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Investigation of a Single Vapour Bubble Confined Between Superheated or Subcooled Parallel Plates

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Abstract We investigate the evolution of a single vapour bubble confined between two parallel plates. The experimental study involves generating a single vapour bubble and recording its evolution using a high speed camera. The working fluid used is FC-72, and the plates are held at controlled temperatures that can be either superheated or subcooled. The speed of growth or collapse of the bubble is determined from the recorded images. A simple theoretical model is presented, the predictions of which are found to be in good agreement with the experimental results for the collapse of a bubble between subcooled plates at high subcooling.

Keywords: Confined Vapour Bubble, Heat and Mass Transfer

1. Introduction

Technological advances in the microelectronics industry have led to a rapid increase in density and speed of electronic chips, and thus a massive increase in the heat fluxes which have to be dissipated. Advanced electronic devices that provide “System on a Chip” (SoC) capability can potentially generate heat fluxes approaching 100 W cm^{-2}, which with conventional cooling systems leads to high chip operating temperatures and accelerated device failure. Boiling heat transfer offers a real possibility for dissipating high heat flux while maintaining the surface at a reasonable temperature (see, for example, Lin et al. 2002). As a consequence of its potential application as a cooling technology for microelectronics, as well as in many other areas including aerospace science, Micro-Electro-Mechanical Systems (MEMS), compact heat exchangers, process intensification and chemical microreactors, there is currently considerable research activity on micro-scale nucleate boiling. In both MEMS and micro-actuators geometrically constrained vapour bubbles are used to move mechanical parts and to pump liquid in microchannels by localized heating. In a bubble jet printer the ejection of ink is controlled by the expansion and contraction of vapour bubbles. Flow boiling in narrow channels is also used to generate vapour bubbles in various refrigeration and power systems, and in cooling systems such as chemical reactors in which intensive heat generation takes place. Heat generating porous materials in which vapour bubbles enter heated capillaries are also of interest because of their relevance to the radioactive debris caused by a serious nuclear accident.

Many authors has investigated the evolution of confined bubbles between plates, including Bretherton (1961), Wilson et al. (1999), Ajaev and Homsy (2001a,b), Das and Wilson (2006), and Kenning et al. (2006). In particular, Wilson et al. (1999) studied the dynamics of a long, two-dimensional vapour bubble confined between two parallel plates held at, in general, different temperatures. Unlike Bretherton's (1961) classical isothermal model, in which the steady translation of the bubble is driven by an externally imposed pressure gradient, they studied the unsteady expansion and contraction of a vapour bubble whose motion is driven by mass transfer between the liquid and the vapour. As in Bretherton's (1961) model, the velocity of the bubble determines the initial thickness of the thin films of liquid laid down on both plates as the bubble expands, but unlike in Bretherton's (1961) model the evaporation from and/or condensation onto those films (which may break up into disconnected patches of liquid as they evaporate) determine the velocity of expansion and/or contraction of the bubble, and so there is a nonlinear coupling with a delay character between the profiles of the thin films and the overall dynamics of the bubble.

Subsequently, Ajaev and Homsy (2001a,b) studied a steady vapour bubble in a rectangular channel with a prescribed temperature distribution on its walls in which there is a balance between evaporation from the hotter parts of the bubble interface and condensation onto the colder parts.

The present paper presents the results of a preliminary study of a vapour bubble confined between two parallel plates which can be either superheated or subcooled. A simple theoretical model is developed to describe the collapse of a bubble between subcooled plates.

2. Experimental Procedure

Figures 1 and 2 show the apparatus used for the present experiments.

The test rig used consisted of two circular parallel plates separated by a 114 μm gap. A circular hole of diameter 0.5 mm was drilled through the lower plate and a resistor (powered by a DC power source) placed at the bottom of the hole. Vapour bubbles were generated by powering the resistor for a short period of time. A backlight white source was used to illuminate the field of view, and a high speed CCD camera was positioned above the plates to record the temporal evolution of the bubble. The recorded images were processed using ImagePro software to determine the evolution of the bubble as a function of time.

The entire experimental setup was housed in a 1 m × 1 m × 1 m plexiglass temperature controlled environmental box, and the temperature of the plates was controlled by maintaining the ambient temperature in the box at the described temperature. Two specific situations are investigated in the present work, namely both plates equally superheated and both plates equally subcooled.

The working fluid used was FC-72 with a boiling temperature of approximately 56°C at atmospheric pressure.

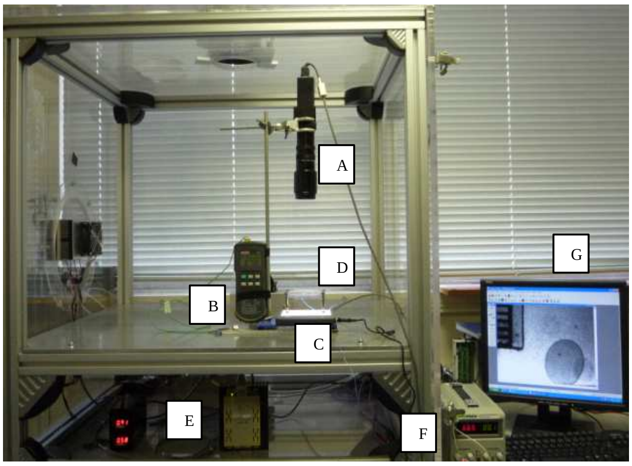
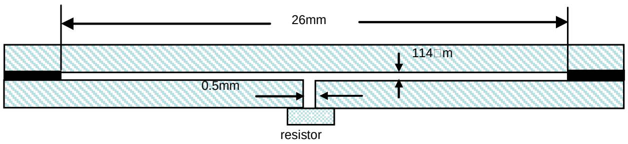


Figure 1: Experimental apparatus: (A) high speed CCD camera, (B) thermocouple and digital thermometer, (C) backlight, (D) test rig, (E) thermal regulation system, (F) power supply, and (G) image processing system.

(a)



(b)

Figure 2: (a) A sketch of the test rig and power source, and (b) a diagram showing the location of the resistor and the geometry of the plate.

3. Results

The first set of experiments examined the case when both plates were subcooled. Bubbles of approximately 4 mm in diameter were generated and then left to evolve freely. The subcooling ΔT_{sub} was varied from 0°C to 36.1°C and, as expected, in all cases the bubbles were found to collapse.

Figure 3 shows a typical sequence of images showing the collapse of a bubble of FC-72 vapour in the case ΔT_{sub} = 13.1 °C.

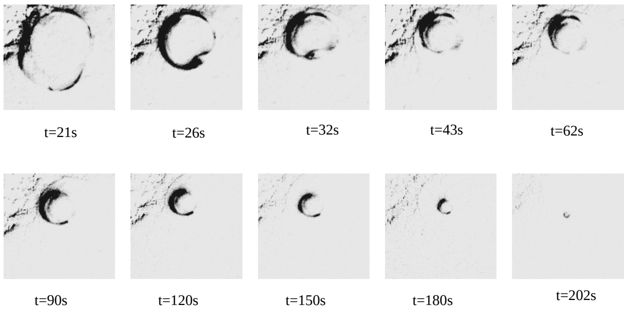


Figure 3: Images showing the collapse of a bubble of FC-72 vapour in the case $\Delta T_{sub} = 36.1^oC$.

Figure 4 shows the evolution of the diameter of a bubble of FC-72 vapour as a function of time for various degrees of subcooling ΔT_{sub}. As expected, as ΔT_{sub} is reduced the speed of bubble collapse slows down, and as ΔT_{sub} approaches 0°C the bubble remains almost steady for a considerable period of time. Figure 5 shows the final collapse time as a function of the degree of subcooling ΔT_{sub} and reveals, as expected, that the collapse time is a decreasing function of ΔT_{sub}.

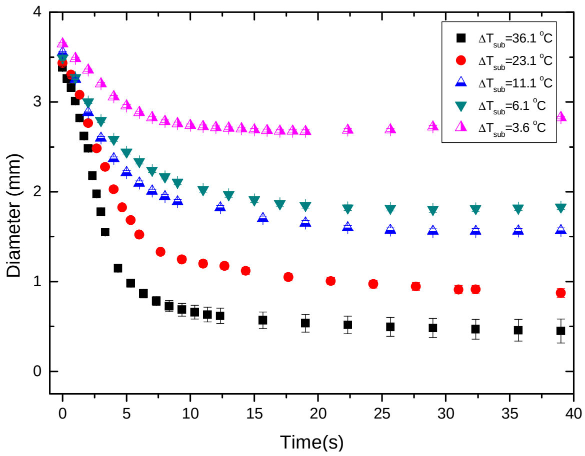


Figure 4: Evolution of the diameter of a bubble of FC-72 vapour as a function of time in the subcooled case.

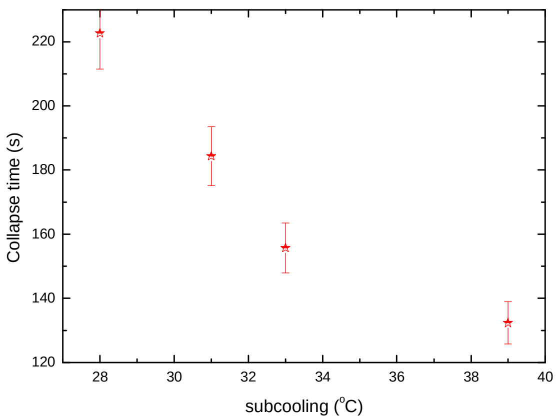


Figure 5: Final collapse time of a bubble of FC-72 vapour as a function of the degree of subcooling ΔT_{sub}.

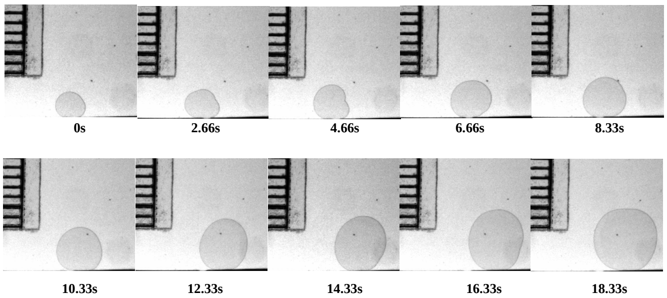


Figure 6: Images showing the expansion of a bubble of FC-72 vapour in the case $\Delta T_{sup} = 3.9$ °C.

The second set of experiments examined the case when both plates were superheated. The superheating ΔT_{sup} was varied from 0°C to 4°C degrees and, as expected, in all cases the bubbles were found to expand.

Figure 6 shows a typical sequence of images showing the expansion of a bubble of FC-72 vapour in the case $\Delta T_{sup} = 3.9$°C.

Figure 7 shows the evolution of the diameter of a bubble of FC-72 vapour as a function of time for various degrees of superheating ΔT_{sup}. In particular, Figure 7 shows that the speed of expansion is an increasing function of ΔT_{sup}.

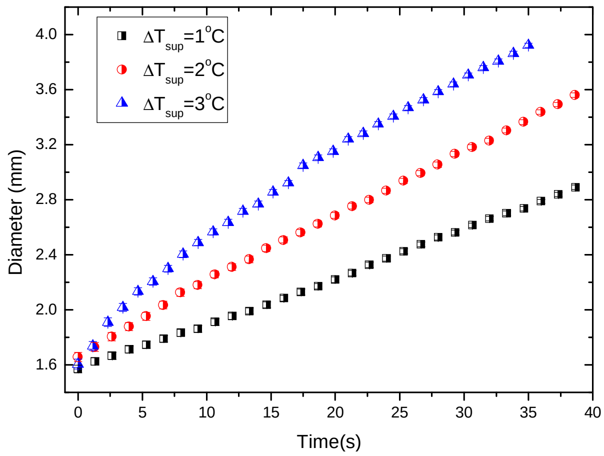


Figure 7: Evolution of the diameter of a bubble of FC-72 vapour as a function of time in the superheated case.

4. Theoretical Model

In the absence of a complete model for the expansion and/or collapse of a vapour bubble here we present a very simple theoretical model for the collapse of a bubble between subcooled plates which assumes that the heat required to condense the vapour onto the plates is supplied by heat conduction through the plates and the liquid films on them.

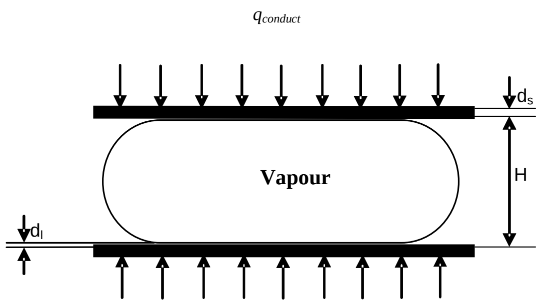


Figure 8: Sketch of the geometry of a confined vapour bubble.

The amount of heat required to condense a volume *dV* of liquid in time *dt* is given by

$$q_{condense} \;=\; \rho_l H_{lv} \frac{dV}{dt}\,, \qquad (1)$$

where H_{vl} is the latent heat of condensation and ρ_l is the density of the working liquid (FC-72).

On the other hand, the amount of heat conducted through the plates and the liquid films on them is

$$q_{conduct} \;=\; \frac{2\pi R^2 \Delta T_{sub}}{\dfrac{d_s}{k_s}+\dfrac{d_l}{k_l}}\,, \qquad (2)$$

where *R* is the radius of the vapour bubble, k_s is the thermal conductivity of the plates (plexiglass), k_l is the thermal conductivity of the working liquid (FC-72), d_s is the thickness of the plates, d_l is the thickness of the liquid films, and ΔT_{sub} is the degree of subcooling.

The assumption that all of the heat conducted is through the plates and the liquid films on them corresponds to setting $q_{conduct} = -q_{condense}$, and, assuming for simplicity that the volume of the bubble can be approximated by $V = \pi R^2 H$ where *H* is the gap between the plates, this means that *V* satisfies

$$\frac{dV}{dt} = -\frac{2\Delta T_{sub} V}{\rho H_{lv} H\left(\dfrac{d_s}{k_s}+\dfrac{d_l}{k_l}\right)}. \qquad (3)$$

Strictly the thickness of the liquid films, d_l, is an unknown function of *t* to be determined as part of the solution to the problem (see, for example, Wilson et al. 1999 and Das and Wilson 2006), but for simplicity here we assume that it is a linear function of *t* given by

$$d_l = Bt + C\,, \qquad (4)$$

where the constants *B* and *C* are determined by fitting with the experimental results. With this assumption equation (3) can be integrated with respect to *t* to yield

$$V = V_0 \left[\frac{\dfrac{d_s}{k_s}+\dfrac{C}{k_l}}{\dfrac{d_s}{k_s}+\dfrac{Bt+C}{k_l}} \right]^{\frac{2\Delta T_{sub} k_l}{\rho_l H_{lv} HB}}\,, \qquad (5)$$

where V_0 is the initial volume of the bubble at $t = 0$.

In this preliminary investigation a constant film thickness $d_l = C$ is assumed, corresponding to taking the limit $B \to 0$ in equation (5) to yield the exponential form

$$V = V_0 \exp\left[-\frac{2\Delta T_{sub} t}{\rho_l H_{lv} H\left(\dfrac{d_s}{k_s}+\dfrac{C}{k_l}\right)} \right]. \qquad (6)$$

The appropriate values of the physical parameters appearing in the theoretical model are given in Table 1.

Latent heat of condensation, H_{lv} (J kg^{-1})	88000
Density of the liquid, ρ_l (kg m^{-3})	1680
Gap between the plates, *H* (mm)	0.114
Thermal conductivity of the plates, k_s (W m^{-2} K^{-1})	1.05
Thermal conductivity of the liquid, k_l (W m^{-2} K^{-1})	0.057
Thickness of the plates, d_s (mm)	1.05

Table 1: Values of the physical parameters appearing in the theoretical model.

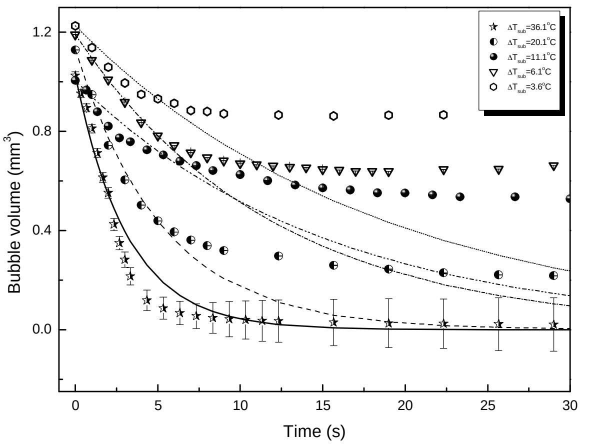


Figure 9: Comparison between the experimentally measured values of the volume of the bubble (symbols) and the corresponding fitted theoretical predictions given by equation (6) (curves) for a range of values of the subcooling ΔT_{sub}.

ΔT_{sub} (°C)	C (mm)
36.1	0.71
20.1	0.66
11.1	1.07
3.6	0.23
0.6	0.16

Table 2: Values of the constant liquid film thickness C for which the theoretical prediction given by equation (6) best fits the experimental values for a range of values of the subcooling ΔT_{sub}.

Figure 9 shows a comparison between the experimentally measured values of the volume of the bubble and the corresponding theoretical predictions given by equation (6) using the fitted values of the constant liquid film thickness C given in Table 2 for a range of values of the subcooling. Figure 9 shows good quantitative agreement only at high subcooling, suggesting that determining the correct evolution of the liquid film thickness may be a key element to successful theoretical modelling at low to moderate subcooling.

The corresponding analysis for the expansion of a bubble between superheated plates is made considerably more complicated by creation of new liquid film as the bubble expands and the possible dry out of the existing liquid film as it evaporates (see, for example, Wilson et al. 1999 and Das and Wilson 2006) and so is not attempted here.

5. Conclusions

In this preliminary study we investigated the evolution of a single vapour bubble confined between two superheated or subcooled parallel plates. When both plates are subcooled the bubble always collapses and the rate of collapse increases with the degree of subcooling. When both plates are superheated the bubble always expands and the rate of expansion increases with the degree of superheating.

A simple theoretical model captures the collapse of a vapour bubble between subcooled plates at high subcooling and suggests that determining the correct evolution of the liquid film thickness may be a key element to successful theoretical modelling at low to moderate subcooling.

Future work will focus on improving the theoretical model to achieve good agreement with the experimental data for both superheating and subcooling. Experimental data for other working fluids and other operating conditions are currently being obtained, and these will hopefully help us to achieve a fuller understanding of this important phenomenon in the future.

6. References

Ajaev, V. S. and Homsy, G. M., 2001a. Steady vapor bubbles in rectangular microchannels. J. Colloid Interface Sci. 240, 259-271.

Ajaev, V. S. and Homsy, G. M., 2001b. Three-dimensional steady vapor bubbles in rectangular microchannels. J. Colloid Interface Sci. 244, 180-189.

Bretherton, F. P., 1961. The motion of long bubbles in tubes. J. Fluid Mech. 10, 166-188.

Das, K. S. and Wilson, S. K., 2006. The unsteady expansion and contraction of a two-dimensional vapour bubble confined between superheated or subcooled plates. In “Progress in Industrial Mathematics at ECMI 2004”. Proceedings of the 13th European Conference on Mathematics for Industry (ECMI 2004), 21st-25th June 2004, Eindhoven, The Netherlands, (eds. A. Di Bucchianico, R. M. M. Matteij, M. A. Peletier), Springer, pp. 489-493.

Kenning, D. B. R., Wen, D. S., Das, K. S. and Wilson, S. K., 2006. Confined growth of a vapour bubble in a capillary tube at initially uniform superheat: experiments and modelling. Int. J. Heat. Mass Trans. 49, 4653-4671.

Lin, S., Sefiane, K. and Christy, J. R. E., 2002. Prospects of confined flow boiling in thermal management of Microsystems. Applied Thermal Engineering, 22, 825-837.

Wilson, S. K., Davis, S. H. and Bankoff, S. G., 1999. The unsteady expansion and contraction of a long two-dimensional vapour bubble between superheated or subcooled parallel plates. J. Fluid Mech. 391, 1-27.