NUCLEATE BOILING UNDER REDUCED GRAVITY CONDITIONS

Vijay K. Dhir
Henry Samueli School of Engineering and Applied Science
University of California, Los Angeles
Los Angeles, CA 90095-1597

Abstract

A number of experimental studies detailing the dependence of nucleate boiling heat flux on wall superheat under reduced gravity conditions have been reported in the literature. These studies have been performed using various microgravity platforms. In the experiments, both directly and indirectly heated surfaces have been used. Flat plates, cylinders, and spheres have been employed as test geometries. Invariably, the results from these studies are neither consistent with each other nor are they predictable from correlations developed with data obtained at earth normal gravity. In this work, we describe a building block type of approach to develop a mechanistic understanding of nucleate boiling under reduced gravity conditions. The approach utilizes complete numerical simulations of the process. The numerical simulations results are validated with data from well-controlled experiments.

1. INTRODUCTION

Nucleate boiling is a phase change process that is associated with high heat fluxes at relatively low wall temperatures. As such, its application in space can be found in the areas of thermal management, fluid handling and control, power systems, on-orbit storage and supply systems for cryogenic propellants and life support fluids, and for cooling of electronic packages for power systems associated with various instrumentation and control systems. Recent interest in exploration of the Moon, Mars and other planets, and the concept of in-situ resource utilization on Mars has highlighted the need to understand the effect of gravity on boiling heat transfer at gravity levels varying from $1 \geq g_e \geq 10^{-6}$.

Reviews of past reduced gravity boiling studies have been performed by Siegel (1967) and more recently by Straub (1994, 2001) and Dhir (2002). In this work, some of the significant results from previous studies are reported while providing new results from a building block type of approach involving complete numerical simulation of the process coupled with data from controlled experiments.

2. NUCLEATE BOILING

In the past, nucleate boiling has been studied using various microgravity platforms, such as drop tower, parabolic flights of aircraft, sounding rocket, and space shuttle. In the experiments, flat plates, cylinders and spheres were used as test geometries and they were directly or indirectly heated. Water, hydrocarbons, and refrigerants have been used as test liquids. Key results from the past studies are described next followed by the building block approach adopted in this work.

2.1 PAST STUDIES

Siegel and Usiskin (1959) studied nucleate boiling on electrically heated vertical and horizontal ribbons under free fall conditions. During the free fall, the platform carrying the test section traveled about 8ft. From the photographic observations, it was found that during the free fall, vapor remained adjacent to the heated surface and did not appear to push away from the heater surface. Nucleate boiling heat flux data were found to be comparable to that at earth normal gravity. Siegel (1967) reviewed the reduced gravity boiling studies and concluded that the effect of the magnitude of gravity on nucleate boiling heat transfer is small. Referring to the work of Cochran et al. (1966), he concluded that the magnitude of gravitational acceleration becomes even less important with liquid subcooling. It should be stressed that although in studies prior to 1967, gravity levels up to $10^{-5}g_e$ were obtained, the duration of the experiments in reduced gravity was less than 7 sec. Transient effects must have played an important role in the nucleate boiling data obtained in these short duration tests.

Oka et al. (1995) have studied pool boiling of n-Pentane, R-113, and water on transparent heaters under parabolic flight conditions. During the flight, significant variation of the gravity level occurred, but for about 5 seconds; reduced gravity, g_z/g_e, of about 0.02 persisted normal to the heater surface. It was noted that during stable nucleate boiling of n-pentane and R-113, bubble merger at the heater surface occurred by the sliding of the bubbles along the surface. However, in water, the coalescence of bubbles occurred in the direction normal to the heaters by the suction of smaller, newer bubbles into larger bubbles. The difference in the bubble merger behavior for water and the two other liquids was attributed to differences in surface tension and wettability characteristics. It was postulated that vapor/liquid/solid contact behavior attains significant importance at low gravities. However, the authors reported no quantitative value of physical parameters (e.g., contact angle), which could be used to relate to the observed behavior. During the period of low gravity, no bubbles were seen to detach from the heater surface. Nucleate boiling heat fluxes under low gravity condition for R-113 and n-pentane were found to be comparable to those obtained under earth normal gravity conditions. However, with water, a substantial reduction in nucleate boiling heat fluxes at a given wall superheat was found at the low gravity levels. All of the reported data were obtained for subcooled liquids with a liquid subcooling as high as 20^{o}C.

In a subsequent work, Abe et al. (1994) have studied pool boiling of a mixture of ethanol and water under free fall conditions of a drop tower. In the experiments, reduced gravity of the order 10^{-5} existed for about 10 seconds. It was found that during boiling with this non-azeotropic mixture, the nucleate boiling heat transfer coefficients were about 20% higher than those obtained under normal gravity conditions.

Ervin et al. (1992) and Ervin and Merte (1993) have studied transient nucleate boiling on a gold film sputtered on a quartz plate by using a 5 second drop tower ($g_z/g_e \simeq 10^{-5}$) at NASA Glenn Research Center. In these experiments, R-113 was the test liquid. From the experiments, it was found that time or temperature for initiating nucleate boiling was greater for a pool at 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. Merte (1994) and Merte et al. (1995) have also reported results of pool boiling experiments conducted in the space shuttle on the same surface that was used in the drop tower tests. Subcooled boiling under microgravity conditions was found to be unstable. Because of a large step in power input to the heater, the heater surface temperature rose rapidly. The nucleation generally occurred at high superheats and resulted in bubbles that grew energetically. From the analysis of the data, the investigators have found evidence of both quasi-homogeneous and heterogeneous nucleation. It was noted that long term steady nucleate boiling could be maintained on a flat plate heater under microgravity conditions when a large bubble, parked a small distance away from the heater, acted as a vapor sink. Also, from runs lasting a few seconds up to about two minutes, it was concluded that nucleate pool boiling heat transfer coefficients in microgravity are higher than those at earth normal gravity. No mechanistic explanation was given for this observation.

These observations have been reinforced through the results of two sets of recent experiments (Merte et al.; 1998) on the space shuttle. In addition, it has been noted that liquid subcooling enhances nucleate boiling heat transfer in microgravity.

Zell (1991) used a directly heated gold-coated flat plate, 2 cm x 4 cm, to study nucleate boiling heat transfer under low and microgravity conditions. From the experiments in the parabolic flights of the KC-135 aircraft and using R-12 as the test liquid, it was found that heat transfer coefficients for saturated boiling were about 10% lower than those at earth normal gravity. Straub, Zell, and Vogel (1990) have found that on a flat surface, with R-113 as a test liquid, the saturated nucleate boiling heat fluxes at $g_z/g_e \simeq 10^{-4}$ (TEXUS) are much smaller than those at earth normal gravity. It has been argued by Straub (2000) that because the system pressure in the TEXUS experiments ($p/p_c = 0.01$) was much smaller than that in the KC-135 aircraft ($p/p_c = 0.18$), large vapor volume in the former case hindered the liquid-vapor exchange at the heater surface. Furthermore, it is also possible that g-jitter in the KC-135 aircraft caused the vapor bubbles to leave the heater surface prematurely. Generally, on the heater surface, two large bubbles surrounded by several smaller bubbles were observed. After merger, as the combined vapor mass protruded into the subcooled liquid, vapor condensed, and the bubble shrank. This process continued as long as liquid subcooling was maintained. A dry patch was believed to form under the bubble base. Evidence of this was found from the superheated vapor temperature recorded by thermocouples that were enveloped by the bubble. In the experiments of Zell (1991), the heater surface temperature was forced to continuously increase even when the heat flux was held constant, which suggested some sort of dryout of the surface. The rate of increase of the surface temperature was found to increase with an increase in power input. This suggests that in Zell's experiments, steady state conditions did not exist. In Fig. 1, the saturated and subcooled nucleate boiling data of Zell (1991) and Lee and Merte (1998) are plotted for $g_z/g_e = 10^{-4}$. The test liquid in both studies was R-113. For saturated boiling, the large increase in temperature at a very low heat flux of about 3 W/cm^2 that was observed by Zell is indicative of at least a partial dryout of the surface. Contrary to the data at earth normal gravity, the subcooled microgravity data show a heat transfer coefficient that decreases with wall superheat. Again, this is indicative of the partial dryout of the surface at relatively low heat fluxes. Lee and Merte's data, however, show a behavior similar to the data at earth normal gravity, in that the heat transfer coefficient is seen to increase with wall superheat. In Lee and Merte's experiments, high heat fluxes were suddenly imposed. After flashing in the superheated liquid layer adjacent to the heater surface, many small bubbles were formed energetically. These bubbles merged away from the heater surface, and the merged bubbles probably did not have sufficient contact with the heater to lead to dryout. This difference in the two results needs to be resolved.

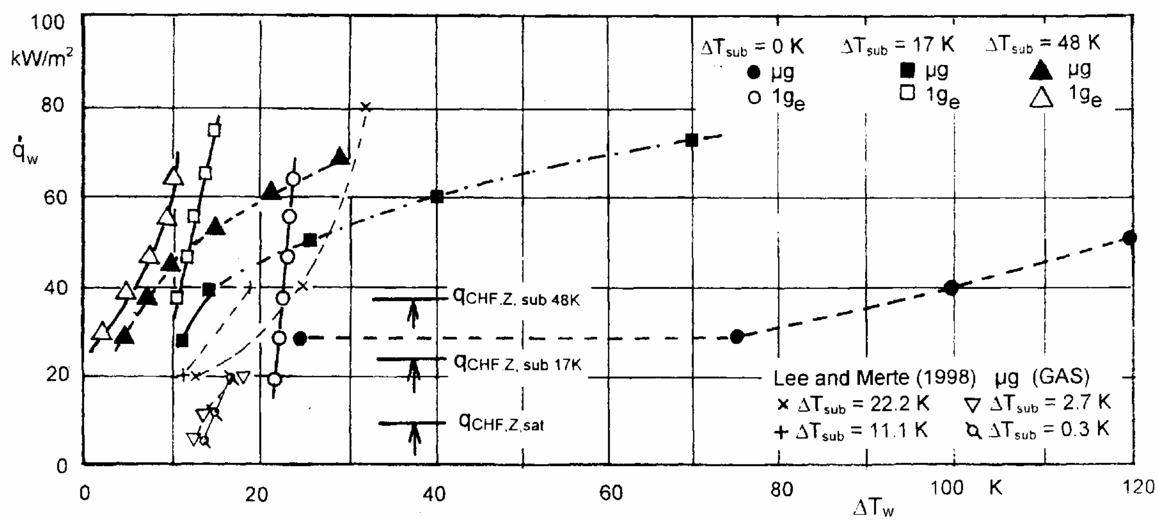


Fig. 1. Nucleate boiling heat transfer data on a flat plate for various subcoolings at $1 - g_e$ and $\mu - g$, and CHF according to hydrodynamic theory extrapolated to $10^{-4}g_e$ (Straub, 2001)

Ohta (1999) has reported results of the boiling of saturated and subcooled ethanol and water on a 50 mm diameter sapphire disc under the microgravity environment of the Japanese ballistic rocket. The back side of the sapphire disc was heated, and the temperature of the test surface was measured with resistance thermometers directly attached to the boiling surface. From visual observations, Ohta characterized nucleate boiling by the behavior of the microlayer underneath the primary bubble supporting a large, coalesced bubble. He claims that for boiling of water, the primary bubbles were distributed in the liquid layer in between the large bubble and the heater surface. However, for ethanol, primary bubbles of a large size filled the entire base of the coalesced bubble. He concluded that in microgravity steady state nucleate boiling was possible due to either the removal of vapor bubbles as a result of residual gravity or because of condensation of vapor at the bubble-liquid interface away from the heater surface. It should be noted that for ethanol, Ohta found a dependence of wall heat flux on superheat that is much stronger than that at earth normal gravity.

Straub and Micko (1996) have reported results of subcooled and saturated boiling of R-134a on 0.05 and 0.2 mm diameter platinum wires under the microgravity environment of the space shuttle. For saturated liquid at reduced pressures less than 0.64, the nucleate boiling heat transfer coefficients on a 0.2 mm wire under microgravity were found to be about 10% higher than those at earth normal gravity. The enhancement decreased slightly with wall superheat. However, for the 0.05 mm wire, the enhancement was less; about 10% degradation was observed at a reduced pressure of 0.21. It was noted that steady state saturated nucleate boiling could be maintained on wires. Furthermore, it was believed that the bubble departure and bubble motion was caused by coalescence process. However, their photographs mostly showed bubbles hovering around the heater without escaping into the bulk. When the liquids were subcooled, the nucleate boiling heat transfer coefficients in microgravity were found to be 10 to 20% higher than those at earth normal gravity. The enhancement was found to diminish with heat flux.

Straub et al. (1996) have reported results of bubble dynamics and pool boiling heat transfer on a 0.26 mm diameter hemispherical surface placed in the BDPU (Bubble, Drop, and Particle Unit) facility. This facility was carried in the space shuttle. Again, little difference in the nucleate boiling data obtained under 1g and μg condition was found. Bubble dynamics were observed to change significantly with change in liquid subcooling, system pressure, and wall superheat. Surface tension, wetting behavior of the liquid, bubble coalescence, and liquid momentum during bubble formation were found to influence the boiling process. Thermocapillary flow was found to play an important role under subcooled boiling conditions.

2.2. BUILDING BLOCK APPROACH

An alternative to the studies that have been described above and the results of which cannot be used with confidence to scale the effect of gravity, is the building block type of approach. In following this approach, it is recognized that in order to develop a credible model for nucleate boiling, one must address four sub-processes and their interactions. These sub-processes being density of active nucleation sites, bubble dynamics that includes bubble growth, merger, and departure; and several mechanisms of heat transfer. These mechanisms being transient conduction into liquid over heater area influenced by a departing vapor bubble, evaporation at vapor bubble base and boundary, thermocapillary convection resulting from surface tension gradient along the interface and convection over areas not occupied by bubbles. Convective motion, however, can be altered by the agitation created by departing vapor bubbles. The fourth sub-process is the thermal response of the solid. Most of the experiments are conducted by controlling heat flux. Because of the spatial and temporal variation of heat transfer coefficient on the liquid side, solid surface temperature will oscillate. To ascertain the surface temperature, one must solve conjugate problem. If the surface temperature is assumed to remain constant, the solid can be decoupled from the thermal processes on the liquid side. Prediction of number density of active nucleation sites on a commercial surface is extremely involved. By using micro-fabricated surfaces, one can control the number of cavities that become active at a given superheat. This is the approach that is employed in the building block approach developed here.

Thus, limiting to bubble dynamics and associated heat transfer, complete numerical simulations are used to model the boiling process. The simulation model is that proposed by Son and Dhir (1998). In that model, the region of interest, as shown in Fig. 2, is divided into micro and macro regions. The micro region is the ultra thin liquid film that forms between the solid surface and the evolving vapor-liquid interface. Heat from the solid is conducted across the film and is utilized for evaporation. At the inner edge, the film has a thickness of the order of a nanometer, i.e., a few molecules of liquid are adsorbed on the surface and do not evaporate. At the outer edge, the film has a thickness of a few microns. Lubrication theory is used for the evaluation of film thickness. Various forces that are considered are those due to viscous stresses, recoil pressure, disjoining pressure, and capillary pressure. The macro region is vapor-liquid occupied space except the micro region. In the macro region, complete conservation equations of mass, momentum, and energy are solved for both phases. The interface shape is captured through a level set function. The interface shape obtained from the macro-solution is matched with that obtained from the micro-solution at the outer edge of the micro-layer. It is required that the tangent to the interface at that point yield the apparent contact angle. Details of the model are given in Son and Dhir (1998). For three dimensional situations, we continue to use the two dimensional model for micro-layer under the assumption that no cross flow exists in the peripheral direction. Numerical simulation results are validated with data from experiments conducted in the parabolic flights of the KC-135 aircraft.

2.2.1. SINGLE BUBBLE DYNAMICS

Figure 3 shows the bubble diameter at departure as a function of gravity level. The solid line is the prediction from numerical simulations, whereas the data are experiments conducted at earth normal gravity and in the KC-135 aircraft. For single bubbles, numerical simulations consistent with the data obtained with water yield inverse square root dependence on gravity of the bubble diameter at departure. Bubble growth period is shown in Fig. 4. Numerical simulations predict growth period, t_g, to vary as $g^{-0.93}$, whereas the best fit to the data yields $g^{-1.05}$. Considerable scatter in the data is seen. This is due to the fact that variables, such as liquid subcooling and time variation of gravity have a more pronounced effect on growth period than on the bubble diameter at departure.

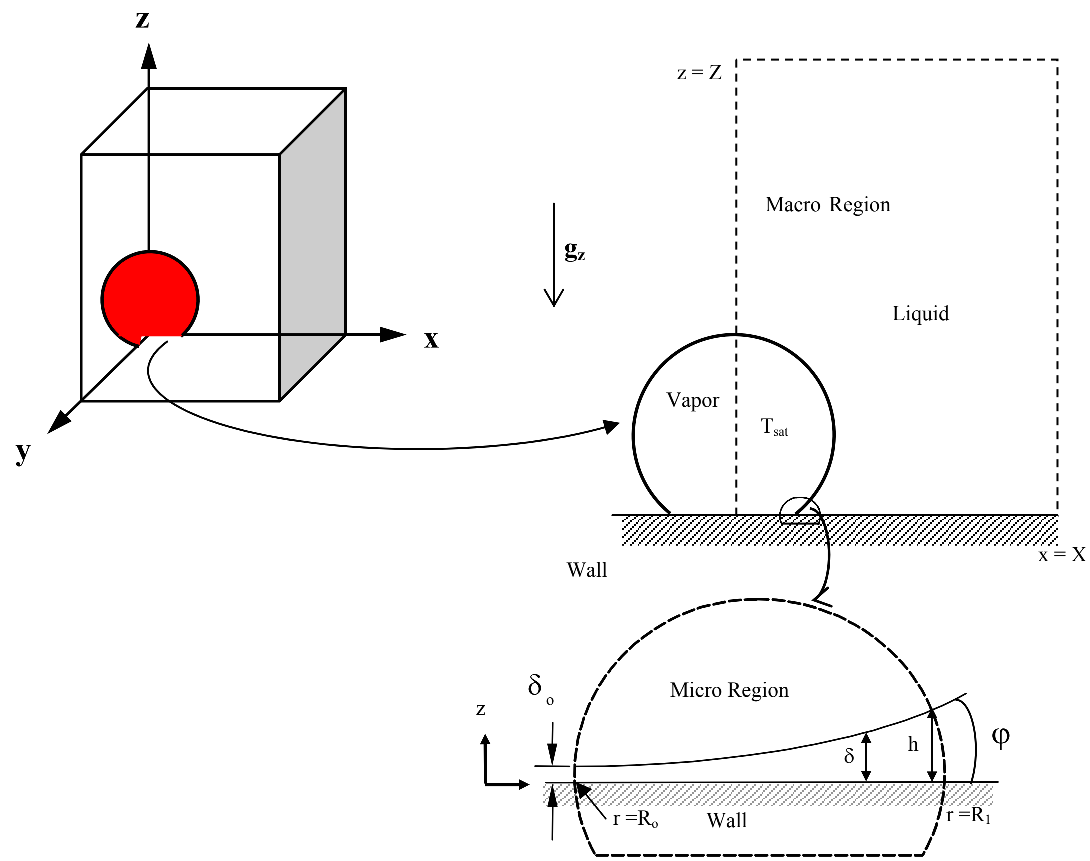


Fig. 2. Micro and Macro regions of the mathematical model for numerical simulation

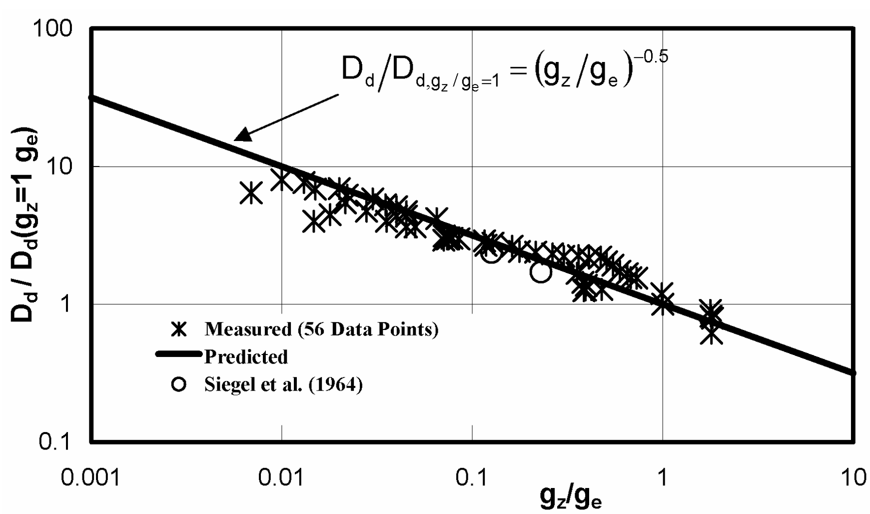


Fig. 3. Bubble diameter at departure as a function of the gravity level

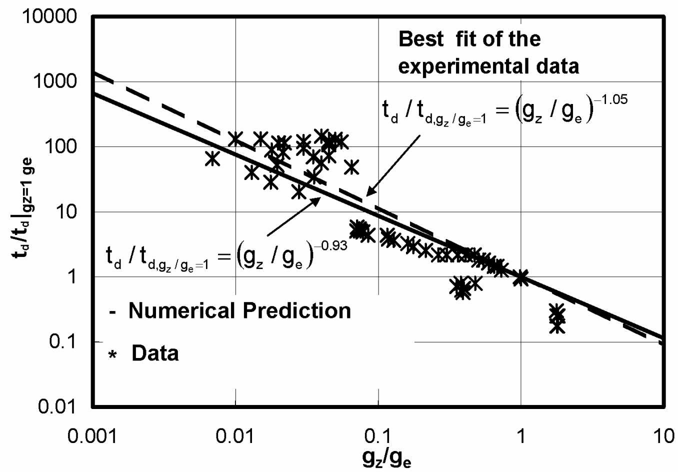


Fig. 4. Bubble growth time before lift-off as a function of the gravity level

2.2.2. BUBBLE MERGER

As the number density of nucleation sites increase, bubbles start to merge laterally. The upper set of frames in Fig. 5 show the results of visual observations from experiments in the KC-135 aircraft with a gravity level of about $10^{-2}g_e$. Results from numerical simulations are shown in the lower set of frames. A phase difference existed in nucleation of bubbles at the neighboring sites. After merger, a mushroom type of bubble with a liquid bridge between the two stems holding the vapor bubble to the heater surface is formed. As the vapor bubble tries to become spherical before departure, vapor tails are seen to form. Numerical simulations are seen to capture the essential physics of the process.

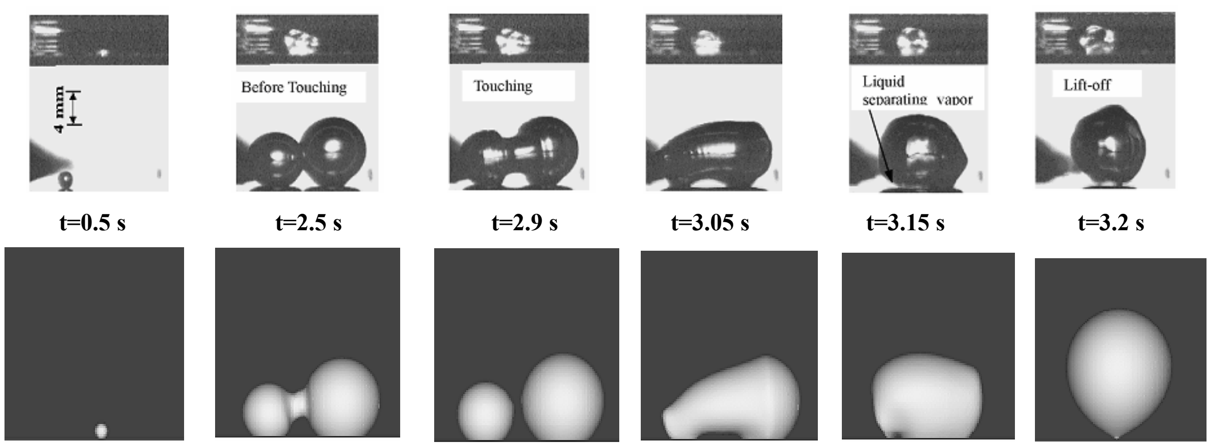


Fig. 5. Comparison of experimental and numerical bubble shapes during the merger of two bubbles at low gravity (fluid: water, $\Delta T_w = 5\ ^oC$, $\Delta T_{sub} = 3\ ^oC$, $g = 0.01g_e$, $\phi = 54^o$, spacing = 7 mm)

In general, bubble diameter at departure has been found to depend on the spacing and orientation of vapor bubbles (Abarajith, Dhir, and Son, 2004). Figure 6 shows the growth, merger, and departure process of three inline bubbles place 1.14 mm apart at a gravity level of 10^{-2} g_e. The calculations were carried out in the computational domain of 7.34 mm x7.34 mm x 14.68 mm. Formation of a mushroom type bubble with three stems is clearly seen. The stems shrink as the bubble tries to become spherical prior to departure. The variation of bubble diameter at departure normalized with the characteristic length, $l_o = \sqrt{\sigma / g(\rho_l - \rho_v)}$ is plotted in Fig. 7(a) for different cavity spacings and orientations. The bubble departure diameter decreases as the spacing increases until the spacing is equal to $D_{ds}/4$, where D_{ds} is the diameter of departure of a single bubble. Thereafter, it increases until the spacing is large enough, so that the bubbles do not merge prior to departure. For a given spacing, bubble diameter at departure increases from inline to right-angled to equilateral triangle orientation. The bubble growth period, t_g, normalized with characteristic time, $t_o = \sqrt{\sigma / g^3(\rho_l - \rho_v)}$ is shown in Fig. 7(b). The growth period is found to vary nonlinearly with spacing in a manner similar to that for bubble diameter at departure.

Figure 8 shows the variation of Nusselt number, $Nu_w = q_w l_o / k_l \Delta T_w$, with the non-dimensional cavity spacing for a gravity level of $10^{-2}g_e$. The heat flux is averaged over the heater surface supporting the computational domain and over the bubble growth period. The Nusselt number decreases initially slightly as the cavity spacing is increased, but subsequently increases with increase in spacing. The increase is due to the increased vapor production rate D^3_d/t_g. Similar results are obtained for a gravity level of $10^{-5}g_e$. Partitioning of wall heat flux into the vapor phase dominates both gravity levels. The energy loss to super heat the liquid is much smaller.

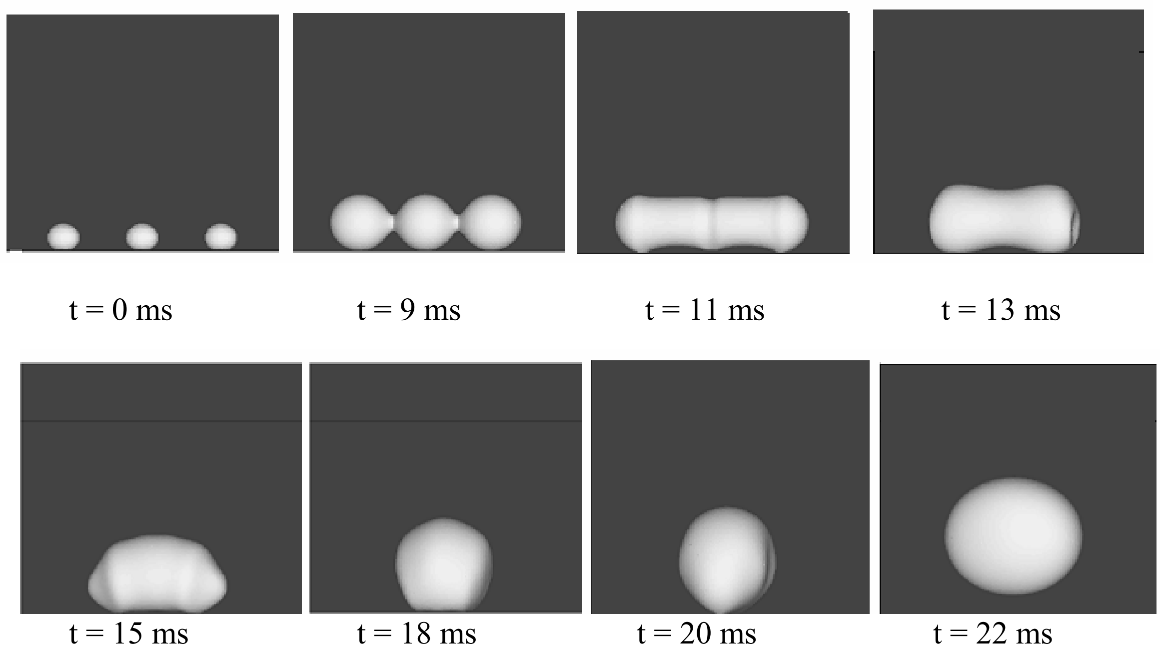


Fig. 6. Growth, merger and departure of three inline bubbles with cavity spacing = 1.14 mm, $g = 10^{-2}g_e$ and $\Delta T_w = 10^oC$.

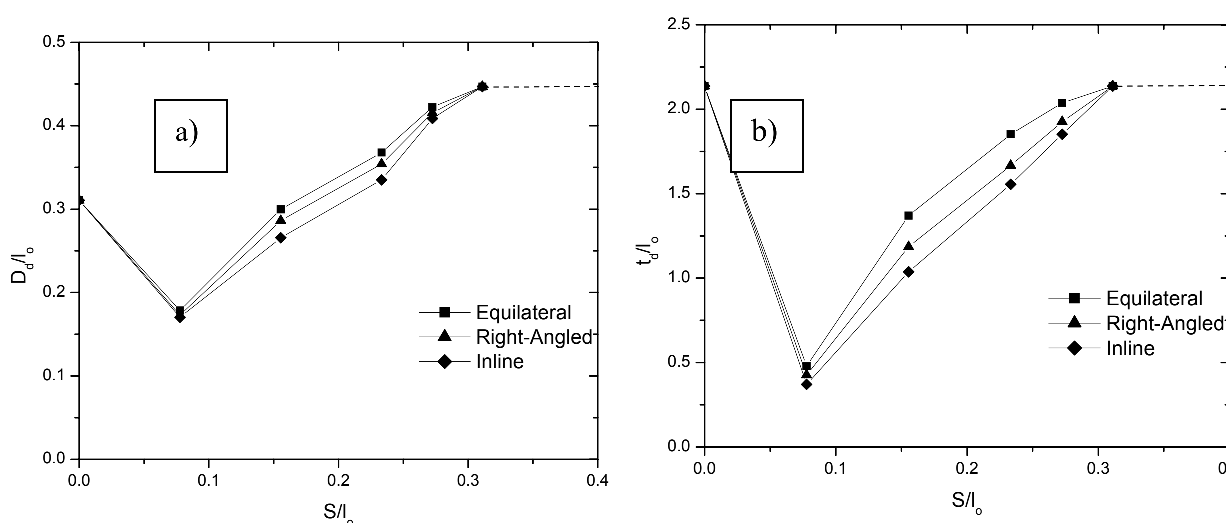


Fig. 7. Variation of non-dimensional a) bubble departure diameter and b) bubble departure time with non-dimensional cavity spacing for $g = 10^{-2}g_e$ and $\Delta T_w = 10\ ^oC$

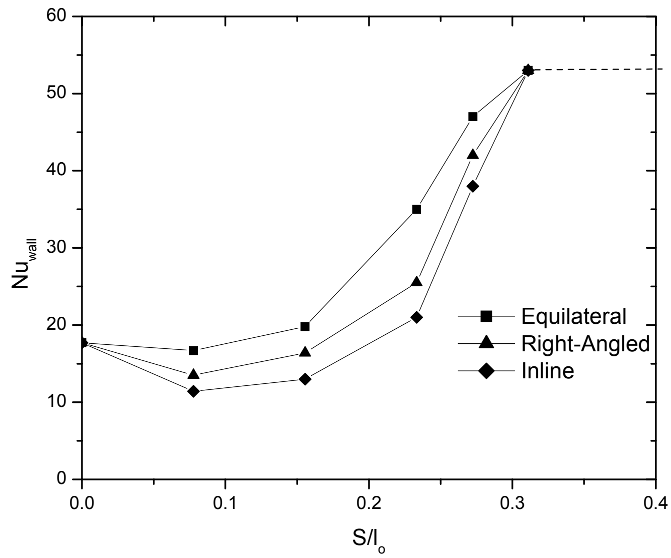


Fig. 8. Variation of time averaged Nu_w with non-dimensional cavity spacing for $g = 10^{-2}g_e$ and $\Delta T_w = 10\ ^oC$

2.2.3. NUCLEATE BOILING HEAT TRANSFER

The numerical simulations were carried out to predict nucleate boiling heat fluxes as a function of wall superheat on a surface simulating a commercial surface. On this polished silicon wafer surface 4 cm x 4 cm in cross-sectional area, cylindrical cavities of 10, 7, and 4 µm in diameter were fabricated as shown in Fig. 9. Different size cavities were chosen, so that smaller cavities will become active with increase in wall superheat as is the case for a commercial surface. Computational domains were defined around clusters of cavities, which are marked in Fig. 9. While carrying out the computations, no interactions are allowed between neighboring domains. Heat flux in the regions between the domains is obtained by interpolating between its values that exist at the boundaries of the domains.

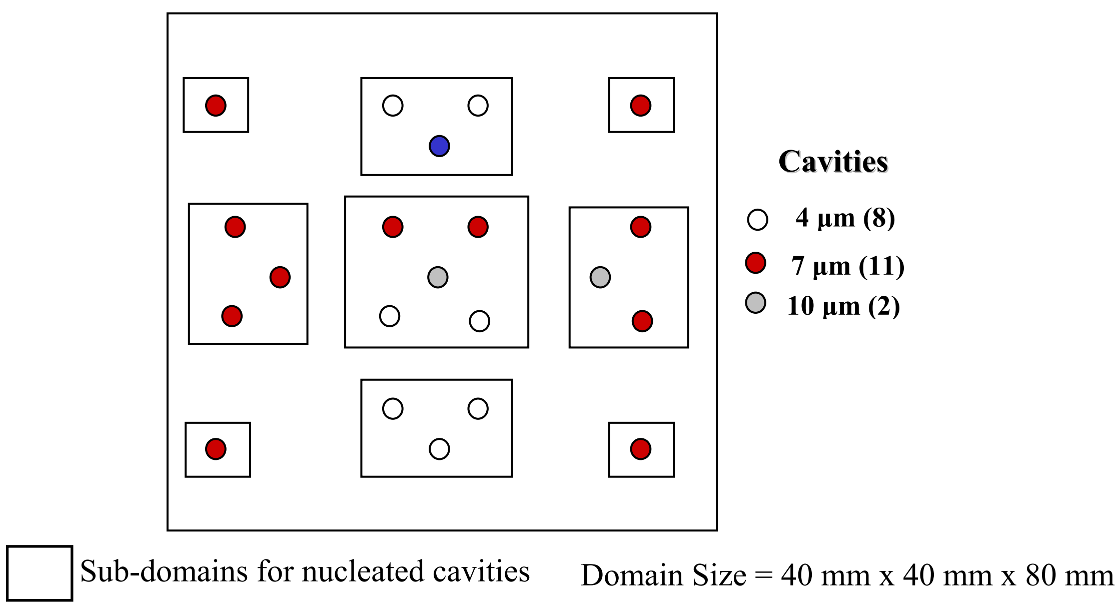
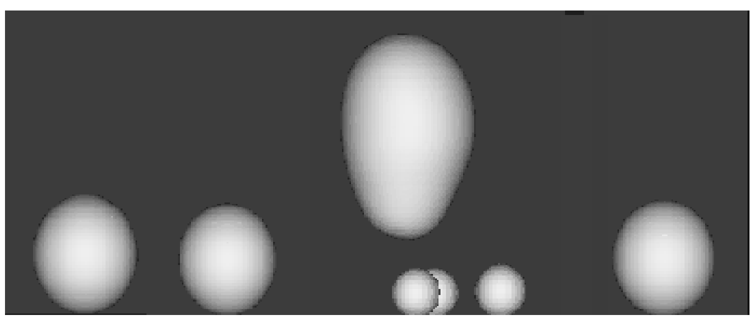


Fig. 9. Simulated commercial surface for $g = 10^{-2}g_e$ and $\Delta T_w = 7^oC$

The top portion of Fig. 10 shows the visual observation of the boiling phenomena on the surface described above when the gravity level was $1/100^{th}$ of earth normal gravity. The lower portion shows the results of computations when 7 cavities are assumed to be active. Observed and predicted vapor removal configurations are in qualitative agreement. A quantitative comparison is made in Fig. 11. The upper solid line is the prediction from numerical simulation of heat flux as a function of wall superheat from numerical simulation when the number of cavities that are active and their location are given as input. Predictions compare well with the data. In comparison to earth normal gravity, the heat flux at the highest superheat is about 30% lower. Large scatter in the data is seen due to uncertainty in calculation of heat loss. The lower curve represents partitioning of wall energy into vapor. It is found that at 12 ºC, superheat about 80% of energy goes into vapor production, whereas only 20% goes into superheating of liquid.

Predication of heat flux at much higher superheats when many more cavities are active and its validation from experiments is still pending.

(a) Experiments of Qiu et al. (2000)



(b) Numerical simulation

Fig. 10. Comparison of experimental and predicted bubble shapes during nucleate boiling on a simulated commercial surface for $g = 10^{-2} g_e$, $\Delta T_w = 7^oC$

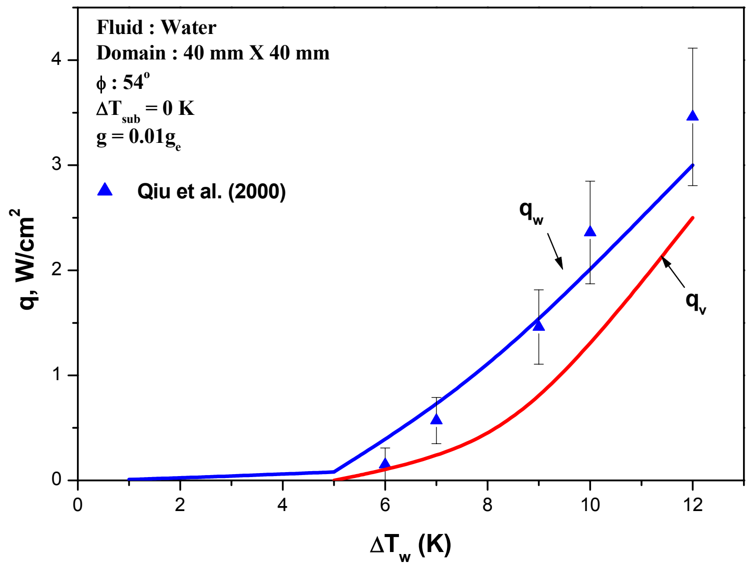


Fig. 11. Variation of average wall heat flux with wall superheat for $g = 10^{-2}g_e$

CONCLUSIONS

1. Results of experimental observations of pool boiling under low gravity environment obtained by different investigators are not always in agreement.
2. A building block approach relying on complete numerical simulations of the phenomena is proposed to provide mechanistic basis for prediction of nucleate boiling heat fluxes under reduced gravity conditions.
3. Numerical simulation results for bubble dynamics including, bubble growth, merger, and departure are in good agreement with those found in the low gravity experiments in the KC-135 aircraft.
4. Predictions of dependence of nucleate boiling heat fluxes on wall superheat are found to be in good agreement with low gravity data obtained on microfabricated surfaces.

References

1. Abarajith H.S., Dhir V.K., and Son G. Numerical Simulation of the Dynamics of Multiple Bubble Merger during Pool Boiling under Reduced Gravity Conditions, Proceedings of Japan- USA Seminar on Multiphase Flows, Japan, 2004.
2. Abe Y., Oka T., Mori Y.H. and Nagashima A. Pool boiling on a non-azeotropic binary mixture under microgravity // Intl. J. Heat Mass Transfer. 1994. Vol. 37(16). Pp. 2405-2413.
3. Cochran T.H., Aydelott J.C. and Frysinger T.C. The effect of subcooling and gravity level on boiling in the discrete bubble region, NASA TN D-34491966.
4. Dhir V.K. Boiling under microgravity conditions, Proc. 12th Int. Heat Transfer Conf., Grenoble, France, 2002.
5. Ervin J.S., Merte H., Kellers R.B. and Kirk K. Transient pool boiling in microgravity // Intl. J. Heat Mass Transfer. 1992. Vol. 35. Pp. 649-674.
6. Ervin J.S. and Merte H. Boiling nucleation and propagation in microgravity, ASME HTD 1993. Vol. 269. Pp. 131-138.
7. Lee H.S. and Merte H. The origin of the dynamic growth of vapor bubbles related to vapor explosion // J. Heat Transfer. 1998. Vol. 120. Pp. 174-182.
8. Merte H. Pool and flow boiling in variable and microgravity // Proc. 2nd Fluid Phys. Conf., paper no. 33. 1994.
9. Merte H., Lee H.S. and Keller R.B. Report on pool boiling experiments on STS-47, STS-57 and STS-60, Report. No. UM-MEAM-95-01. 1995.
10. Merte H., Lee H.S. and Keller R.B. Dryout and rewetting in the pool boiling experiments flown on STS-72 (PBE-11B) and STS-77 (PBE-11A), Report no. UM-MEAM-98-091. 1998.

11. Oka T., Abe Y., Mori Y.H. and Nagashima A. Pool boiling of n-Pentane, CFC-113, and water under reduced gravity // J. Heat Transfer. 1995. Vol. 117. Pp. 498-507.
12. Ohta H. Boiling experiments under microgravity conditions by using transparent heaters //Proc. United Engr. Conf. on Microgravity Fluid Phys. and Heat Transfer. 1999. Pp. 151-159.
13. Qiu D.M., Dhir V.K., Hasan M.M. and Chao D. Single and multiple bubble dynamics during nucleate boiling under low gravity conditions, Proc. 34th Natl. Heat Transfer Conf., NHTC 2000-12207. Pp. 1-15. 2000.
14. Siegel R. and Usiskin C. A photographic study of boiling in the absence of gravity // Trans. ASME J. Heat Transfer, 1959. Pp. 230-236.
15. Siegel R. Effects of reduced gravity on heat transfer // Advances in Heat Transfer. 1967. Vol. 4. Pp. 143-228.
16. Son G. and Dhir V.K. Numerical simulation of a single bubble during partial nucleate boiling on a horizontal surface // Proc. 11th Intl. Heat Transfer Conf. 1998. Vol. 2. Pp. 533-538.
17. Straub J. The role of surface tension for two phase heat and mass transfer in the absence of gravity, Experimental Thermal and Fluid Sci. 1994. Vol. 9. Pp. 253-273.
18. Straub J. Boiling heat transfer and bubble dynamics in microgravity // Advances in Heat Transfer, 2001. Vol. 35. Pp. 57-172.
19. Straub J., Zell M. and Vogel B. Pool boiling in reduced gravity field // Proc. 9th Intl. Heat Transfer Conf., 1990. Pp. 129-155.
20. Straub J. Microscale boiling heat transfer 0 g and 1 g conditions // Intl. J. Therm. Sci. 2000. Vol. 39. Pp. 490-497.
21. Straub J. and Micko S. Boiling on a wire under microgravity conditions – first results from a space experiment performed in May 1996 // Proc. Eurotherm Seminar No. 48. Pp. 275-282.
22. Straub J., Picker G., Steinbichler M., Winter J., and Zell M. Heat transfer and various modes of bubble dynamics on a small hemispherical heater under microgravity and 1 g condition // Proc. Eurotherm Seminar 1996. No. 48.
23. Zell M. Untersuchung des Siedvorgangs unter reduzierter schwerkraft, dissertation, TU München. 1991.