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Boiling of droplets on a hot surface in low gravity

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Abstract—The boiling of single droplets of water and *n*-heptane on a hot stainless steel surface was observed in a low gravity environment, obtained on board a platform in free fall. Droplet impact was photographed using a single-shot flash-photographic method. Surface temperature variation during droplet impact was recorded using a fast-response thermocouple. Droplets could not be maintained in stable film boiling in low gravity: the pressure of vapour under droplets pushed them away from the surface. Nucleate boiling of droplets was not affected by a reduction in gravity. Vapour bubbles nucleating on the solid surface separated and rose into the liquid even in the absence of buoyancy forces.

1. INTRODUCTION

Acceleration due to gravity, *g*, appears as an independent variable in most pool boiling correlations [1]. For example, nucleate boiling heat flux is predicted to vary as $g^{1/2}$, and both the critical heat flux and minimum heat flux as $g^{1/4}$. An intriguing implication of these correlations is that in the limit that $g \rightarrow 0$ all heat fluxes would be expected to vanish, which, if true, would prevent heat transfer equipment from functioning in the low gravity environment found on board a spacecraft. Gravitational forces were originally introduced into the analysis of boiling on the basis of dimensional arguments, even though no direct observations had then been made of the effect of gravity on boiling. Experiments on pool boiling in low gravity were started in the late 1950s in an effort to obtain heat transfer correlations applicable to spacecraft design. Siegel [2] has reviewed much of the early work. The principal findings were that: gravity has little effect on nucleate pool boiling heat transfer coefficients; for low wall heat flux, vapour bubble departure diameters increase at low gravity; the critical heat flux decreases in the absence of buoyancy forces; and stable film boiling can be maintained at low gravity, but heat transfer is reduced.

These results contradicted the assumption made in models of boiling that buoyancy forces lifted vapour bubbles off the heater surface during nucleate boiling, and that this was the dominant means of heat transfer. It had also been thought that stable film boiling would not be achieved in the absence of gravity. Recent investigations [3–5] have tried to resolve these contradictions and determine the fundamental mechanism of boiling. Straub *et al.* [3] studied boiling of R-12 and R-113 on wires and flat plates, and found that vapour accumulated on the heater surface during nucleate boiling in low gravity. This, however, had little effect on the heat transfer coefficient. Thermocapillary convection was proposed as the dominant heat transfer mode during nucleate boiling in the absence of buoyancy. Measured values of the critical heat flux were much higher than those predicted from models based on hydrodynamic instability theories. Oka *et al.* [4] studied nucleate boiling of *n*-pentane in low gravity, and confirmed that vapour accumulation on the heater surface reduced heat transfer by only a small amount. High wall heat flux caused rapid bubble growth, producing inertial forces large enough to detach bubbles from the heater surface even in the absence of buoyancy. Ervin *et al.* [5] noted that most previous experiments had been done using wires as heaters whose diameters were smaller than the size of nucleating vapour bubbles. Surface tension effects for bubble nucleation on wires would be different from those on large flat plates. They photographed boiling of R-113 on a flat quartz surface and identified several different types of bubble motion during nucleate boiling in microgravity.

A few studies have examined the effect of reducing gravity on heat transfer in flow boiling, in which inertial forces are present. Cochran [6] found that at low liquid subcooling and flow velocity bubbles accumulated on the heating surface during nucleate boiling in reduced gravity. Westbye *et al.* [7] studied quenching of a heated tube over which R-113 was injected and found that at low gravity nucleate boiling was not affected, but film boiling heat transfer coefficients were reduced.

Low gravity boiling experiments [2–5] have shown that inertial and surface tension forces are sufficient to cause bubble departure during nucleate boiling, even in the absence of buoyancy. However, there is still no consensus as to the mechanism controlling transition from nucleate to film boiling. Theoretical analyses of the onset of film boiling have generally assumed one of two different mechanisms: hydro-

NOMENCLATURE

Bo	Bond number
d	diameter of wetted area
$d_{\max}$	maximum diameter of wetted area during droplet spreading
D	droplet diameter
Fr	Froude number
g	acceleration due to gravity
g_0	earth normal gravity
k	thermal conductivity
t	time
T_c	contact temperature, defined in equation (1)
T_{critical}	critical temperature
T_{DNB}	departure from nucleate boiling temperature
T_{Leid}	Leidenfrost temperature
T_{sat}	saturation temperature
T_w	surface temperature
T_{wi}	initial surface temperature
$\Delta T_{\max}$	maximum surface temperature drop during droplet impact
V	droplet impact velocity.

Greek symbols

α	thermal diffusivity
β	spread factor ($= d/D$)
γ	$= (k\rho C)^{1/2}$
δ	vapour film thickness
λ	latent heat of vaporization
μ	viscosity
ρ	density
σ	surface tension.

Subscripts

a	air
l	liquid
v	vapour
w	solid surface.

dynamic or thermodynamic. Hydrodynamic models [8, 9] postulate that fluid instability causes transition to film boiling, in which case the minimum film boiling temperature is a function of g. Thermodynamic models [10–12] assume this temperature to depend on liquid and solid properties, and to be independent of g. Measurements made during pool boiling experiments [2] showed that film boiling heat transfer coefficients vary as $g^{1/4}$ for $10^{-2}g_0 < g < g_0$, confirming predictions from hydrodynamic theory. However, Straub *et al.* [3] found that for $g < 10^{-2}g_0$, heat transfer was independent of changes in gravity. They pointed out that no theory can predict critical heat flux in the limit that $g \rightarrow 0$.

The effect of gravity on the temperature at which transition to stable film boiling takes place (often called the 'Leidenfrost temperature' [10]) is unclear, and appears to be different in pool boiling and flow boiling. Merte and Clark [13] observed boiling on the surface of a copper sphere dropped into a pool of liquid nitrogen and found that the minimum film boiling temperature increased when gravity was reduced. However, Westbye *et al.* [7] found that during quenching of a heated tube the re-wetting temperature decreased when gravity was lowered. They concluded that their results could be explained using a hydrodynamic instability model. These differing effects of gravity on film boiling highlight the fact that there may be several possible mechanisms for transition to film boiling, with the relative importance of each depending on fluid physical properties, solid surface properties, fluid flow characteristics and heater geometry.

The film boiling of liquid droplets on a hot surface (known as Leidenfrost evaporation) has been studied extensively [14], being encountered in a number of applications such as spray cooling of hot surfaces, cryogenic liquid spills, nuclear reactor safety and dispersed flow in heat exchanger tubes. However, our search of the literature found no study on Leidenfrost evaporation in low gravity: it was not known whether stable film boiling of droplets was possible in the absence of gravity. This study was undertaken to examine the effect of reducing gravity on the boiling of a droplet on a hot surface. Experiments on droplet impact on a hot surface in low gravity, where the surface was heated prior to impact to a temperature high enough to support film boiling, allowed direct observation of the transition to film boiling. Droplet impact was photographed with sufficient clarity to allow bubble formation and departure in the liquid to be observed directly.

Results from experiments on the impact of liquid droplets on a hot surface have practical applications in modelling heat transfer during dispersed flow following dryout in heat exchanger tubes, in which liquid droplets transported by a stream of vapour impinge on the tube surface [1]. Reducing gravity is known to alter two-phase flow patterns in tubes [15, 16]. They are also relevant to the design of spray cooling systems, which give heat transfer rates an order of magnitude higher than those obtained during pool boiling, making them attractive for use in spacecraft for electronic cooling, fire extinguishment and environmental temperature control. No experiments have been done to observe spray impact on a hot surface at low gravity. However, several studies [17–19] were done to measure heat transfer from an inclined surface to an impinging spray in normal gravity, and their results suggested that cooling efficiency may be influenced by orientation of the surface with respect to gravity. Heat flux from a horizontal, upward facing surface to an impacting spray was found to be higher than that from a downward facing [17] or vertical surface [18]. The effect of gravity forces on boiling raises the possibility that changing the magnitude, rather than the direction, of gravity may influence heat transfer from a hot surface to impinging droplets.

We photographed the impact and boiling of droplets on a hot surface in a low gravity environment, and measured surface temperature variation during droplet impacts. By comparing these observations with similar measurements made under normal gravity conditions [20], we intended to isolate the effect of buoyancy forces on droplet impact and boiling. Our main objective was to study the effect of gravity and liquid properties on transition from nucleate to film boiling. Additional observations were made of droplets in nucleate boiling and droplet impact dynamics. Experiments were done with droplets of water and *n*-heptane, which have widely differing physical properties. The surface material (polished stainless steel), droplet initial diameter (2.0 mm for water, 1.5 mm for *n*-heptane), impact velocity (0.8 m s^{-1}), ambient temperature ($\sim 25°C$), and initial droplet temperature (equal to ambient) were held constant. The surface temperature was varied from 25 to 320°C, spanning the entire range of heat transfer regimes, from evaporation to film boiling.

2. EXPERIMENTAL APPARATUS

A low gravity environment can be obtained by placing the experimental apparatus on board a platform in free fall [2]. Previous investigators have used drop towers, aircraft in parabolic flight, or ballistic rockets to provide such a platform. The height from which the test package is dropped depends on the total low gravity time required, which has typically varied in pool boiling experiments from a few seconds (drop towers) to several minutes (ballistic rockets). In our experiments, the impact and spread of a droplet took less than 20 ms. To obtain low gravity for this duration requires a minimum drop height of only 2 mm, which could be easily achieved in a table top experiment in the laboratory.

Figure 1 is a schematic diagram of the experimental apparatus. The droplet generator and test surface were placed in a closed aluminium chamber (356 mm long × 203 mm wide × 216 mm high) that could be released in free fall. Clear plastic windows in the front and rear walls allowed illumination and observation of the chamber interior. A cable suspended below the drop package carried electric power and sensor signals. The package fell through a distance of 15 mm, providing a low gravity time of 55 ms; a foam cushion arrested its drop.

The droplet generator consisted of a syringe pump that forced liquid through a 0.2 mm o.d. hypodermic needle. The droplet detached and fell under its own weight onto the test surface, located 50 mm below the needle tip. The stainless steel test surface was 50.8 mm square, with a thickness of 6.35 mm. It was polished with 600 grit emery paper, and brought to a mirror finish with metal polish. The surface was mounted on a copper block that housed two cartridge heaters. Surface temperature was monitored by three chromel-alumel thermocouples inserted into holes drilled in the surface. A temperature controller regulated power to the cartridge heaters, holding the surface temperature constant to within $\pm 1°C$.

The test package was suspended from a support frame by means of an electromagnet. The electromagnet, operating on a 12 V d.c. supply, had a lift capacity of 180 kg and was attached to a steel plate bolted to the top of the drop package. The package was released by triggering a circuit that reversed the voltage across the electromagnet: it separated 7.0 ± 0.2 ms after receiving the triggering signal. The exact time of release was ascertained by continuously monitoring the electrical resistance between the electromagnet and steel plate.

Photographs of droplet impact were taken using a single-shot flash photographic technique, which provides much better image quality than can be obtained using high speed ciné cameras [20]. A strobe unit with an 8 μs flash duration was used to provide illumination to take a single 35 mm photograph of a droplet at one instant during its impact. By varying the time delay between the droplet first touching the surface and triggering of the flash, different stages of droplet impact could be photographed. The droplet release and impact were sufficiently repeatable that the entire droplet deformation process could be reconstructed from photographs of different droplets, captured at progressively advancing stages of impact. The flash duration was short enough to eliminate any blurring of photographs due to droplet motion, providing clear images in which details such as bubble formation could be discerned. The camera equipment and lighting have been described earlier [20].

To take a droplet impact photograph, the drop package was suspended from the electromagnet. The syringe pump was then switched on, forming a droplet at the needle tip. Detachment of the droplet was detected by an optical interrupter placed approximately 5 mm below the tip of the needle, which sent a signal to a time delay circuit. The timing unit controlled a sequence of three events. First, it opened the camera shutter for 1/8 s. Next, after a duration of approximately 80 ms, it sent a signal to release the drop platform. The platform took another 7 ms to detach from the electromagnet; it was therefore in free fall approximately 10 ms before the droplet reached the surface, providing a low gravity environment during impact. Finally, after a time delay that could be varied with a resolution of 1 μs, the timing circuit triggered the flash. The illumination provided by the flash was much brighter than the ambient light, so that the film was effectively exposed only during the 8 μs flash duration, even though the camera shutter

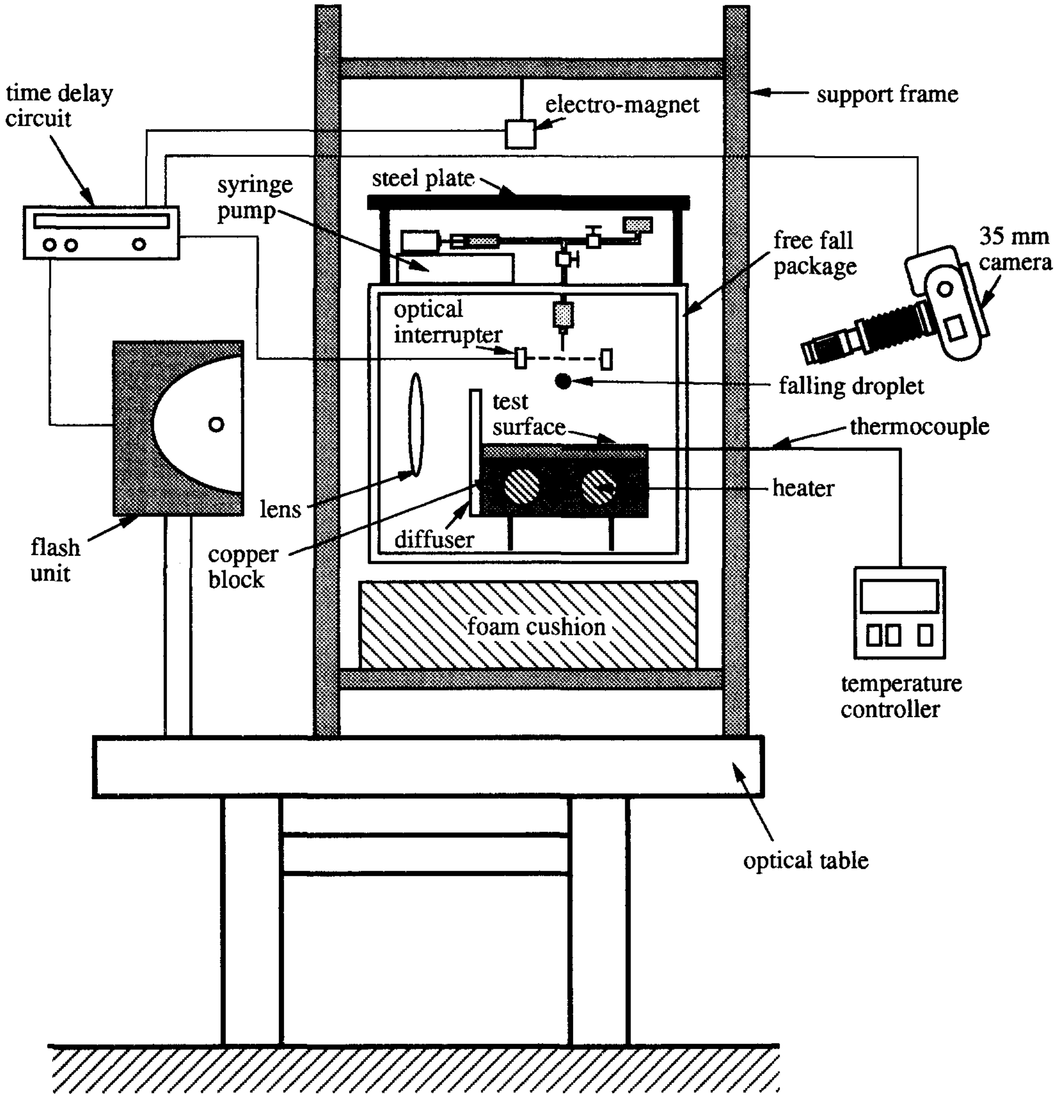


Fig. 1. Schematic diagram of the experimental apparatus.

was open for 1/8 s. Droplets were photographed for periods of up to 20 ms from the instant of impact, during which the platform moved through a distance of only a few millimetres. It was therefore not necessary to place the camera and flash on the drop platform, since the droplet remained in the field of view even when the camera was kept stationary.

Air drag on the platform slowed its velocity in free fall. Calculations showed that this would be expected to produce a maximum gravity level on board of only $10^{-5}g_0$. The position of a falling droplet, relative to the test surface, was photographed at 1 ms intervals prior to its impact on the surface. Droplet velocity, determined by measuring from these photographs the distance moved in a given time period, was found to be constant at 0.8 m s^{-1} after the platform was released. Since we could locate the droplet in photographs with a resolution of ± 0.01 mm, we concluded that any gravitational acceleration felt by the droplet was less than $10^{-2}g_0$, since a larger acceleration would have produced measurable changes in velocity. Attempts to measure gravity forces directly with an accelerometer were unsuccessful: the time taken by the accelerometer to respond to a step change in g level was longer than the duration of low gravity in our experiments.

Surface temperature measurements during droplet impact were made using a commercially available chromel-alumel thermocouple (E12-3-K, Nanmac Inc., Framingham, MA) with a 10 μs response time (measured by the manufacturer). The thermocouple was inserted vertically through the test surface, and the exposed junction ground flush with the surface. The entire surface was electroplated with a 10 μm thick layer of nickel to protect the thermocouple. The temperature measurement technique was similar to that described by Hsu [21]. The thermocouple output was amplified and recorded during droplet impact using a data acquisition system. Surface temperature measurements were estimated to be accurate to within $\pm 0.5^\circ$C, and temperature changes as small as 0.1°C could be resolved.

3. RESULTS AND DISCUSSION

The impact and spreading of a water droplet on a stainless steel surface in low gravity can be seen in Fig. 2. Each column is a sequence of photographs, taken at a particular surface temperature, showing successive stages of droplet deformation during impact. Reflections of droplets in the polished stainless steel surface can also be seen. Evolution of droplet shape during impact was characterized by measurements of the diameter of the wetted surface area (d). Non-dimensionalizing by the droplet initial diameter (D), we define the 'spread factor', $\beta(t) = d(t)/D$, an important parameter in formulating spray models [17], since it gives the liquid–solid heat transfer area. Figure 3 shows measurements of β made under both low gravity and normal gravity conditions during impact of water and n-heptane drops on a surface at 25°C. Values of β for water drops were much lower than those measured for n-heptane, since the high surface tension of water restrained spreading. Water drops recoiled after impact, so that β reached a maximum and then decreased. As surface temperature increased the pressure of vapour generated at the liquid–solid interface increased the height to which droplets rebounded (Fig. 2, $t = 10$ ms). Drops of n-heptane did not recoil but remained at their maximum extension.

Reduction of buoyancy forces did not affect liquid flow during initial droplet impact and spreading. Under normal gravity the Froude number ($Fr = V^2/gD$), which is a ratio of inertial to gravitational forces, was 33 for water and 44 for n-heptane in our experiment. Since $Fr \gg 1$ in both cases, inertial forces were dominant and lowering of gravity would not be expected to affect droplet deformation. However, once inertial forces were overcome by liquid viscosity and surface tension, droplet spreading stopped. Water droplets then rebounded from the surface (Fig. 3, $6 < t < 10$ ms), with their flow controlled by surface tension. The relative magnitude of gravity compared to surface tension is given by the Bond number ($Bo = g\rho D^2/\sigma$), which was 0.5 for water drops at normal gravity. Since $Bo \sim 1$, gravitational forces were comparable to surface tension forces; Fig. 3 shows that the recoil was slightly faster in low gravity than in normal gravity.

The mechanism of heat transfer to a droplet placed on a hot surface depends on the surface temperature. Figures 4 and 5 are droplet evaporation time curves, determined by depositing droplets of water (Fig. 4) or n-heptane (Fig. 5) on a horizontal, stainless steel surface in normal gravity, and recording the evaporation with a video camera (details of the method have been published in ref. [20]). The time taken by a droplet to evaporate completely was measured at different surface temperatures. Each data point in Figs. 4 and 5 represents the average time taken for the evaporation of six droplets; error bars denote the maximum and minimum evaporation times observed. For temperatures above the liquid boiling point (100°C for water, 98°C for heptane), heat transfer was significantly enhanced by the onset of nucleate boiling, with a concomitant reduction in droplet lifetime. However, when the surface temperature was greater than approximately 170°C for water and 165°C for n-heptane, the pressure of vapour escaping from below the drop was sufficient to completely lift it off the surface after impact. This temperature marked a departure from nucleate boiling, and is denoted by T_{DNB}. Further increases in surface temperature produced more vapour, which insulated the drop from the surface and reduced heat transfer, increasing the droplet lifetime. The maximum evaporation time was reached when the droplet was completely levitated on a thin film of its own vapour, a state known as Leidenfrost evaporation. Heat transfer took place by conduction across this vapour film; raising the surface temperature further enhanced heat transfer and reduced the droplet lifetime. The surface temperature corresponding to maximum droplet evaporation time marks the onset of stable film boiling, and is known as the Leidenfrost temperature (T_{Leid}). Our measured values of T_{Leid} (270°C for water and 200°C for n-heptane) agree well with those reported in the literature [10, 20].

A droplet could not be maintained in Leidenfrost evaporation in a low gravity environment. Figure 6 shows photographs of a droplet of water, initially placed on a concave stainless steel surface at 320°C in normal gravity. Prior to release of the test package, the weight of the droplet was supported by the pressure of the vapour film below it. At $t = 0$ the package was released in free fall. In a low gravity environment the droplet weight was negligible and the force exerted by escaping vapour was no longer balanced: the droplet was pushed away from the surface ($t \geqslant 2.5$ ms). Similar observations were made for n-heptane droplets. Movement of droplets away from a hot surface in low gravity may reduce spray cooling effectiveness compared to that in normal gravity where droplets remain on the surface, providing additional cooling. Experiments and analysis [19] show that this secondary cooling can enhance heat transfer by over 50%. Flow patterns during dispersed flow through tubes may also be affected, since droplets will move away from heated channel walls in low gravity [15, 16]. Cryogenic liquids, such as liquid nitrogen, go into Leidenfrost evaporation when spilled on a surface at room temperature [22]. In the event of such a spill on board a spacecraft, liquid droplets will be propelled away from any solid surface.

Values of the Leidenfrost temperature are important in designing boiling equipment: heat transfer

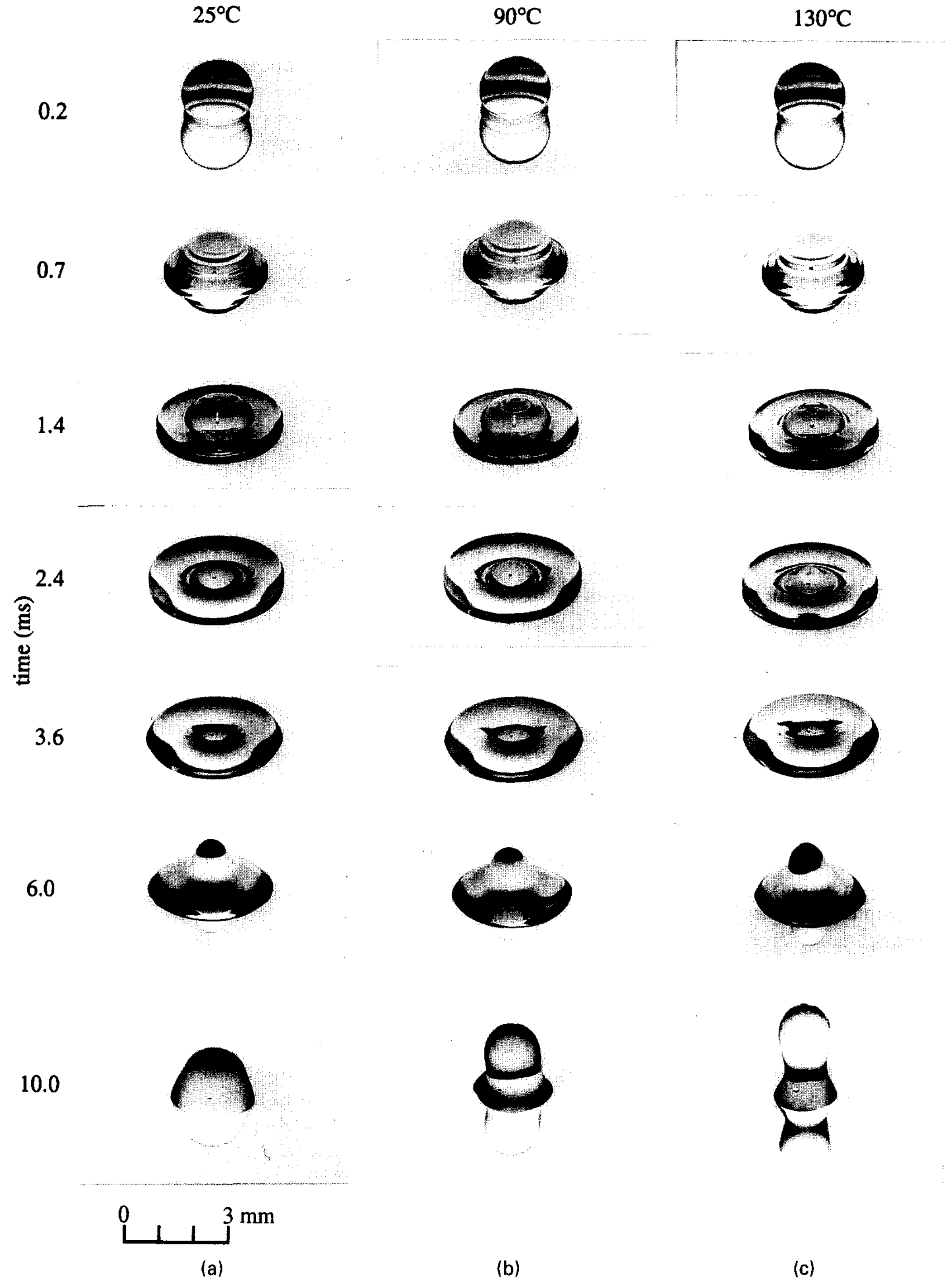


Fig. 2. Impact of a water droplet on a stainless steel surface in low gravity, with initial surface temperature (T_{wi}) of (a) 25°C, (b) 90°C and (c) 130°C.

greatly decreases when the surface temperature is above T_{Leid}. However, since stable film boiling of droplets cannot be achieved in low gravity there are no maxima on the evaporation curves (see Figs. 4 and 5) at which T_{Leid} can be measured. In fact it is not clear if the Leidenfrost point, measured from an evaporation curve under normal gravity, is physically significant in low gravity. If it is we expect to see changes in droplet impact dynamics and surface-to-liquid heat transfer when the surface temperature exceeds T_{Leid}, which should be apparent from droplet impact photographs and surface temperature measurements.

Photographs of the impact of n-heptane droplets in low gravity (Fig. 7) did indeed show significant

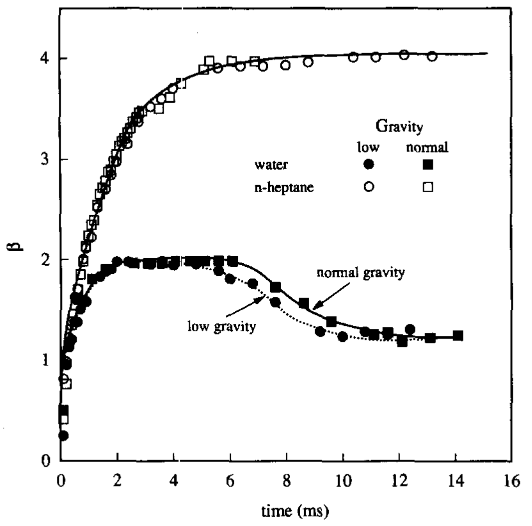


Fig. 3. The evolution of β during the impact of droplets of water and n-heptane on a stainless steel surface at 25°C, in both normal and low gravity.

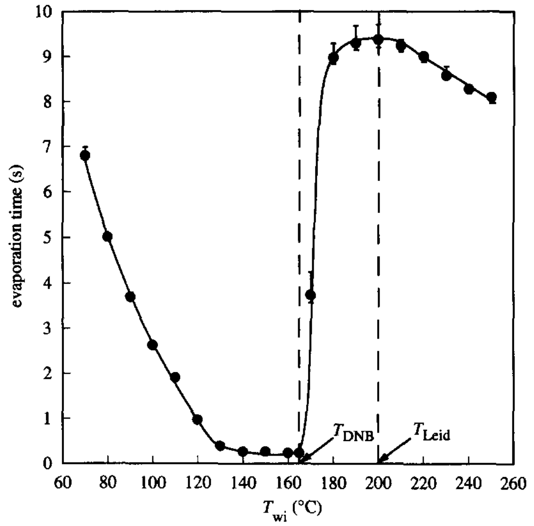


Fig. 5. Average evaporation time for droplets of n-heptane (1.5 mm initial diameter) placed on a hot stainless steel surface.

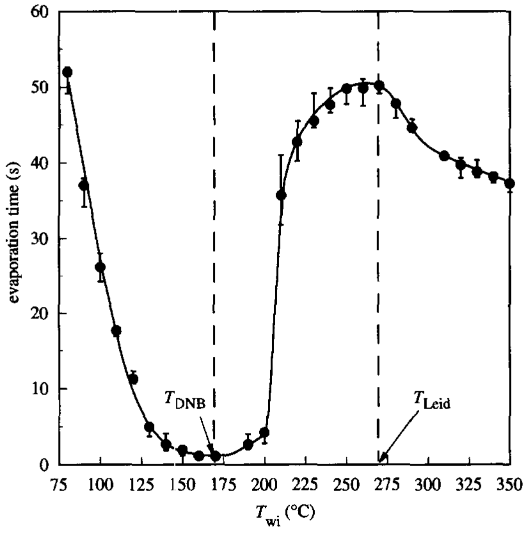


Fig. 4. Average evaporation time for droplets of water (2.0 mm initial diameter) placed on a hot stainless steel surface. Error bars mark the maximum and minimum evaporation times observed.

changes in behaviour when the surface temperature was raised above T_{Leid}. At temperatures below 200°C [Figs. 7(a) and (b)] vigorous bubble formation could be seen inside the liquid, suggesting that the droplet made contact with the solid surface, which provided nucleation sites for vapour bubbles. For T_{wi} = 210°C [Fig. 7(c)], which was above the Leidenfrost temperature, no bubbles were visible in the droplet. We surmised that the droplet was in film boiling, separated from the surface by a thin film of vapour which prevented bubble nucleation.

Figure 8 shows typical surface temperature variation traces during impact of a n-heptane droplet in low gravity. The maximum temperature drop during droplet impact (ΔT_{max}) was used as a measure of surface cooling. Variation of ΔT_{max} with initial surface temperature (T_{wi}) is summarized in Fig. 9, for both normal and low gravity. Heat transfer from the surface during droplet impact did not appear to be affected by a reduction in buoyancy forces, a result that was consistent with previous measurements made in pool boiling experiments in low gravity [2–4].

Formation of a vapour film when the surface temperature exceeded T_{Leid} would be expected to reduce heat transfer from the surface to the droplet. Inspection of Fig. 9 shows that ΔT_{max} is sharply reduced for $T_{wi} > 200$°C. To support the conjecture that a vapour film separates the liquid and solid, we compared the measured surface temperature variation with results from an analytical model [23, 24] that assumes the surface and drop to be semi-infinite bodies, suddenly brought into contact. Assuming that heat transfer is by conduction alone, the interface is predicted to be at the 'contact temperature':

$$T_c = \frac{T_{wi}\gamma_w + T_l\gamma_l}{\gamma_w + \gamma_l} \qquad (1)$$

where $\gamma = (k\rho C)^{1/2}$. The model assumes perfect liquid–solid contact. Therefore, if the measured surface temperature did not decrease to T_c during droplet impact, it would imply that a vapour layer formed between the droplet and surface, reducing heat transfer. The predicted surface cooling, calculated assuming $\Delta T_{max} = T_{wi} - T_c$, is shown in Fig. 9. The predictions agreed well with the measured values for $T_{wi} < 80$°C; the slight under-estimate of ΔT_{max} may have been because of enhanced surface cooling due to forced convective motion in the droplet, which was not accounted for in the conduction model. The measured surface temperature drop was greater than that predicted for $T_{wi} > 80$°C, perhaps because Marangoni

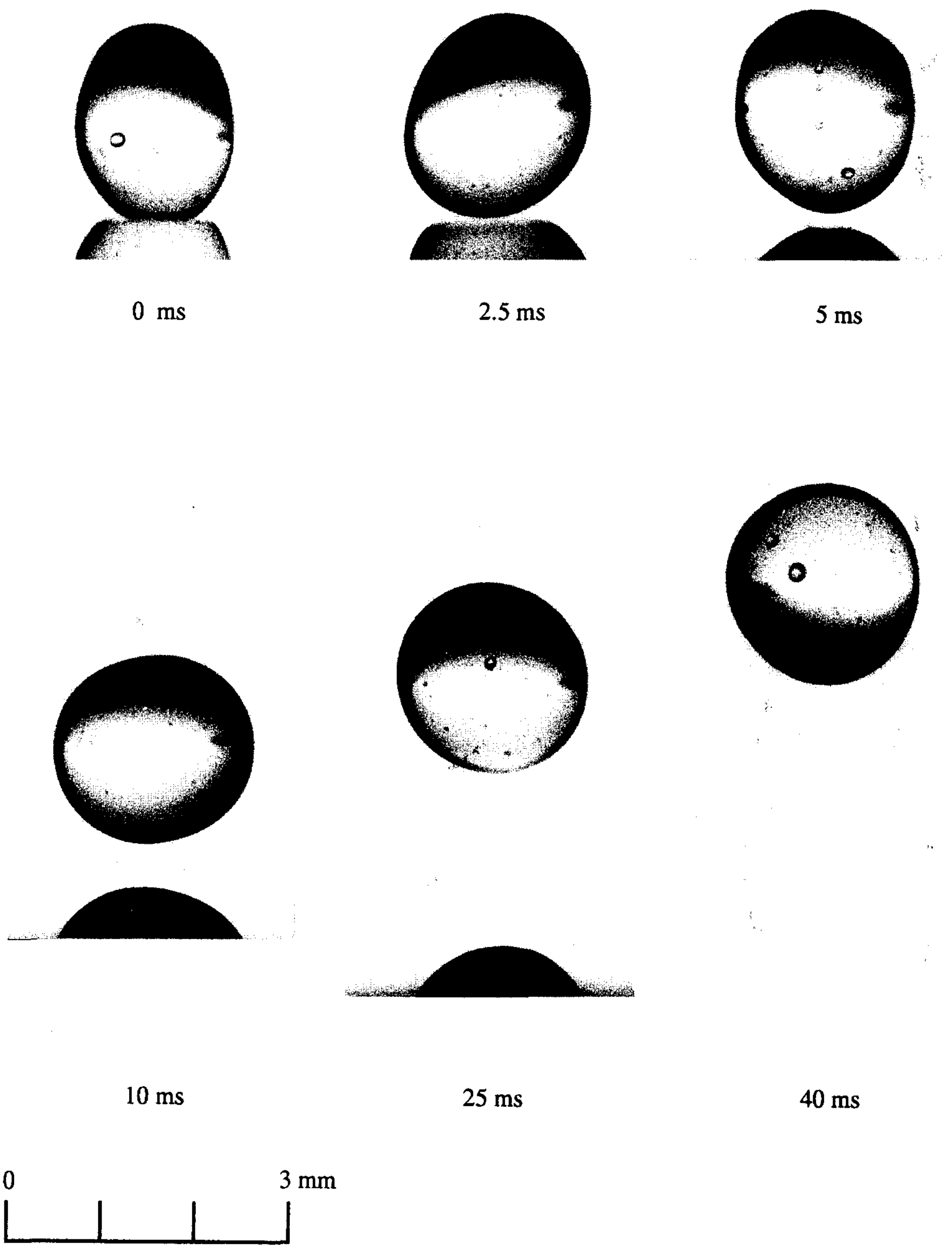


Fig. 6. A water droplet, initially in film boiling on a concave stainless steel surface at 320°C. At $t = 0$ the surface was released in free fall. The droplet was lifted off the surface by the pressure of the vapour below it.

convection (described in ref. [20]) enhanced heat transfer from the surface. For $T_{wi} > 100°C$ nucleate boiling became the dominant heat transfer mechanism, and the simple conduction model was no longer valid; measured values of ΔT_{max} were twice those predicted. The maximum value of ΔT_{max} was reached when the surface temperature equalled T_{DNB}. ΔT_{max} then started to decrease, and became less than that predicted by equation (4) for $T_{wi} > T_{Leid}$, suggesting that an insulating vapour layer formed at that temperature.

If the impacting droplet does not touch the surface, we can obtain a simple analytical solution for the surface temperature variation during impact by modelling the surface as a semi-infinite body, initially at uniform temperature T_{wi}. The droplet, assumed to be

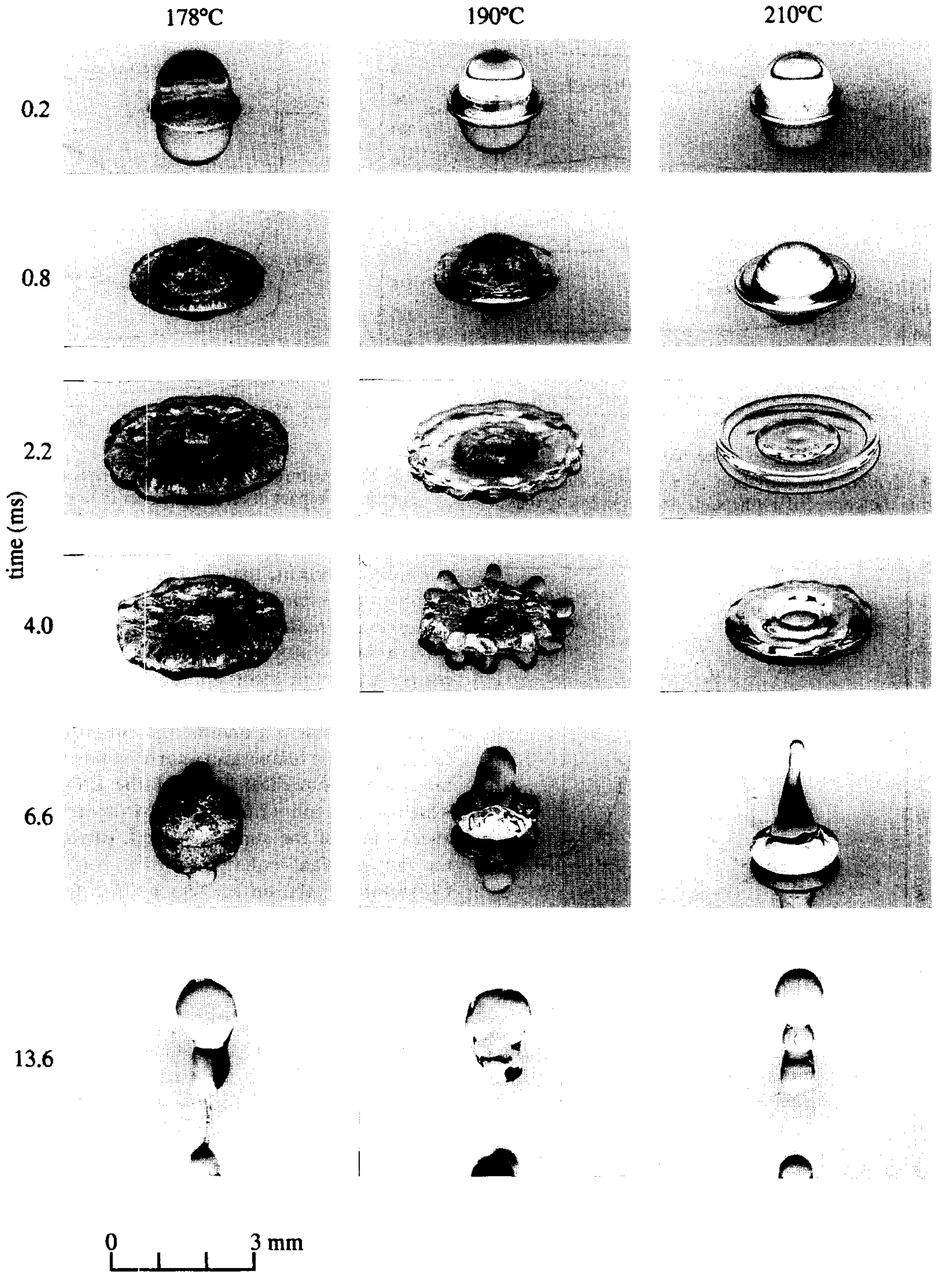


Fig. 7. Impact of an n-heptane droplet on a surface with initial temperature (T_{wi}) of (a) 178°C, (b) 190°C and (c) 210°C. No vapour bubbles are seen in the droplet for $T_{wi} > T_{Leid}$.

at the liquid saturation temperature T_{sat}, is brought in proximity to the surface at $t = 0$, the two being separated by a vapour film of uniform thickness δ. If heat transfer occurs by one dimensional conduction across the vapour film, the surface temperature variation is given by [25]:

$$\frac{T_w - T_{wi}}{T_{sat} - T_{wi}} = \frac{2}{1+\gamma_w/\gamma_v} \sum_{n=0}^{\infty} \left(\frac{\gamma_w - \gamma_v}{\gamma_w + \gamma_v}\right)^n \operatorname{erfc}\left(\frac{(2n+1)\delta}{2\sqrt{(\alpha_v t)}}\right). \quad (2)$$

An estimate of the thickness of the vapour layer

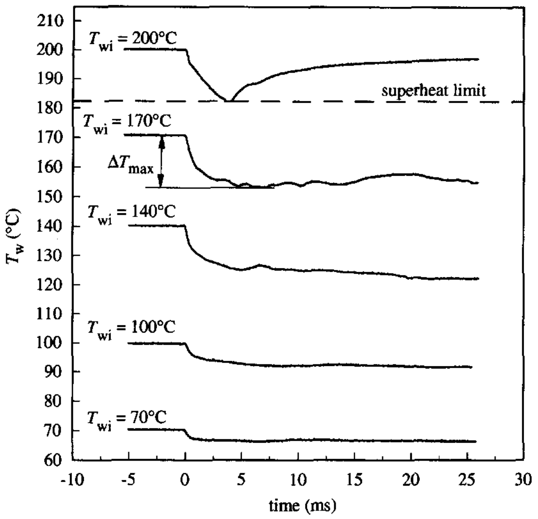


Fig. 8. Temperature variation of a stainless steel surface during the impact of a *n*-heptane droplet in low gravity.

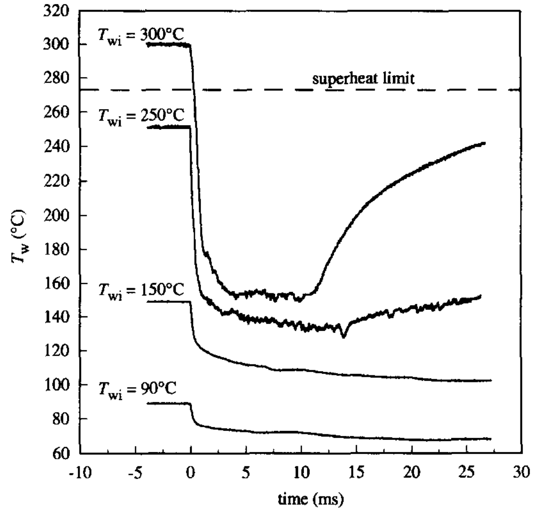


Fig. 10. Temperature variation of a stainless steel surface during the impact of a water droplet in low gravity.

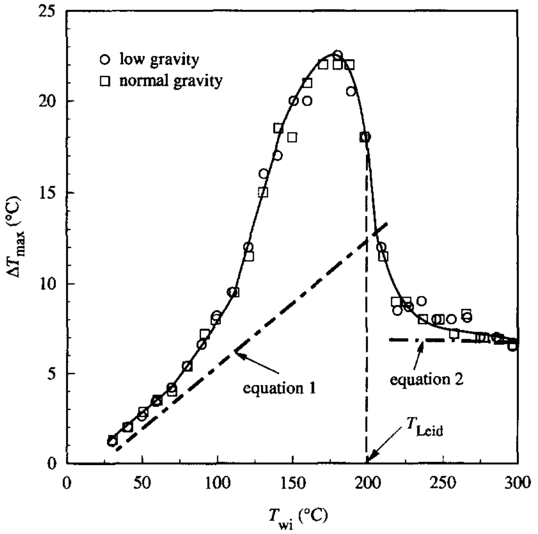


Fig. 9. The maximum decrease in temperature of a stainless steel surface during the impact of an *n*-heptane droplet, for varying initial surface temperature.

under an impacting drop can be obtained [22] by equating the stagnation pressure in the liquid to the pressure in the vapour (assumed to be flowing between parallel disks). The vapour layer thickness is given by:

$$\delta \approx \left(\frac{3\mu_v d_{max}^2 k_v (T_{wi} - T_{sat})}{16V^2 \rho_v \rho_l \lambda}\right)^{1/4} \qquad (3)$$

where d_{max}, the maximum diameter of the spreading liquid drop, was measured from photographs. Equation (2) was evaluated at $t = 5$ ms, the time corresponding to the maximum surface temperature drop (see Fig. 7), and the calculated values of ΔT_{max} plotted in Fig. 9. Good agreement between predictions and measurements supports the hypothesis that a vapour film completely separated the droplet and surface.

Surface temperature measurements and photographs both indicate that the Leidenfrost temperature of *n*-heptane is physically significant even when gravity forces are reduced, and that it corresponds to the surface temperature at which liquid–solid contact ceases. It therefore seems appropriate to use a thermodynamic model, which is independent of g, to predict T_{Leid}. Baumeister and Simon [10] postulated that the Leidenfrost temperature corresponds to the thermodynamic superheat limit of the droplet, above which liquid cannot exist and must vaporize. A theoretical value of the superheat limit, calculated using the van der Waals equation of state, is $(27/32)T_{critical}$. Correcting for the surface temperature decrease during droplet impact by adding ΔT_{max}, the Leidenfrost temperature is given by:

$$T_{Leid} = \tfrac{27}{32} T_{critical} + \Delta T_{max}. \qquad (4)$$

Reading $\Delta T_{max} = 18$°C from Fig. 9, equation (4) predicts $T_{Leid} = 201$°C for *n*-heptane, in remarkably good agreement with our measurement. The calculated superheat limit for *n*-heptane is marked in Fig. 8, and it is seen to equal the surface temperature under the drop when $T_{wi} = T_{Leid}$.

This simple thermodynamic model of film boiling failed when applied to water drops. Figure 10 shows representative surface temperature variation traces during impact of water droplets in low gravity. Surface temperatures under the drop were always much lower than the superheat limit, even when $T_{wi} > T_{Leid}$. Values of ΔT_{max} obtained from temperature measurements at both normal and low gravity are given in Fig. 11. There was no difference between results obtained in low and normal gravity. Values of ΔT_{max} were much larger than those measured for *n*-heptane, because water has a much higher latent heat of vaporization, and cools the surface more effectively. Equation (1) predicted surface cooling reasonably accurately for $T_{wi} < 100$°C. However, there was no reduction in ΔT_{max} above the Leidenfrost point (Fig. 11). Mea-

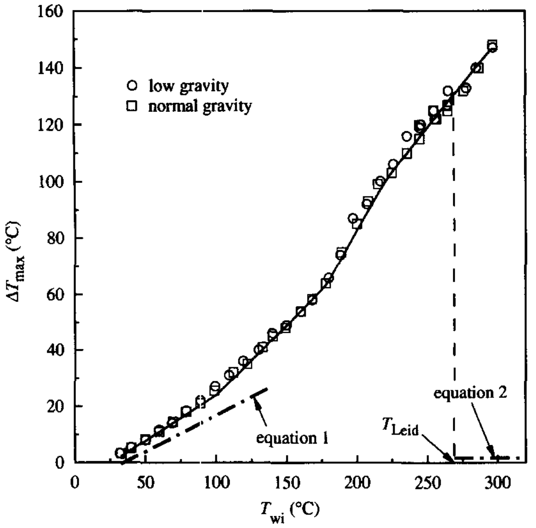


Fig. 11. The maximum decrease in temperature of a stainless steel surface during the impact of a water droplet, for varying initial surface temperature.

sured values of $\Delta T_{\max}$ were several orders of magnitude greater than those predicted by equation (2). This high heat transfer can be explained only if we assume that there was direct liquid–solid contact during water droplet impact, in which case the thermodynamic model is no longer valid. Equation (4) predicts $T_{\mathrm{Leid}} \approx 400$°C, whereas the measured value was 270°C.

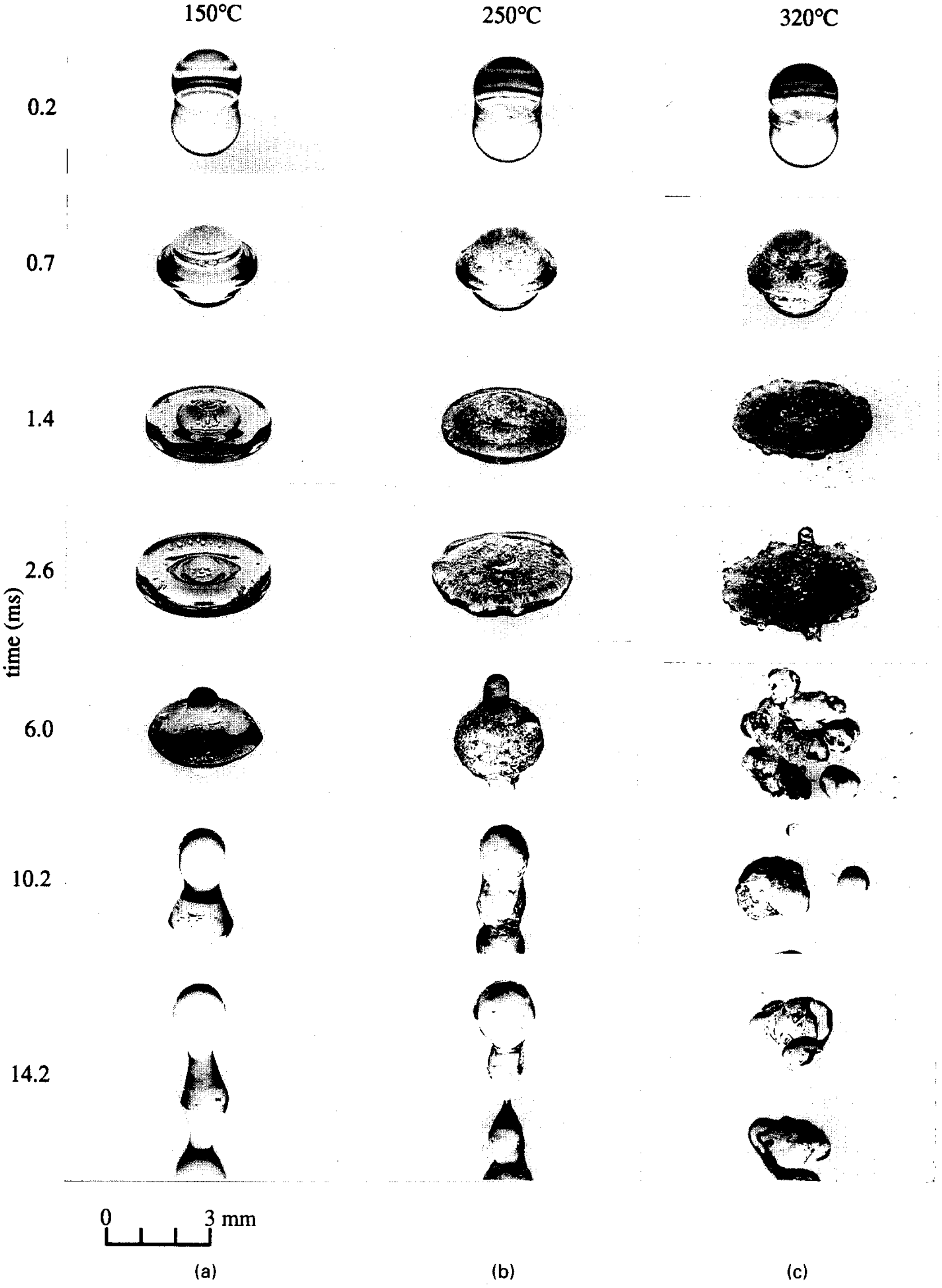
Photographs of water droplet impact (Fig. 12) support the belief that the droplet touched the surface even when $T_{\mathrm{wi}} > T_{\mathrm{Leid}}$. At an initial surface temperature of 320°C [Fig. 12(c)] there was vigorous bubble formation in the drop, indicating that the liquid found heterogeneous nucleation sites on the surface. Explosive boiling, which fragmented the drop, has been observed previously [26] during impact of water drops on a hot surface. This behaviour contrasted with that of *n*-heptane, where no bubbles could be seen in the liquid [Fig. 7(c)] for surface temperatures above T_{Leid}. Vapour bubbles were also seen inside water droplets in film boiling (see Fig. 6), suggesting that liquid–solid contact occurred during impact; no bubbles were seen in *n*-heptane droplets. Previous experiments [24, 26] have confirmed that liquid touches the surface during the impact of water droplets on surfaces at initial temperatures of up to 600°C. Baumeister *et al.* [27], in a study of vibration of liquid drops in Leidenfrost evaporation, found that hydrocarbon droplets oscillated freely when placed on a surface at the Leidenfrost temperature. However, water droplets did not oscillate until the surface was heated to almost the thermodynamic critical temperature of water, when liquid no longer touched the solid surface and droplet motion was no longer retarded by friction at the liquid–solid interface.

The difference in boiling of water and hydrocarbon droplets has previously been noted [23], though it could not be explained. The difference can be attributed to water having much higher values of surface tension (water: 72 mN m^{-1}; *n*-heptane: 20 mN m^{-1}) and liquid–solid contact angle (water: 90°; *n*-heptane: 10°) than *n*-heptane. High contact angle reduces the energy required for heterogeneous nucleation to occur at a solid surface [28]. Therefore, vapour bubbles nucleate in water drops impacting on a surface at a temperature well below the thermodynamic superheat limit. Once bubbles nucleate at the solid–liquid interface, the high surface tension of water prevents drops from spreading on the surface, and the pressure of vapour under them forces them to recoil. Vapour bubbles breaking through the liquid also cause droplet breakup [Fig. 12(c)] during impact. In experiments done at normal gravity, where the droplet is placed on a concave surface, these fragments of liquid recoalesce, after which the droplet goes into film boiling (Fig. 6). Measured droplet evaporation time depends on the total volume of liquid present after the droplet recombines. However, in a low gravity environment portions of the droplet fly apart after break up, and there is no recoalescence [see Fig. 12(c) $t = 6.0$ and 10.2 ms].

n-Heptane has a very low equilibrium contact angle ($\sim 10°$) on stainless steel so there is little heterogeneous bubble nucleation at the solid surface, and the volume of vapour formed is insufficient to lift droplets off the surface after impact. Impinging droplets remain on the surface until its temperature reached the superheat limit, after which liquid can no longer exist in contact with the surface. At this surface temperature vapour bubble nucleation in the droplet ceases [see Fig. 7(c)], so that there is no droplet breakup and measurements of Leidenfrost temperature are not sensitive to the extent of droplet recoalescence.

The Leidenfrost temperature of *n*-heptane corresponds to its thermodynamic superheat limit, a property that is not affected by gravity. However, values of the Leidenfrost temperature of water reported in the literature, measured from an evaporation curve under normal gravity, are not simply a liquid property, but depend on surface thermal properties, surface wettability, and the extent of droplet break up and recoalescence. They cannot be compared directly with data for the minimum film boiling temperature obtained from pool boiling or quenching experiments. T_{Leid} for water does not correspond to any change in droplet impact dynamics or heat transfer, and therefore cannot be measured or defined in low gravity.

Nucleate boiling in the droplet did not appear to be affected by a reduction in buoyancy forces. Figure 13 shows enlarged views of the impact of a *n*-heptane droplet on a surface at 130°C in low gravity. Vapour bubbles were seen to nucleate at the liquid–solid interface ($t = 0.5$ ms). The bubbles separated and moved away from the solid surface ($0.7 < t < 1.3$ ms). Bubble separation from the liquid–solid interface could

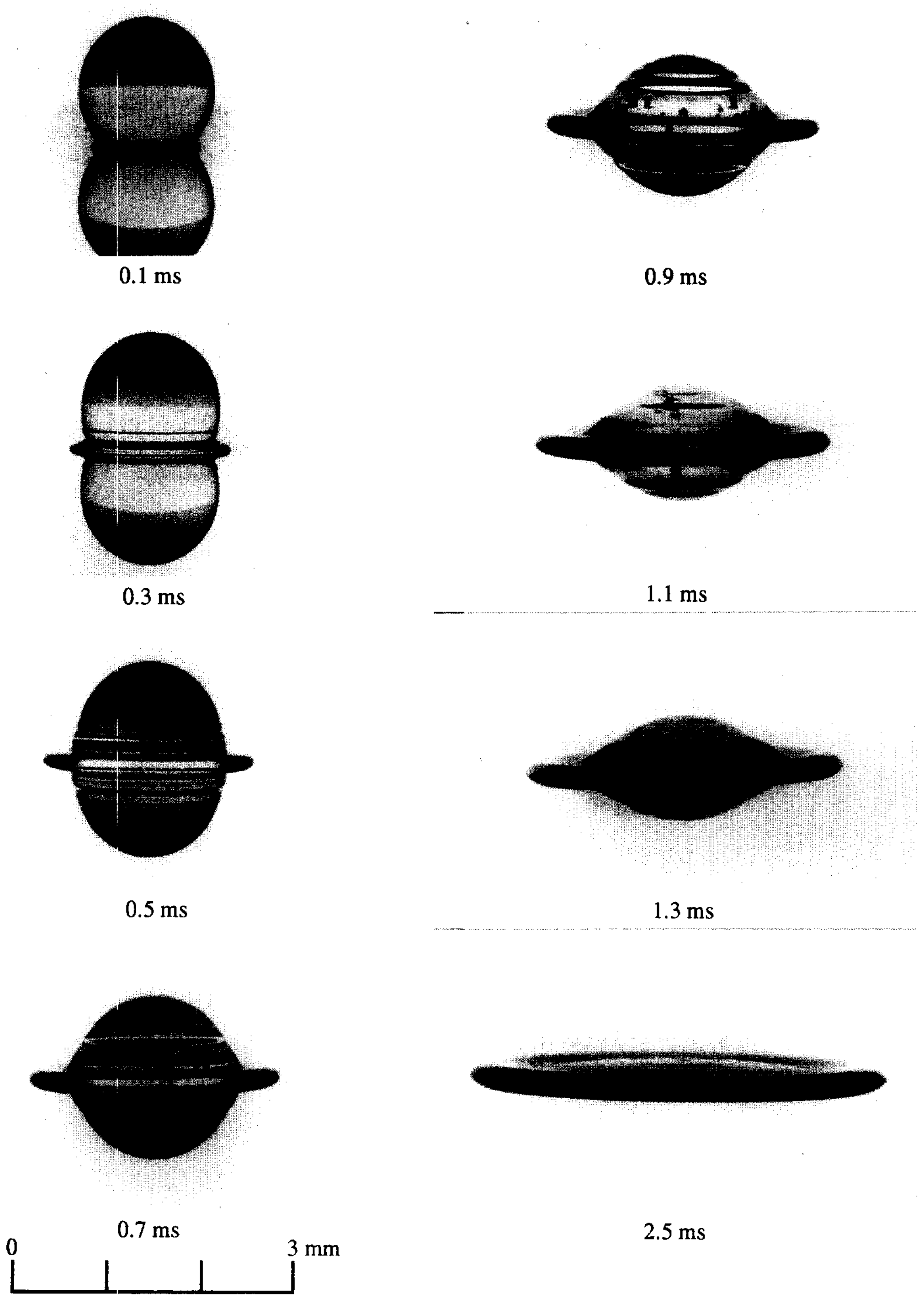


(a) (b) (c)

Fig. 12. Impact of a water droplet on a surface with initial temperature (T_{wi}) of (a) 150°C, (b) 250°C and (c) 320°C. Bubbles can be seen forming in the drop even for $T_{wi} > T_{Leid}$.

also be seen during the impact of water droplets in low gravity. Figure 14 shows photographs of a water drop impacting a stainless steel surface at 150°C. Vapour bubbles could be seen in the bulk of the liquid (e.g. $t = 0.6$ ms). The pressure of the vapour below the liquid lifted it off the surface ($t = 9.2$ ms), and as the droplet recoiled its temperature decreased and the bubbles in the bulk of the liquid collapsed ($t = 15.2$ ms).

Traditional models of bubble departure during nucleate boiling [1] have assumed that buoyancy forces lift bubbles off the surface. Such models lead to expressions that predict bubble departure diameter varies as $g^{-1/2}$; in the limit that $g \rightarrow 0$ bubbles would



0.1 ms

0.3 ms

0.5 ms

0.7 ms

0.9 ms

1.1 ms

1.3 ms

2.5 ms

Fig. 13. Impact of an *n*-heptane droplet on a stainless steel surface at 130°C in low gravity. Vapour bubbles nucleating at the liquid–solid interface detach and rise into the liquid.

be expected to remain at the surface, reducing heat transfer. We did not observe vapour accumulation at the surface, which suggests that forces other than buoyancy are responsible for bubble departure. Bubble detachment could not have been caused by liquid movement since bubble motion was opposed to the direction of liquid flow (see Fig. 13). Oka *et al.* [4] observed bubble departure from the heater surface during pool boiling in low gravity when wall heat flux exceeded 30 kW m^{-2}. Estimates of the wall heat flux in

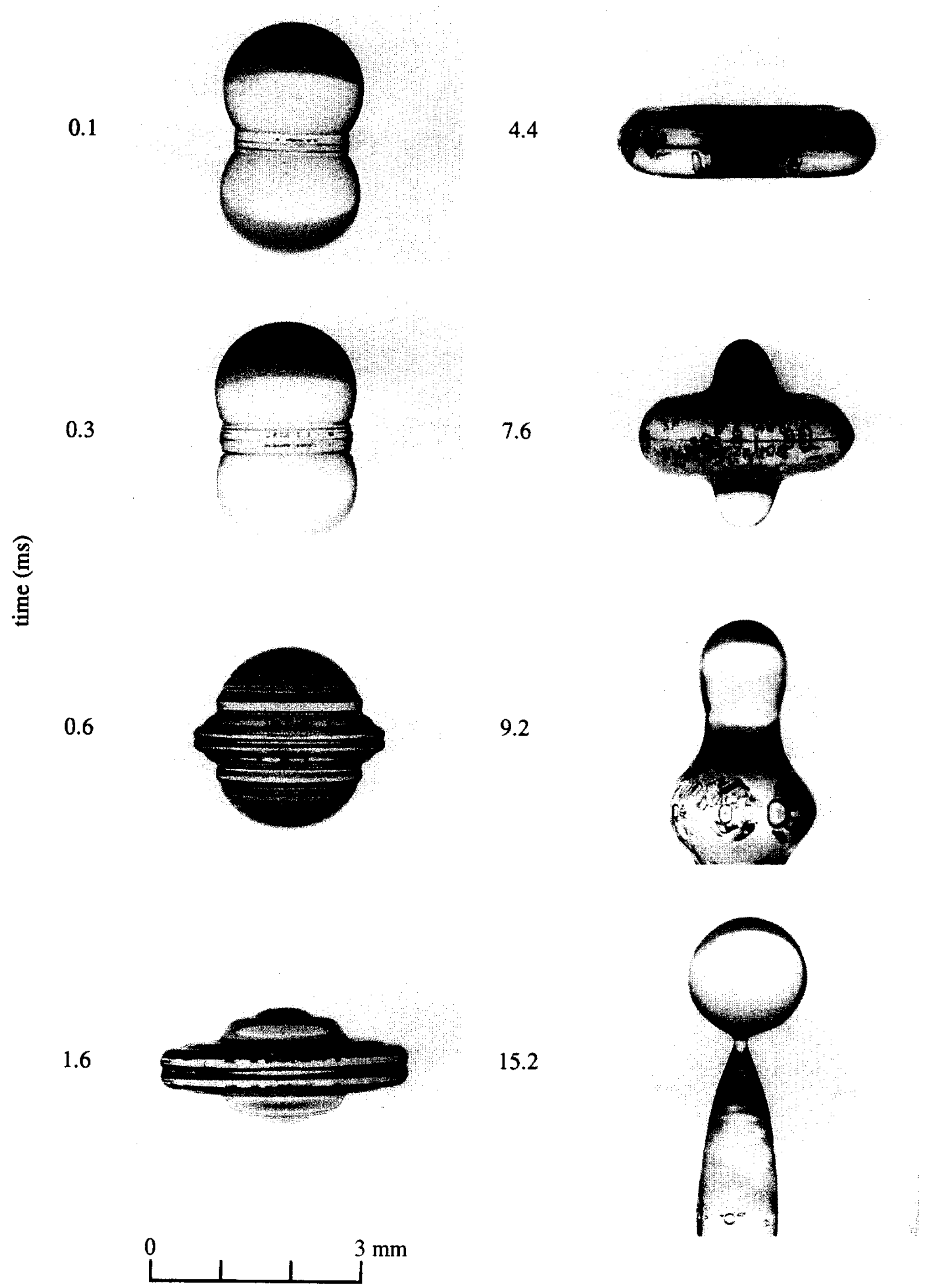


Fig. 14. Impact of a water droplet on a stainless steel surface at 150°C in low gravity.

our experiments, calculated from surface temperature measurements assuming the test surface to be a semi-infinite body undergoing 1D heat conduction, gave much larger values: 400 kW m^{-2} and 1200 kW m^{-2} for the conditions of Figs. 13 and 14, respectively. Bubbles grow very rapidly when wall heat flux is so high, producing inertial forces sufficient to tear bubbles off the surface even in the absence of buoyancy.

4. CONCLUSIONS

Experiments were done to observe the boiling of water and *n*-heptane droplets on a hot surface in low gravity. Droplets did not stay at the surface during film boiling in low gravity, but were pushed away by the pressure of vapour below them. The Leidenfrost temperature could not be defined, therefore, on the basis of an evaporation curve. For *n*-heptane, the Leidenfrost temperature was identified with the thermodynamic superheat limit, above which liquid–solid contact ceased. However, the Leidenfrost temperature of water did not appear to have any physical significance in low gravity. Water drops continued to touch the surface even when its temperature exceeded T_{Leid}, and the surface temperature under the drop remained below the superheat limit. This difference in behaviour was attributed to the surface tension and liquid–solid contact angle of water being much higher than that of *n*-heptane. Reduction of gravity had no effect on nucleate boiling. Vapour bubbles separated from the liquid–solid interface, even in the absence of buoyancy forces.

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