INVESTIGATION OF NUCLEATE BOILING MECHANISMS UNDER MICROGRAVITY CONDITIONS *

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ABSTRACT

The present work is aimed at the experimental studies and numerical modeling of the bubble growth mechanisms of a single bubble attached to a heating surface and of a bubble sliding along an inclined heated plate. Single artificial cavity of 10 μm in diameter was made on the polished Silicon wafer which was electrically heated at the back side in order to control the surface nucleation superheat. Experiments with a sliding bubble were conducted at different inclination angles of the downward facing heated surface for the purpose of studying the effect of magnitude of components of gravity acting parallel to and normal to the heat transfer surface. Information on the bubble shape and size, the bubble induced liquid velocities as well as the surface temperature were obtained using the high speed imaging and hydrogen bubble techniques. Analytical/numerical models were developed to describe the heat transfer through the micro-macro layer underneath and around a bubble formed at a nucleation site. In the micro layer model the capillary and disjoining pressures were included. Evolution of the bubble-liquid interface along with induced liquid motion was modeled. As a follow-up to the studies at normal gravity, experiments are being conducted in the KC-135 aircraft to understand the bubble growth/detachment under low gravity conditions. Experiments have been defined to be performed under long duration of microgravity conditions in the space shuttle. The experiment in the space shuttle will provide bubble growth and detachment data at microgravity and will lead to validation of the nucleate boiling heat transfer model developed from the preceding studies conducted at normal and low gravity (KC-135) conditions.

INTRODUCTION

Boiling is known as a highly efficient mode of heat transfer. It is employed in component cooling and in various energy conversion systems. For space applications boiling is the heat transfer mode of choice since the size of the components can be significantly reduced for a given power rating. For any space mission the size, and in turn the weight of the components plays an important role in the economics of the mission.

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Applications of boiling heat transfer in space can be found in such areas as thermal management, fluid handling and control, and power systems. For space power systems based on the Rankine cycle (a representative power cycle), the key issues that need to be addressed are the magnitude of boiling heat transfer coefficient and the critical heat flux under low gravity conditions.

The investigations of boiling heat transfer for space applications impose unique constraints in terms of the number of experiments that can be conducted under microgravity conditions, the duration of the experiments, the expense and the difficulties involved in performing the experiments. Thus, for space applications, it is even more important that a better understanding of the boiling mechanism be developed so that experiments are needed only for confirmation of the predictions.

The objectives of the present work are to delineate through experiments and analysis, the contributions of some of the key mechanisms to total heat transfer rate during nucleate boiling under microgravity conditions. This includes the contribution of micro/macro layer evaporation on single and merged bubbles attached to a heated wall, heat transfer during sliding motion of a bubble along the heater wall and heat transfer due to fluid motion resulting from bubble growth and Marangoni effect. The effect of fluid motion induced by a growing sliding bubble is also considered.

Under microgravity conditions the early data of *Keshock and Siegel*[1] and *Siegel and Keshock*[2] on bubble growth and heat transfer show that the effect of reduced gravity is to reduce the buoyancy and inertia forces acting on a bubble. As a result, under reduced gravity bubbles grow larger and stay longer on the heater surface. This in turn leads to merger of bubbles on the heater surface and existence of conditions similar to fully developed nucleate boiling. Thus, under microgravity conditions partial nucleate boiling region may be very short or non-existent.

Erwin et al[3] and *Erwin and Merte*[4] have studied transient nucleate boiling on a gold film sputtered on a quartz plate by using a 5-second drop tower (10^{-5} g_e) at NASA Lewis Research Center. R-113 was used as the test liquid in the experiments. It was found that the time or temperature for initiation of nucleate boiling was greater for pool at near saturation temperature than that for a subcooled pool. They also noted the occurrence of energetic boiling at relatively low heat fluxes. The energetic boiling in which vapor mass rapidly covered the heater was postulated to be associated with an instability at the wrinkled vapor-liquid interface. Recently, *Merte et al*[5] have reported results of pool boiling experiments conducted in the space shuttle for the same surface that was used in the drop tower tests. Subcooled boiling during long periods of microgravity was found to be unstable. The surface was found to dryout and rewet. Average heat transfer coefficients during the dryout and rewetting periods were, however, found to be about the same. The nucleate boiling heat fluxes were higher than those obtained on a similar surface at earth normal gravity conditions.

Experimental studies of flow boiling under low gravity conditions are far fewer and limited than those for pool boiling. The earliest study of flow boiling under reduced gravity conditions is that of *Cochran*[6] . The experiments were conducted in the drop tower with flow velocities varying from 4.2 to 11.5 cm/s . These short-duration (2.2 second) low gravity tests were focused on the boiling process near inception. In comparison to normal gravity tests, it was found that in microgravity, bubbles tended to stay on the heating surface, become large enough to coalesce with neighboring bubbles and acquired irregular shapes. The size of bubbles along the heating surface was found to correlate with thickness of the thermal layer. More recently, *Saito et al*[7] have studied flow boiling of water on a heater rod placed in a square channel. The experiments were conducted in Japanese low gravity experimental aircraft (MU-300) at 0.01 g_e for 20 seconds. In the experiments, subcooled nucleate boiling heat transfer data for water were taken at velocities varying from 3.7-22.9 cm/s and pressure in the range of 0.9 to 2.4 bars. Nucleate boiling heat transfer coefficients were found to increase slightly in the direction of flow and the magnitudes of the heat transfer coefficients were about the same as at normal gravity.

Finally, it appears that recent studies of nucleate boiling under microgravity have shed light on this complex phenomena, however, the studies are non-conclusive. Questions remain on the stability of nucleate boiling, the reasons for equivalence of magnitudes of heat transfer coefficients at normal gravity and low gravity conditions and on the physics that underlies the phenomena. As such, there is no mechanistic model that describes the observed physical behavior and the dependence of nucleate boiling heat flux on wall superheat.

DESCRIPTION OF THE RESEARCH

In view of the above discussion, the natural question that arises: how does microgravity affect nucleate boiling heat transfer? Thus, the main objective of present work is to develop a physical understanding of the key phenomena and to advance mechanistic models so that development of a global model for nucleate boiling under microgravity conditions is facilitated. The work is both experimental and analytical/numerical in nature and is first focused on a single bubble, i.e. without interaction of neighboring bubbles. To be able to predict nucleate boiling heat transfer under microgravity conditions, a quantitative understanding of several mechanisms during nucleate boiling at normal gravity is needed which includes 1) Heat transfer to a single bubble as well as that associated with micro/macro layer evaporation; 2) Heat transfer and flow field for a bubble sliding along a heated wall. For item 1) the numerical results and the experimental data have been compared.

THEORETICAL/NUMERICAL STUDIES

Complete numerical simulation of the flow and temperature field during the bubble growth cycle on a horizontal surface was conducted. The computational domain is divided into micro and macro regions as shown in Fig.1. The micro-region contains the thin film that forms underneath the bubble whereas the macro region consists of the bubble and the liquid surrounding the bubble. Finite difference scheme along with a level set method was used to solve the equations governing the conservation of mass, momentum and energy. The disjoining pressure effect is included in the numerical simulation to account for heat transfer through the liquid micro-layer. The pressure gradients in the vapor and liquid are related through the drag experienced by the liquid in the microlayer, the capillary force resulting from the change in the shape of the interface, the disjoining pressure and the recoil pressure.

Figure 2 shows the calculated bubble growth patterns at 1 atm pressure and saturated water. Table 1 gives the calculated bubble diameter at departure and the time for bubble growth for different *g* levels. In obtaining the results water at one at atmosphere was used as the test liquid and the contact angle was assumed to be 38°. The wall superheat was 6.7 °C. It is found that the bubble diameter at departure approximately scales as $g^{-1/2}$ and the bubble growth time scales as $g^{-0.9}$. High heat flux was observed to exist in the micro layer. (for details, see *Son and Dhir*[8])

Table 1 Prediction of Bubble Growth Period and Departure Diameter for Saturation Water

Gravity	Bubble departure diameter (mm)	Bubble growth Period (sec.)
1 g	2.3	0.0034
0.126 g	6.2	0.25
0.01 g	21.5	2.7
0.0001 g	209	135

EXPERIMENTS AT NORMAL GRAVITY

The ongoing experiments have the objective to provide, in a very clean manner, the basic information to validate a mechanistic model for prediction of nucleate boiling heat flux as a function of wall superheat. With the presumption that dependence of cavity site density on wall superheat is known (true for designed surface with artificial cavities) the prediction of heat flux requires a knowledge of interfacial area per cavity, interfacial heat flux, and heat transfer on the unpopulated area of the heater. Size of bubbles at breakoff, bubble release frequency and the number of bubble release sites influence the time and area averaged heat transfer and also determine the vapor generation rate.

Experiments at normal gravity were conducted on the set-up using a polished Silicon wafer (4" in diameter) as heat transfer surface. 10μm diameter cavity was formed in the center of the wafer. The schematic is shown at Fig.3. The processes of nucleation, the bubble growth and merger (in vertical direction) were recorded with a high speed video camera using saturated and subcooled PF-5060 and water as test liquid at one atmosphere pressure.

Fig.4 compares the bubble shape and size just prior to departure predicted from the numerical simulations and that observed in the experiments. The contact angle was 50°. A good agreement between predicted and observed bubble shapes and sizes is seen.

Experiments of bubbles sliding along a downward-facing rectangular heating surface have also been conducted. The micro gage heaters were bonded on the back side of the Silicon wafer on which miniature thermocouples were also attached. Each of the micro heaters was separately connected to the power supply so that the heater surface superheat profile could be controlled. Single vapor bubbles were generated upstream of the heat transfer surface and were allowed to slide over the surface. Fig.5 shows the schematic of the set-up. Three glass windows are used for the purpose of optical measurements including interferometry for the temperature field around the sliding bubble. A provision was made to hold and orient on a standard optical table the set-up at different angles to the gravitational acceleration vector.

The bubble shapes and size, and in turn the bubble growth rate along the surface were recorded using high speed video camera in two directions simultaneously. The wall superheat priori to the sliding of bubble and the transient temperature variation due to the sliding bubble were measured at different subcoolings, heating rate and inclination angles of the surface. A large wake region was observed behind the sliding bubble. This region became smaller with increase in the inclination angle. Preliminary information has been obtained on the temperature field around a sliding bubble (using interferometry) and the local velocity field around a sliding bubble (using silvered glass particle as tracers for PF-5060 and hydrogen bubbles for water).

Figure 6 shows the changes in typical shape and size of a bubble sliding along the surface at a small inclination angle. It is found that bubbles change shape from a initially shape of a sphere to a long ellipsoid or deformed long ellipsoid at the downstream end of the inclined plate. Between the sliding bubble and the heat transfer surface wedge-like liquid gap was observed. The angle of the wedge is found to be a function of plate angle of inclination and bubble size.

Figure 7 shows the sliding bubble volume along the surface at three inclination angles. Larger inclination angle, i.e. smaller gravitational acceleration component normal to the surface, leads to lower bubble growth rate, indicating lower heat transfer rate between the bubble and the surface. The effective bubble diameter has been found to increase at a rate higher than $\sqrt{t}$ for a thermally controlled growth.

EXPERIMENTS IN THE KC-135 AND IN THE SPACE SHUTTLE

Since at normal gravity, there is always a gravitational component parallel to and normal to an inclined surface, the bubble shape and detachment, which are sensitive to magnitude of gravitational acceleration, must be studied under low gravity conditions. As such, experiments are being conducted in KC135 and are proposed to be performed in space shuttle to further quantify the effect of significantly reduced gravity (10^{-5} g_e) on the bubble detachment process in particular, and on the heat transfer in general. It is necessary that boiling experiments be carried out on "designed" surface. These experiments will not only provide data on the scaling effect of gravity on various processes, including bubble growth and departure, but will also be valuable in validating the predictive model for nucleate boiling heat transfer under microgravity conditions.

The data of the ongoing experiments in KC-135 will be very helpful in assessment of the overall heat transfer model, and in the design of the experiment for the space shuttle.

CONCLUDING REAMARKS

Complete numerical simulations and experiments for bubble growth, detachment and merger (vertically) at an artificial cavity formed on a polished Silicon wafer for PF5060 and water have been carried out. The bubble departure diameter and release frequency have been analyzed for different wall superheats, subcoolings and contact angles. The scaling of these parameters with magnitude of gravitational acceleration has been carried out. For sliding bubble experiments, the results for bubble growth rate, surface temperature, and the liquid motion were obtained. The effects of subcooling and component of gravitational acceleration normal to the surface was studied. During their sliding motion, the bubbles are formed to elongate into an elliptical shape and a liquid wedge is formed between the heater surface and the vapor liquid interface.

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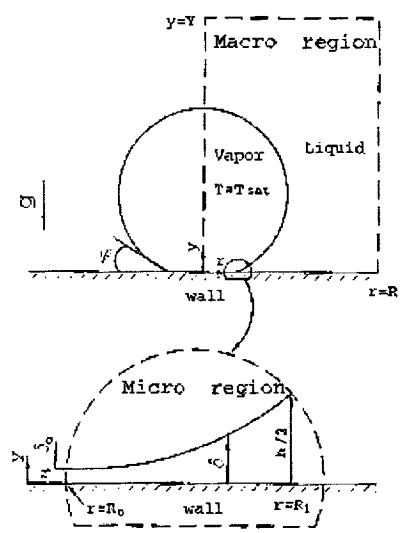


Fig. 1 Micro and macro-regions in numerical simulation

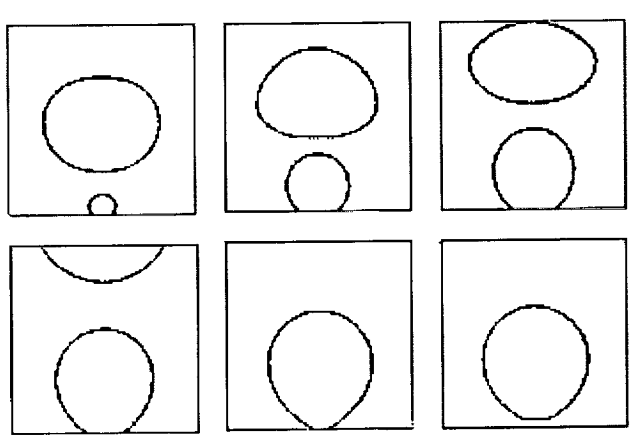


Fig. 2 Bubble growth patterns from numerical simulation and the images from the experiments on the micro-machined Silicon wafer

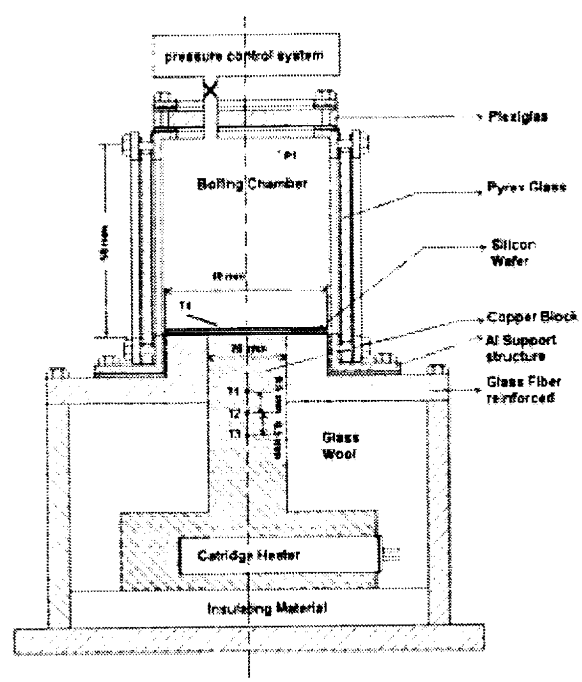


Fig. 3 Schematic of the set-up for nucleate boiling experiments with the micro-machined Silicon wafer

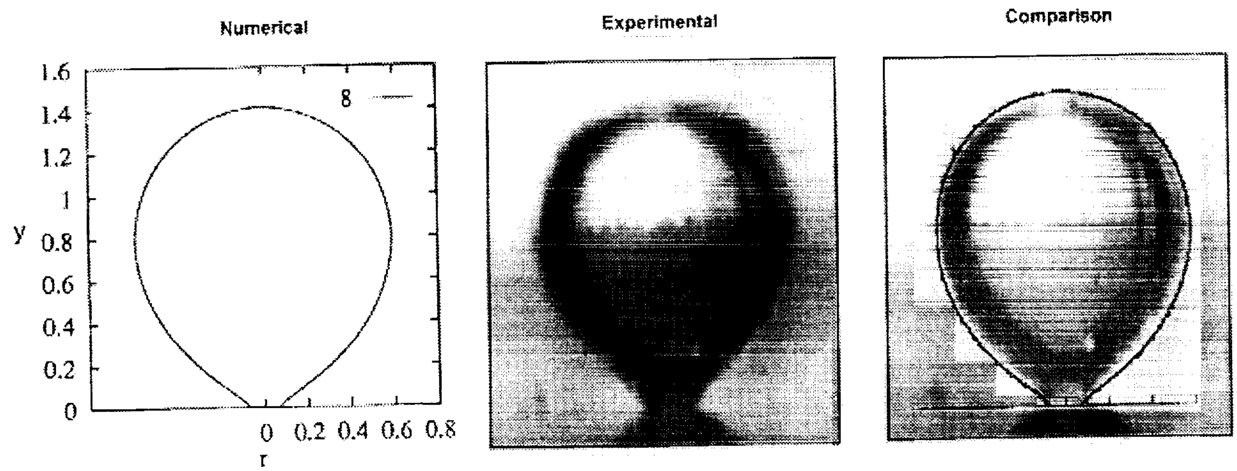
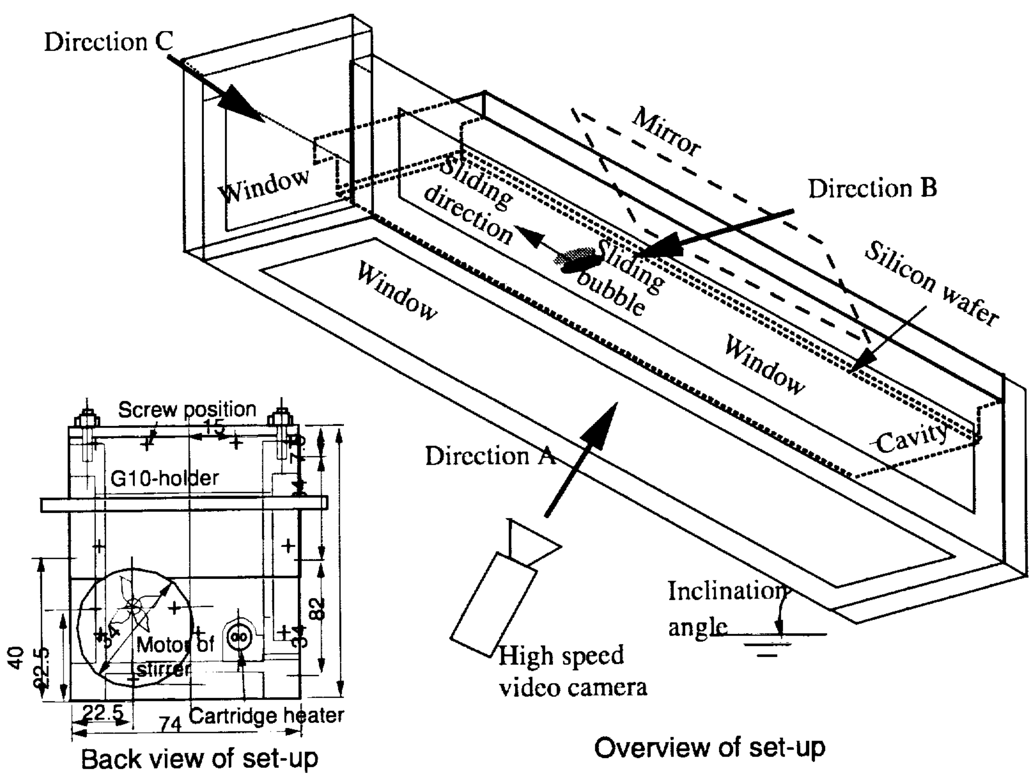
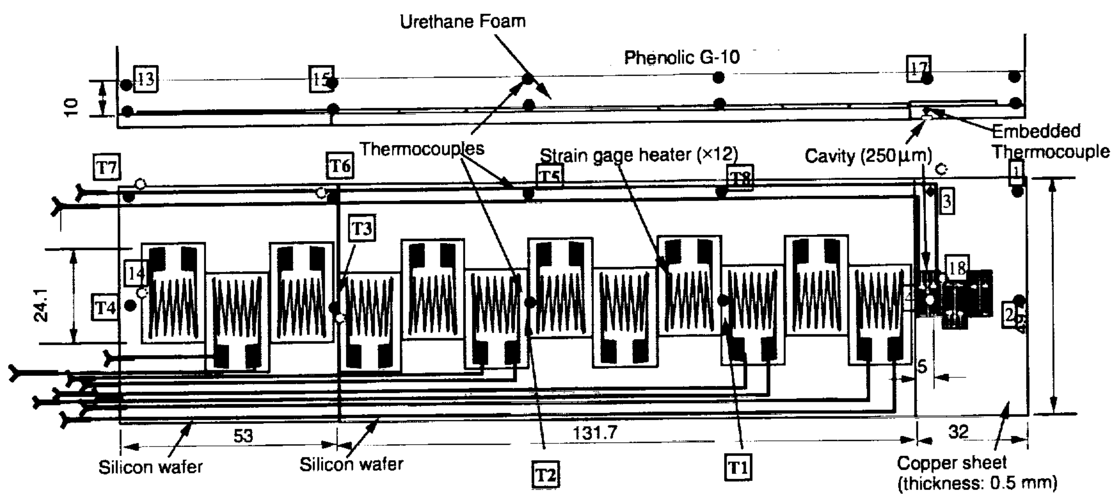


Fig. 4 Bubble shapes from numerical simulation and experiments for saturated water at contact angle 50° and wall superheat 8.5 K



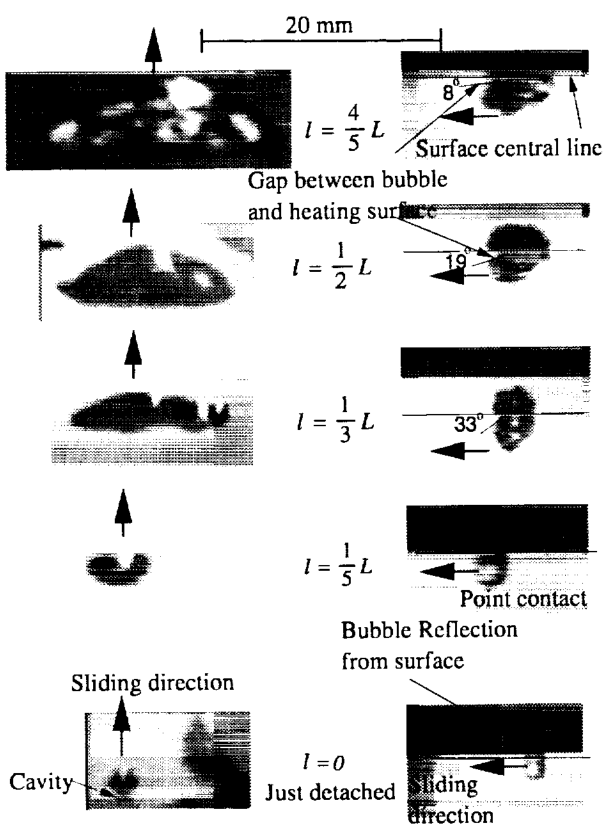
(a) Overview of set-up

Fig. 5 Schematic of the set-up for sliding bubble experiments (to be continued)



(b) Configuration of heating plate

Fig. 5 Schematic of the set-up for sliding bubble experiments (continued)



Viewed in direction A   Viewed in direction B

Fig. 6 Change of sliding bubble shape at surface inclination angle 15°, subcooling 1 K and wall superheat 7.3 K (l: distance from cavity; L: distance from cavity to upper end of plate)

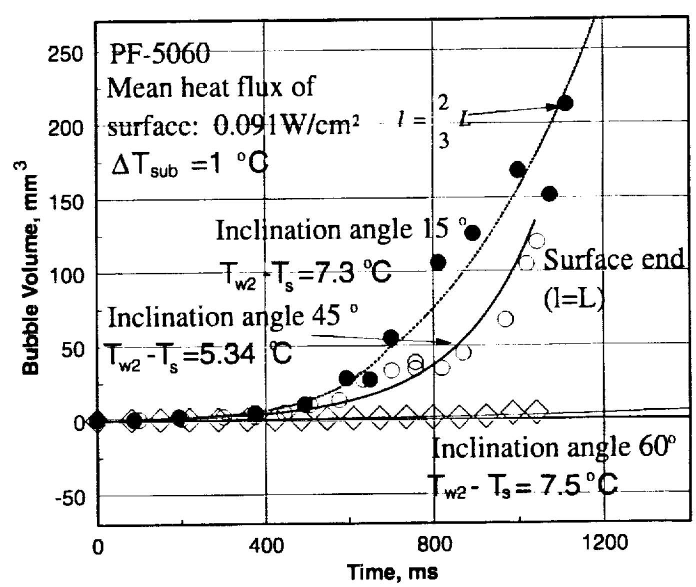


Fig. 7 Influence of inclination angle on sliding bubble growth rate