HETEROGENEOUS FLASHING IN WATER DROPS

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Abstract—This paper is concerned with the vaporization of superheated water drops. When calculating the heat and mass transfer from drops in this condition, it is not known to what temperatures the drops will superheat before they react through explosive flashing. An experimental study has been carried out in which water drops with diameters between 1 and 3 mm have been suspended on a thermocouple junction in a saturated steam environment within a vessel at pressures up to 9 bar abs. By rapidly depressurizing the vessel at different rates so that the drop superheated, it was possible to measure the temperature of the drop and to observe its reaction. For superheat temperatures up to 5°C the drops experienced only quiescent surface evaporation. For superheat temperatures between 5 and ~18°C, the drops reacted through internal boiling but did not disintegrate. For temperatures above about 18°C the drops reacted by flashing explosively.

Key Words: flashing, drops, evaporation, phase-change, two-phase flow, heat and mass transfer, superheated liquid

INTRODUCTION

When a liquid is at a temperature above the saturation temperature for its pressure, it is superheated and is out of thermodynamic equilibrium. In a static situation and under carefully controlled conditions (pure substance, perfectly clean and smooth vessel and no physical disturbances) it is possible for a liquid to be maintained in this metastable state. Under most practical circumstances, however, the ideal conditions cannot be met and the metastable liquid will return to its equilibrium condition through evaporation, thus releasing its superheat as latent heat. A liquid at its saturation temperature and pressure can gain superheat in one of two ways: it can be heated to a higher temperature while its pressure is maintained, or it can be depressurized rapidly so that its thermal inertia ensures the internal temperature remains nearly constant and above its new saturation temperature. In the former case, the higher temperature will be at the interface of the liquid and its surroundings, and evaporation, when it occurs, will be at the interface. In the latter case, the highest temperature will be inside the liquid and evaporation will tend to be from within.

In the present work, it is this latter case which is of interest. If the superheat within the depressurized liquid can be conducted to the liquid surface, the latent heat will be released through surface evaporation. If, however, the heat cannot be conducted at a sufficiently high rate to the surface, evaporation will occur within the liquid through bubble growth. This process can be extremely violent and explosive. When a saturated liquid is depressurized, therefore, it will react in one of the two ways just described. In this paper we distinguish between these two reactions by referring to the former as evaporation and the latter as flashing (in general, the term flashing refers to the evaporation of a liquid due to its sudden depressurization and is often used to describe both reactions).

This paper is concerned with the flashing of superheated water in the form of a drop which was produced by depositing a small amount of water onto a looped thermocouple wire. The suspended drops were held in a small pressure vessel filled with saturated steam at pressures up to 9 bar abs. By rapidly depressurizing the vessel, the drops were left in a superheated condition where their temperatures could be measured and their reactions observed. Because the water of the drop is in contact with the thermocouple it will experience heterogeneous nucleation promoted by the surface.

FLASHING

For a superheated liquid to regain equilibrium it must lose internal energy; this is preferentially achieved through latent heat transfer. The release of latent heat of vaporization is initiated through

nucleation within the liquid and this topic is well-reported in standard texts on the subject of boiling (e.g. Whalley 1979). Nucleation theory is based on the thermodynamics of phase change, on bubble dynamics and on the probability theory of the existence of molecular clusters within a liquid. It is readily shown that if the bubble nucleus reaches a critical diameter, d_c, then it will grow spontaneously and boiling will occur. The temperature at which this event occurs is referred to as the superheat limit, ΔT_s, and given by

$$\Delta T_s = T - T_s = \frac{4\sigma T_s v_G}{h_{FG} d_c},$$ [1]

where T_s is the saturation temperature of the liquid and σ, v_G and h_{FG} are, respectively, the surface tension, specific volume and latent heat of vaporization.

The critical radius at which nucleation will begin is influenced by many factors and, in practice, is usually indeterminate. This uncertainty leads to difficulties in predicting the behaviour of superheated liquids. If the superheat limit is reached, the liquid experiences homogeneous nucleation. If the liquid nucleates before the limit, the liquid experiences heterogeneous nucleation. Some liquids, e.g. n-octane, will support sufficient superheat for them to nucleate homogeneously; others, and water is in this category, cannot be taken to the superheat limit and will nucleate heterogeneously.

When individual liquid drops, or a spray, are contained in a saturated environment which is suddenly depressurized, the drops may flash and fragment. These conditions will be encountered, for example, in flashing atomizers, in wet steam turbines and in geothermal two-phase nozzles. Consider a drop initially in thermal equilibrium with its vapour, figure 1. The temperature throughout the drop will be the saturation temperature for the system pressure $T_s(P_1)$. If the surrounding pressure falls instantaneously to P_2, the surface of the sphere and the vapour "shell" adjacent to it will adopt the saturation temperature for the new pressure, $T_s(P_2)$. This will be the case regardless of whether the surrounding vapour is at saturation conditions or not, i.e. it is only the pressure of the surroundings that is important. It is tacitly assumed that the drops are sufficiently large that the excess internal pressure due to surface tension is unimportant, but if this
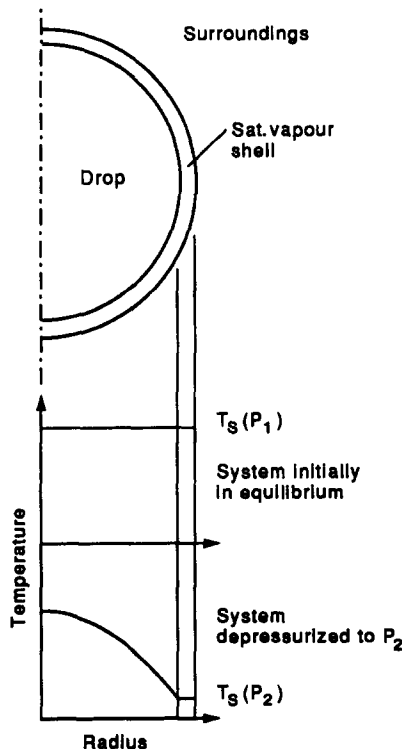

Figure 1. Temperature in a drop.

is not the case, a correction can be made (e.g. Whalley 1979). If the internal heat transfer is assumed to be due to conduction alone, then the centre temperature of the sphere, T_c, at a time t can be calculated (Carslaw & Jaeger 1959) by

$$\frac{T_c - T_s(P_2)}{T_s(P_1) - T_s(P_2)} = \theta = -2 \sum_{n=1}^{\infty} (-1)^n \exp\left[\frac{-4\alpha n^2 \pi^2 t}{d^2}\right],$$ [2]

where d is the diameter of the sphere and α is the thermal diffusivity of the liquid. If the superheat $[T_c - T_s(P_2)]$ is too great, explosive flashing will result. It is the magnitude of this critical superheat which is of interest in the present study.

Another, similar situation which has been investigated and which also has a well-defined geometry, is the flashing of a superheated jet. This topic has received attention because of its importance in atomizers and also as a model for the loss of coolant accident (LOCA) scenario related to water-cooled nuclear reactors. Much of the work has concentrated on the critical flow condition (e.g. Henry 1970; Schrock et al. 1977; Lackme 1979), but others have considered the behaviour of the superheated jet as it emerges from a sharp orifice. Brown & York (1962) made measurements of the level of superheat required to produce an effective spray and made size measurements of the drops produced. Lienhard & Stephenson (1966) also considered the flashing in a superheated water jet issuing from sharp-edged orifices. They deduced a simple expression for the delay time required before homogeneous nucleation would occur in the jet. In a later paper, Lienhard & Day (1970) extended this line of enquiry and made comparisons of the predicted delay time with experimental measurements. The delay time is the time between a liquid becoming superheated and the onset of boiling. It was shown that the delay time, t_D, is related to the superheat by

$$T_D \propto \Delta T_s^{-2/7}.$$ [3]

By considering their jet as an infinitely long cylinder of diameter d with an initial uniform temperature which experiences a step-change in the surface temperature, from $T_s(P_1)$ to $T_s(P_2)$, as it emerges from the orifice, they were able to calculate its cooling rate by conduction theory. The resulting centreline temperature is shown in figure 2 as a function of dimensionless time. It was reasoned by Lienhard & Day (1970) that since the superheat is proportional to $t_D^{-2/7}$, if the jet cooled at a rate faster than this, it would escape flashing. From figure 2, the point at which this occurs for the cylinder is at a Fourier number of 0.0205 and a dimensionless temperature of 0.91. Thus, if the jet does not flash before a time $0.0205\, d^2/\alpha$, it will escape flashing.

The reasoning of Leinhard & Day (1970) is easily extended to the cooling rate of a solid sphere. Reference to figure 2, which also includes the centre temperature of a cooling sphere, shows the
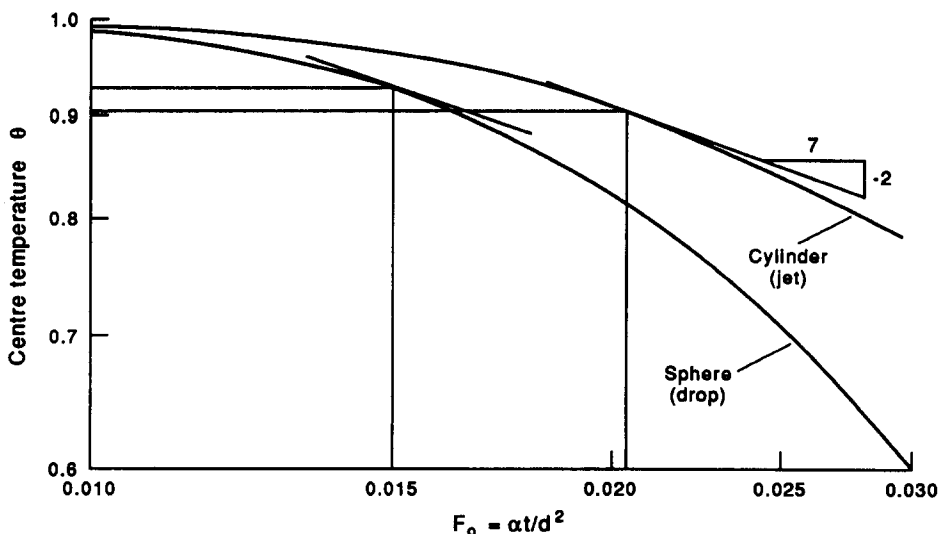

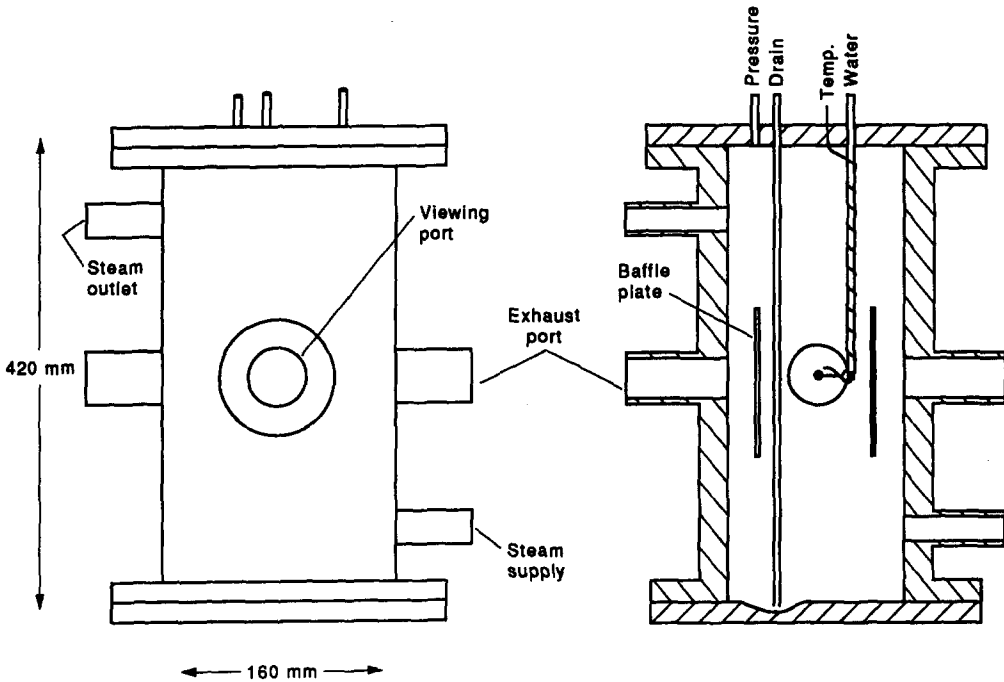
Figure 2. Cooling rate of a jet and drop.

Figure 3. Steam vessel.

corresponding time and temperature to be $0.015\ d^2/\alpha$ and 0.95. Thus, if a drop is saturated at a temperature of, say, 200°C and is then depressurized to a saturation temperature of 100°C, if its centre can cool to 195°C and the drop remain intact, it will escape flashing. Superheat temperatures of up to 95°C may be possible for some liquids but they are certainly not sustainable in water. Hewitt (1981) suggests that superheat temperatures found in practice for water are about 10°C and Lienhard & Stephenson (1966), in their experiments with water jets, found the water could not withstand superheat temperatures higher than about 27°C. Some fluids, on the other hand, can be heated to temperatures close to their superheat limit from where they will nucleate homogeneously, e.g. diethyl ether, pentane, isopentane, butane and n-octane.

EXPERIMENTAL INVESTIGATION OF FLASHING WATER DROPS

Apparatus and procedure

The apparatus used in the investigation is shown in figure 3. The steam vessel was supplied with saturated steam at pressures up to 9 bar abs from a 9 kW electric boiler. The steam was exhausted from the vessel to a condenser. The water drop was formed using the arrangement shown in figure 4, in which a fine thermocouple wire (about 0.05 mm dia) was looped as shown so that it
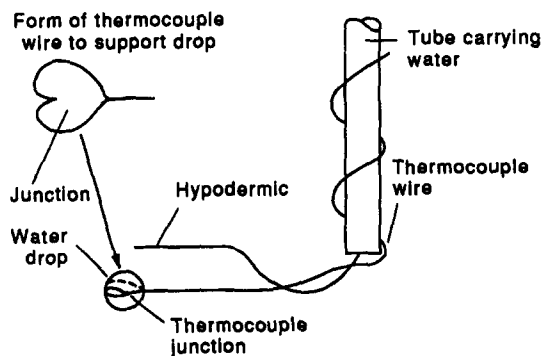

Figure 4. Method of supporting the water drop.

would support a drop by surface tension in such a way that the thermocouple junction was inside the drop. The drop was placed onto the thermocouple by the fine hypodermic tube which was formed in the way shown to prevent condensate running down it and dislodging the drop. The drop, being in contact with the thermocouple, experienced heterogeneous nucleation promoted by the thermocouple surface.

While the vessel was being charged by the steam, a small amount was bled continuously from the top of the vessel to help vent any air that might collect. During this period the drop was placed onto the thermocouple. The water was obtained from a purification unit (reverse osmosis, deionization and membrane filtration) and was forced into the vessel using compressed nitrogen gas. In this way it was ensured that the water quality was not variable. When the drop and its surroundings were in thermal equilibrium at the required pressure, the steam supply was closed and the vessel opened to the condenser. Prior to the steam being exhausted, the condensate which collected in the well at the bottom of the vessel was expelled since this water would also flash if left, and ruin the experiment. The opening to the condenser was via a quarter-turn ball valve; by opening the valve through different angles in different experiments it was possible to obtain different rates of depressurization and levels of superheat. The drop was protected from the rush of steam as it flowed to the two exhaust ports by two shields; one either side between the drop and each port.

The transient pressure was measured using a pressure transducer connected to the vessel by a short, flooded tube. The response time of the pressure transducer was estimated to be <0.01 s. The thermocouple response was estimated to be about 0.08 s and this led to some error in the transient temperature reading. For the most rapid rate of depressurization, the time to the maximum level of superheat was a couple of seconds—longer for smaller valve openings and lower pressures. For these faster processes, it was estimated that the recorded superheat was up to 3°C lower than the actual value. Rather than correct the readings, they have been left as recorded but this possible error should be borne in mind. The readings from the pressure transducer and thermocouple were recorded on a microcomputer.

It was possible to produce drop sizes of only a limited range since large drops would detach during blowdown and for small drops the relative size of the thermocouple wire was considered too large. (The thermocouple bead had a diameter of about 0.12 mm.) The size range obtained was 1–3 mm; the size of the drop being measured through the viewing ports using an optical cathometer.

The reaction of the drop to the process was also viewed through the cathometer and was found to fall into one of three main categories. For the slower rates of depressurization, the drop reacted through quiescent surface evaporation; for medium rates it reacted by boiling from within, but with insufficient violence to fracture the drop; for high rates the drop fragmented (i.e. in our terminology, it flashed). When the drop reacted through boiling, it took upwards of about a second to react (a lot longer with large drops and medium rates of depressurization) and the reaction was easily observed by eye through the cathometer.

In an attempt to provide an extreme upper limit to the drop size, two small water-filled glass beakers were also used in different experiments and their temperatures recorded as before. The equivalent sphere diameters were 11 and 22 mm.

RESULTS

The microcomputer recorded the transient pressure and the drop temperature. Figure 5 shows, schematically, the principal features of the recorded data. The difference between the temperature in the drop and the saturation temperature corresponding to the system pressure, is the superheat. Figure 6 shows how the superheat evolved in a typical experiment: rising to a maximum before the drop reacted and the temperature fell. The slight subcooling at the end of the process is believed to be due to the presence of air in the vessel. The physical reaction of the drop in each experiment was observed and recorded. For the case shown in figure 6, the drop reacted by flashing.

By repeating the experiment using different drop sizes and different starting pressures and valve openings, it was possible to record the reaction of the drops for different levels of superheat. Figure 7 shows how drops of different sizes reacted to the different superheat temperatures. The delay time for the water was calculated to be the order of 1 ms; this is much shorter than the time
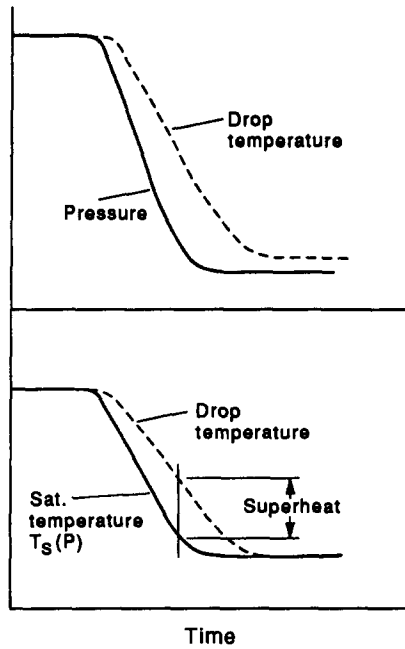
Figure 5. Development of superheat in a drop.

period over which the drop reacted. Therefore when the drops reacted, they did so because of the level of superheat, and not simply because the delay time was exceeded.

DISCUSSION

The main results of this study are shown in figure 7. The boundaries between the different reactions of the drops are not precise, but distinct regions can be identified. For superheat levels up to 4 or 5°C, the drops reacted through quiescent surface evaporation. There is then a wide range of superheat over which the drop boiled from within, but remained intact. For higher superheats (upwards of 18–24°C for drop sizes 1–3 mm), the drops liberated their superheat through explosive flashing. It is at these higher levels of superheat that the errors in the thermocouple reading mentioned earlier were incurred. The larger drops will be mechanically weaker than smaller ones and they therefore flash more readily. The water contained in the small beakers always reacted by boiling, but at different rates depending on the levels of superheat. This reaction is not surprising since the glass will have provided a large surface area for artificial nucleation sites. Water drops
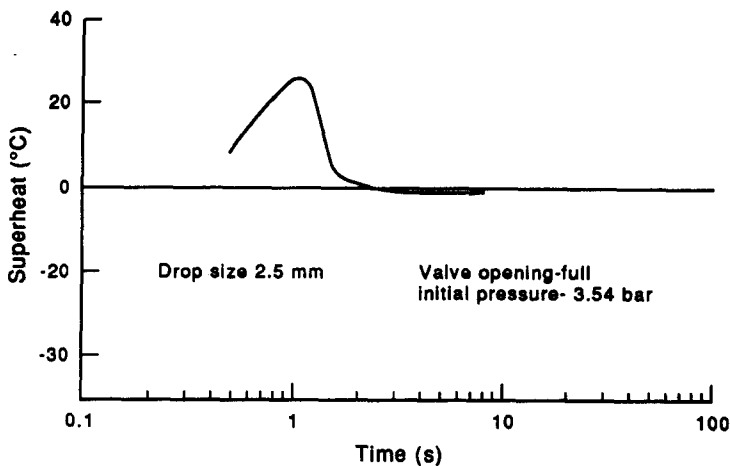

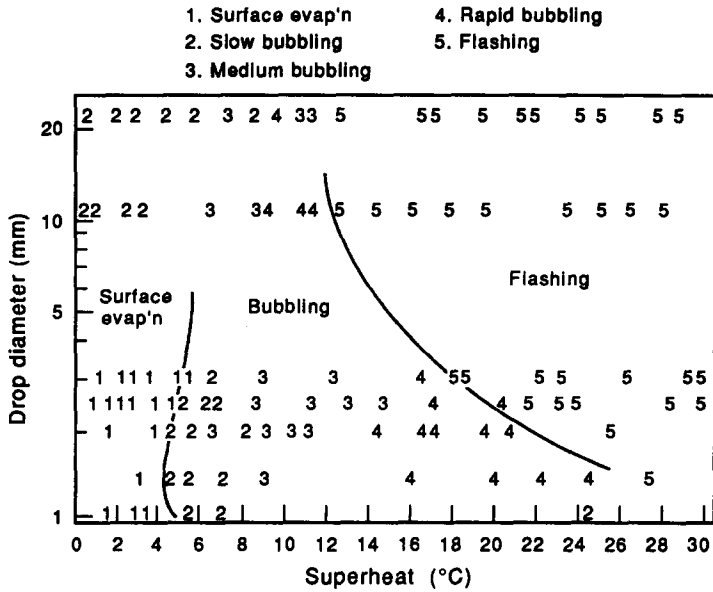Figure 6. Superheat in a flashing drop.

Figure 7. Reaction of water drops to superheat.

of the size represented by the beakers are not encountered in normal circumstances. However, this part of the experiment assisted in drawing the boundaries in figure 7.

For a wide range of temperatures the drops had internal boiling but remained intact. This feature has been observed in organic liquid drops suspended in an immiscible fluid at temperatures above the saturation temperatures of the drop. In these studies (Shepherd & Sturtevant 1982; Avedisian 1982; Frost 1987a,b), the interest was related to the evaporation of fuel drops and to vapour explosions. Photographic evidence showed clearly the extent to which the drops suffered internal boiling without disintegrating.

Gyarmathy (1963) calculated the cooling rate of small water droplets suspended in the expanding flow of a wet steam turbine. He assumed that the drops did not flash until the centre of the drop became superheated by 5°C or more. This criterion was intuitive and is, in fact, not inconsistent with the present findings. Although figure 7 shows the drops can remain intact with superheats much higher than 5°C, in the turbine situation the drops will also be experiencing aerodynamic forces and it is likely that if the drops were weakened by internal boiling, they would be torn apart.

In their experiments into the flashing of superheated water jets, Lienhard & Stephenson (1966) found that a superheat of about 27°C was required for the jet to disintegrate at atmospheric pressure. The present authors, in a similar study, obtained comparable results where the critical superheat increased from 23 to 30°C as the jet diameters were increased from 2.5 to 5.0 mm. These values are broadly in agreement with the data in figure 7.

In a geothermal power plant the geofluid can be flashed and the vapour portion separated and expanded through the turbine with the liquid portion being reinjected to the reservoir. Another technique is to expand the whole of the geofluid through a total flow nozzle in a more robust design of turbine. In a discussion of the thermal disequilibrium encountered in total flow nozzles, Owen & Ryley (1985) showed how the extra enthalpy available within the liquid phase may not be realized because the water would simply superheat. The extent to which the water can superheat without yielding its superheat enthalpy is, from figure 7, about 5°C and at temperatures above this in the violent flow inside the nozzle, the water will flash.

The water drops produced by condensation in a turbine will be very pure and will therefore not have the nucleation sites such as those provided by the thermocouple in the present experiment. The water in the superheated jet experiments was tap water and, although not pure, it would have only limited dissolved and suspended material. The geofluid being atomized in the total flow nozzles will have significant dissolved salts and suspended particulates and this case will be more closely represented by the present experiment.

The superheat temperatures being discussed were obtained at pressures close to atmospheric. It is known that pressure has an effect on cavitation and boiling, and at higher pressures it is likely that the reaction boundaries shown in figure 7 will be different. Avedisian (1982) investigated the bubble growth within *n*-octane drops suspended in glycerine under pressure. It was shown how, at high pressures, the excess pressure within the bubble due to vapour generation is reduced and the growth rate of the bubble is controlled by the rate of heat transfer from the liquid. The bubble growth rate, and therefore the likelihood of flashing, is thus reduced.

CONCLUSIONS

The metastability of explosive flashing of water makes it very difficult to specify the conditions under which it will occur. When calculating the heat and mass transfer from drops it has not been possible to put an upper limit, above which they disintegrate, on their superheat temperatures. The purpose of the work described in this paper was to obtain the level of superheat that water drops might be expected to sustain before they flashed. The results suggest that the drops will withstand superheat temperatures of about 5°C before they begin to boil from within. In a quiet atmosphere the drops may sustain superheat temperatures in excess of 18°C without disintegrating, but they will suffer increased internal boiling.

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