperature is not given. However, the fact that in a number of cases a steady state was obtained before the first bubble came along suggests less than one bubble a second, and Logan *et al.* [7] state that the interval between starting to increase power and nucleation was 40 s, implying one bubble every 20 s (the sodium was subcooled for half the time). So for test section velocities of 1 m/s the limited experimental evidence suggests one bubble every 10 s or so. This is rather fewer than the estimate from mass-transfer considerations at the beginning of the paper (one bubble a second), but close enough in view of the lack of detailed information either about the rigs or the way they were operated.

The only other explanation that has been put forward for any of these effects is that the reduction in superheat with velocity is due to turbulent pressure fluctuations. Consider the dynamic pressure $\Delta p = \frac{1}{2}\rho \mathbf{v}^2$ required to reduce a superheat of 70°C at 0·3 m/s to 0°C at 2 m/s. It is equivalent to $\mathbf{v} = 15$ m/s. That is, locally within the sodium the turbulence is causing the liquid to flow backwards with six times the mean forward velocity. This result is not credible. More detailed calculations suggest that the pressure reduction due to turbulent pressure fluctuations would be less than 1 per cent of the value needed to cause the effect [1].

Looking at this another way, the pressure fluctuations in fully developed turbulent flow in a given geometry will depend largely on the mean flow velocity, to a small extent on Reynolds number, but not on anything else. So just one measurement of high superheats at high velocities is sufficient to disprove the pressure fluctuation theory. This one measurement has in fact been done, in a blow-down type of experiment [13]. The advantage of this over a circulating system is that there is no time for gas bubbles to grow. Superheats of 44°C independent of velocity were obtained at velocities up to 6 m/s.

CONCLUSIONS

All the main effects that have been observed in forced convection liquid metal superheat can be explained on the assumption of nucleation by entrained gas bubbles.

The number of gas bubbles required is consistent with estimates based on the inert gas mass-transfer processes.

Consequently no intrinsic dependence of superheat upon heat flux, flow velocity or temperature ramp has so far been convincingly demonstrated, if indeed such dependence exists.

However, under restricted circumstances, the superheat will depend upon parameters related to heat flux and flow velocity. If the liquid metal is superheated rapidly to a new equilibrium temperature before the first gas bubble arrives, then the bulk outlet superheat is determined by a heat balance across the test section, and this is the superheat that will be measured when the bubble arrives and nucleates boiling. In this sense superheat will increase with increases in either inlet temperature or total heat supplied to the test section, and will decrease with increase in the mass flow rate.

Future experiments to measure the superheat required to initiate boiling of liquid metals in forced convection should include a gas bubble detector sensitive to single bubbles down to a few μm radius.

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SURCHAUFFE DE METAL LIQUIDE EN CONVECTION FORCEE

Résumé—L'analyse du transfert massique de gaz inerte dans les systèmes utilisés dans les mesures expérimentales de surchauffe montre que l'écoulement est susceptible de contenir des bulles gazeuses qui se dégagent de la solution et le nombre de bulles croît rapidement quand la vitesse augmente dans le tube froid. L'article étudie l'influence que ces bulles peuvent avoir sur les mesures de surchauffe. Selon la façon dont est conduite l'expérience, il peut y avoir un effet apparent d'acroissement de la surchauffe quand le flux de chaleur ou l'écart de température est augmenté, ou de décroissance de surchauffe quand la vitesse de l'écoulement est accentuée.

ÜBERHITZUNGSWÄRME FLÜSSIGER METALLE BEI ERZWUNGENER KONVEKTION

Zusammenfassung—Bei Untersuchungen der Stoffübertragung von Inertgasen in Meßeinrichtungen für die Bestimmung der Überhitzungswärme wird festgestellt, daß die Strömung anscheinend Gasblasen enthält, die aus der Lösung stammen und daß ihre Anzahl rasch zunimmt, wenn die Flußgeschwindigkeit im kalten Teil des Rohrnetzes, wo die Blasen ausgeschieden werden, erhöht wird. Die Abhandlung untersucht die Auswirkungen, die diese Blasen bei der Messung der Überhitzungswärme haben könnten. Je nach Versuchsdurchführung wird ein scheinbarer Effekt auftreten, entweder als Anstieg der Überhitzungswärme bei Erhöhung des Wärmeflusses oder als Temperaturgradient oder als Verringerung der Überhitzungswärme bei Erhöhung der Flußgeschwindigkeit.

ПЕРЕГРЕВ ЖИДКИХ МЕТАЛЛОВ В УСЛОВИЯХ ВЫНУЖДЕННОЙ КОНВЕКЦИИ

Аннотация — Анализ массопереноса инертного газа в системах для экспериментального измерения перегрева показывает, что в потоке жидкости, вероятно, содержатся газовые пузырьки, вышедшие из раствора, и число пузырьков быстро увеличивается при увеличении скорости потока в холодном трубопроводе, где выделяются пузырьки. В работе исследуется влияние пузырьков на измерение перегрева. В зависимости от путей проведения эксперимента, можно наблюдать кажущееся увеличение перегрева при увеличении теплового потока или температуры, или снижение перегрева при увеличении скорости течения.