the table throughout the 0 3 m fall For convenience the fixed pivot was placed two thirds of the way along the main link (of length L mass M_L) so that free fall of that link without counterweight caused the longer end to fall with the local acceleration of gravity g_e With a counterweight of mass m placed (βL) to the right of the fixed pivot the acceleration of the table of mass M_T is a_T where

$$a_T/g = 1-[3\beta/2+(3\beta/2)^2]m/[M_T+M_L/4+(3\beta/2)^2m]$$

or since M_T is much the largest mass

$$a_T/g \approx 1-[3\beta/2+(3\beta/2)^2]m/M_T$$

so a_T is less than g_e if β is positive and reaches a maximum greater than g_e when β is $-1/3$ Effective gravity fields of $+4\%$ to -1% g_e were therefore obtained by using a counterweight of mass approximately 7% of the mass of the table and varying β from 0 28 to -0 33 Negative gravity could of course be obtained alternatively by inverting the test apparatus but it was often simpler to move the counterweight

OPERATION AND INSTRUMENTATION

Air resistance causes appreciable upward force and various means exist for reducing its effect such as dropping simultaneously an inner test package and a separate outer drag shield [4] Such additional complication was avoided here since the residual effective gravity was measured in any case (as described below) and a compensating downward force could be applied using the linkage Without linkage the amount of residual gravity was nearly constant at about 0 4% g_e implying a nearly constant air resistance of 0 4% of the weight of the table A constant resistance is perhaps surprising but it could arise from inviscid effects since it is known that to impose an acceleration a_s on a massless sphere in infinite inviscid fluid will require a force 0 5 $m_d a_s$ where m_d is the mass of displaced fluid [5] The mass of air effectively displaced by the irregularly shaped table was not clear but might well be of order 0 2% of the mass of the table In addition viscous effects must arise increasing in magnitude as the velocity increases Early experiments with the longer fall suggested that effects of viscous drag and/or wake caused additional resistance roughly proportional to the square of the velocity which became increasingly important after about 0 2 s of fall [1]

Transducers to measure small effective gravity are highly developed for rockets and space craft but a simpler cheaper and very robust fly ball system was preferred for these tests taking advantage of the presence of the cine camera If a body is resting on a spring on the table before release then at the time of release the body effectively loses its weight and the spring expands throwing the body into motion relative to the table The initial relative velocity is $(g_e\delta)^{1/2}$ where δ is the initial spring deflection and by suitable choice of parameters that velocity can be a few mm s^{-1} The body used was a steel ball and its flight was confined to a transparent box which moved with the table The ball was therefore in very nearly free fall since the air resistance due to such low relative velocity is very low indeed If cine photographs then showed the continuing relative motion between ball and table to be a steady velocity then the table was also in free fall Deviations from steady velocity indicated residual effective gravity In the first such design for use by Pike [1] on the longer fall the field of view of the cine camera was split to provide simultaneous photographs of bubble and fly ball the latter having a relative flight path of 75 mm For the 0 25 s drop table a more refined compact design was developed for use by Chandratilleke [3] with a relative flight path of 8 mm occupying almost all of the cine field during special calibration tests The position of the ball could then be measured to 10 μm and the motion could be seen to differ little from a steady acceleration To determine deviations from that steady acceleration would need further refinement of measurement to a few μm There was no point in doing so in these experiments since the bubbles were of order 10 mm diameter and could not be expected to be sensitive to such small deviations from steady acceleration

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THE 'MIRAGE' IN BOILING

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INTRODUCTION

OBSERVATION of bubbles in boiling may be much affected by a version of the phenomenon of the mirage or total reflection It is a refraction effect commonly seen when light falls at glancing incidence on a hot flat surface such as a road on a sunny day The light is bent upwards by refraction not reflection though it looks as if reflected from a pool of water the lower part of a distant vehicle cannot be seen the upper part may be seen twice once reasonably undistorted through nearly isothermal air and again inverted in the apparent reflection The cause is well known in outline as the air near the road has a lower refractive index μ (greater light velocity) than the cooler air immediately above it Light therefore follows a path which is curved concave upwards Analogous phenomena of waves travelling in regions with varying wave velocity arise in many fields including propagation of sound in the atmosphere and through geological strata which have been much studied Techniques are available involving ray tracing and use of the eikonal equation Optical analyses include an engaging explanation of the merman of Norse legend [1] and a detailed analysis [2] related to boiling For boiling where the temperature field is generally much confused by fluid motion an experiment and a simple rough calculation and assessment are given here since they may be of more value than a complex precise analysis

TEMPERATURE GRADIENTS IN BOILING

The problem may arise in the detailed study of growth of vapour bubbles at a wall when the bubbles are viewed in the customary way from the side at a small angle to the wall It does not arise if there are no initial temperature gradients e g if an individual bubble grows in a system in which the temperature is initially uniform throughout the liquid and wall [3] Under those circumstances photographs taken from the side can show the whole of the perimeter of the bubble including detail at the wall Usually in boiling the initial temperature field is not uniform partly because the wall is hot being the source of heat and also because other bubbles disturb the liquid Such a situation is confused but there is often the possibility of sufficient temperature field for a mirage to be seen in a side view

A more controlled situation has been studied here in recent experiments on individual bubbles grown into a temperature field which had been carefully established in a stagnant liquid and was accurately known [4] As discussed in ref [4] a mirage was immediately observed and the method of taking measurements was adapted to accommodate it though the true shape of the base of the bubble remained unobservable and that bedevilled part of the analysis of growth

The variation of mean temperature with distance from the wall has been measured in boiling by Marcus and Dropkin [5] and others as discussed in [4] who found temperature changes of order 5 or 10 K in 0 5 or 0 2 mm implying temperature gradients normal to the wall $(-\mathrm{d}T/\mathrm{d}n)$ of order 10^4 or 5×10^5 K m^{-1} strongly dependent on heat flux though not simply given by (heat flux)/(liquid conductivity)

SIMPLE ANALYSIS

It is readily seen by considering motion of a wave front that a ray of light truly parallel to the wall would follow a curved path with radius of curvature at that point given by

$$R_p = \frac{\mu}{(\mathrm{d}\mu/\mathrm{d}n)}$$

Empirical expressions describe how μ for a liquid varies with temperature and they indicate that $(\mu-1)$ is nearly proportional to density so we can take it that

$$\frac{\mathrm{d}\mu}{\mathrm{d}T} \approx (\mu-1)\frac{1}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}T} = -(\mu-1)\alpha$$

and

$$\frac{\mathrm{d}\mu}{\mathrm{d}n} \approx -(\mu-1)\alpha\frac{\mathrm{d}T}{\mathrm{d}n}$$

where α is the coefficient of volumetric expansion For our test liquid n hexane values of μ and α are 1 33 and $1\,4 \times 10^{-3}$ K^{-1} so

$$R_p \approx -\frac{\mu}{(\mu-1)\alpha(\mathrm{d}T/\mathrm{d}n)} \approx \frac{3 \times 10^3}{(-\mathrm{d}T/\mathrm{d}n)}$$

and this is typical of many liquids

As the path curves away from the wall its radius of curvature increases but it can be seen from R_p alone that a ray will be seriously affected if it is expected to travel through that temperature gradient for a distance of the order of R_p In the experiments reported in ref [4] a controlled temperature field was established over a region of 30 × 30 mm with temperature gradient of order 10^5 K m^{-1} hence R_p was 30 mm so the observed mirage was to be expected

EXPERIMENT

The apparatus in ref [4] was suitable for further tests without boiling as it was designed to produce firstly a uniform temperature T_0 throughout the liquid and wall then a rapid jump ΔT_w in wall temperature and maintain that for a second or longer while the temperature field diffused above it forming an error function

$$T = T_0 + \Delta T_w \operatorname{erf}(z/2\sqrt{\kappa t})$$

where κ is thermal diffusivity A steel ball 4 mm diameter was supported at a distance of 0 4 mm above the heated wall and movies taken at 50 frames s^{-1} showed the onset of the mirage and its development After a time the error function had grown upwards so that the bottom of the ball was seen reflected in the mirage [Fig 1(a)] Later the mirage moved higher the bottom of the ball was obscured and the reflection of the ball merged with the direct view of the ball giving the appearance of a sphere with a neck attaching it to the wall [Fig 1(b)] Many photographs of bubbles in boiling have appeared to include a stage like Fig 1(b)

On Figs 1(a) and (b) lines are sketched to show roughly the height where a simple horizontal mirror should be placed to produce much the same reflection The position of that equivalent mirror is towards the top of the thermal boundary layer— a loose phrase but it would be misleading to imply greater precision The temperature gradient at these levels is even less accurately determinable as the slope of the error function changes rapidly there but it is approximately 10^4 K m^{-1} so R_p would be approximately 300 mm

Movies were continued for several seconds during which time convective movement of the liquid must have started The simplicity of the temperature field was then lost and the image of the ball and wall went through a variety of shapes some sketched in Figs 2(a)–(f) Many of these are recognisable among pictures of bubbles growing at a hot wall As shown in Figs 2(e) and (f) some 2 s after the heating started the images of the ball and wall appeared to separate again and then move steadily apart The combination of thermal diffusion and convection had reduced the temperature gradients below the ball so that light could again pass beneath the ball and into the camera lens

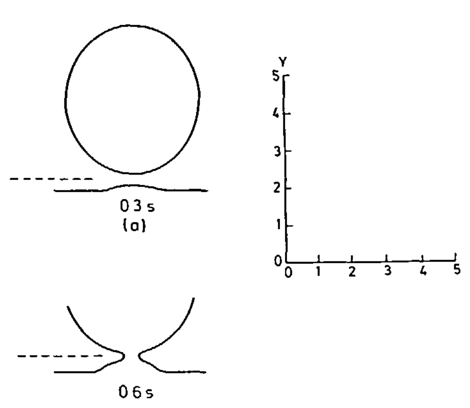

FIG 1 Spherical ball bearing above a plane wall $y = 0$ photographed through temperature field $T = T_0 + \Delta T_w \operatorname{erf}[y/2(\kappa t)^{1/2}]$ at times t shown Scales of x and y differ due to refraction at the cylindrical test vessel

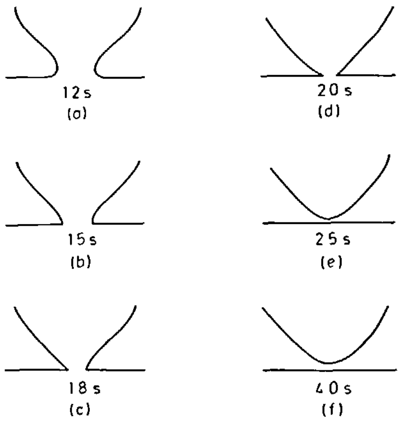

FIG 2 Spherical ball bearing above a plane wall photographed through a temperature field which is decaying in a complicated way at times t shown

DEPARTURE OF BUBBLES

During the growth and departure of a bubble at a wall the impossibility of observing the base of the bubble may prevent observation of the actual detachment of that base from the wall What appears to be detachment may in fact occur when the base of the bubble breaks through the top of the thermal boundary layer It may appear then that the bubble is connected to the wall by a neck, which thins down and breaks off apparently allowing the bubble to depart while part of the neck is left behind to retreat back to the wall But what is really happening may be that a complete bubble had in fact already detached from the wall and it is now passing through the stages of Fig 1(b) then Fig 1(a) as it moves away from the equivalent mirror at the top of the thermal boundary layer It is not easy to determine which explanation is correct since the normal technique of looking in the obvious direction (from the side) is fundamentally prevented when R_p is small compared with the size of the bubble Sonic investigation would meet the same problem Optical investigation from below would be an unwelcome complication and is generally not so effective Detailed analysis would require knowledge of the temperature field not usually available in boiling

CONCLUSIONS

When interpreting movies of bubbles at a hot wall in boiling the possibility of a mirage should be borne in mind and a useful rough guide may be obtained by the simple calculation of R_p for comparison with the distance light travels through the temperature gradient

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NOTE ON THE PULSATING NATURE OF THERMALLY-DRIVEN OPEN CAVITY FLOW

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THERMALLY DRIVEN laminar and turbulent flows arise frequently in numerous configurations and shapes of engineering interest A literature review [1] shows that the heated flat plate and the rectangular enclosure are among the shapes most extensively investigated Recently the heated open cavity configuration has also become the object of intense and concerted research in relation to for example the ventilation of rooms and corridors [2] the spread of flames and smoke in buildings [3] and the evaluation of convective losses from solar thermal central receiver systems [1 4]

With the view in mind of extending the transient 2 dim laminar flow calculation procedure described in ref [5] to the turbulent flow regime we have been concerned with obtaining a clearer understanding of the nature of thermally driven turbulent flow in a strongly heated open cavity of rectangular cross section The purpose of this note is to report some significant findings concerning the pulsating nature of this flow for certain conditions A more detailed exposition of these findings including measurements of temperature in the cavity configuration is available [6]

For the purposes of this study an experimental apparatus has been constructed as explained in ref [1] The flow test section shown in Fig 1 is an open rectangular cavity of variable aspect ratio (a/b) and orientation angle (α) $a/b = 0$ corresponds to zero cavity depth (flat plate conditions) and $\alpha = 0$ corresponds to an orientation with the cavity aperture