A Study of Nucleate Boiling with Forced Convection in Microgravity

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Introduction

Boiling is a rather imprecise term applied to the process of evaporation in which the rate of liquid-vapor phase change is large. In seeking to determine the role and significance of body forces on the process, of which buoyancy or gravity is just one agent, it becomes necessary to define the term more precisely. It is generally characterized by the formation and growth of individual vapor bubbles arising from heat transfer to the liquid, either at a solid/liquid or liquid/liquid interface, or volumetrically. The terms "bubble" boiling and "nucleate" boiling are frequently used, in recognition of the interactions of surface tension and other forces in producing discrete bubbles at distinctive locations (although not always).

Primary considerations are that evaporation can occur only at existing liquid-vapor interfaces, so that attention must be given to the formation of an interface (the nucleation process), and that the latent heat for this evaporation can come only from the superheated liquid, so that attention must also be given to the temperature distributions in the liquid.

The elements that constitute the nucleate boiling process - nucleation, growth, motion, and collapse of the vapor bubbles (if the bulk liquid is subcooled) - are common to both pool and flow boiling. It is well known that the imposition of bulk liquid motion affects the vapor bubble behavior relative to pool boiling, but does not appear to significantly influence the heat transfer. Indeed, it has been recommended in the past that empirical correlations or experimental data of pool boiling be used for design purposes with forced convection nucleate boiling [1, 2]. It is anticipated that such will most certainly not be the case for boiling in microgravity, based on preliminary observations to be described below. In earth gravity buoyancy will act to remove the vapor bubbles from the vicinity of the heater surface regardless of how much the imposed bulk velocity is reduced, depending, of course, on the geometry of the system. The major so-called forces governing the motion of the bubbles are buoyancy, liquid momentum and viscosity. With sufficiently high flow Reynold's Numbers, it can be intuited that the latter two forces will outweigh the first, and the process will be the same whether at earth gravity or microgravity. However, as the Reynold's Number is reduced the magnitude of the liquid momentum and viscous forces are correspondingly reduced, and in microgravity buoyancy cannot take over as a "back-up" mechanism for vapor removal, leaving only the reduced levels of liquid momentum and viscous forces. Vapor bubbles have been observed to dramatically increase in size in the limit of pool boiling in microgravity [3], but will be bounded in size by the action of the liquid momentum and viscous forces of forced convection in microgravity.

Certain other effects that can be neglected at normal earth gravity, such as surface tension, both at the solid-liquid-vapor contact line and at the liquid-vapor surface associated with the interface temperature variation, will be of consequence at microgravity conditions. The net quantitative effect of these on the vapor bubble behavior is unknown, at present, as are the related effects on the heat transfer, and provides one of the motivations for the study of the flow boiling process in microgravity. As a case in point, the departure size of vapor bubbles at low velocities in microgravity will be an important parameter in the design of vaporizing heat exchangers for space applications, since its size relative to that of the flow passage has a significant influence on the mechanisms and magnitudes of the local heat flux.

The ultimate objective of the basic studies of flow boiling in microgravity is to improve the understanding of the processes involved in boiling, as manifested by the ability to predict its behavior. This is not yet the case for boiling heat transfer even in earth gravity, despite the considerable research activity over the past 30 years. Hahne et al [4], for example, compared 7 different correlations with their own R12 forced convection boiling data, for both up and down flow, with quite disparate results. With changes in the dimensional and time scales of boiling arising due to microgravity, more detailed observations of its elements will be possible, and perhaps disclose or clarify certain phenomena. For example, a source of the dynamic vapor bubble growth observed with pool boiling in microgravity [3] has been disclosed [5]. Figure 1, from [5], shows computed spherical vapor bubble dynamics beginning from the initial critical size nucleus, along with the time interval during which the bubble growth is predicted to become unstable. This instability conforms to observations, in which a "roughened" liquid vapor interface is formed. The accompanying increase in the liquid-vapor interfacial area produces a significant increase in the bubble growth rates, as reported in [6], leading to so-called vapor explosions.

Effects of Velocity

In the absence of buoyancy, a bulk liquid being heated at a solid surface can undergo dramatic changes in temperature distributions due to externally imposed velocities. This in turn influences both the nucleation characteristics and the subsequent vapor bubble growth. The latter effect is illustrated in the computed spherical vapor bubble growths in Figure 1, from [7, 8]. The heavy curves apply to the case where the bulk liquid is taken to be uniform at the measured heater surface temperature at nucleation, while the light curves show the results where the actual one-dimensional temperature distribution in the liquid, as heated from the plane surface, is taken to be the initial one dimensional radial distribution about the critical size vapor bubble. It is noted that differences between the two only become manifest during the later stages of growth, which conforms to comparisons with measurement.

One of the unique advantages of transient heating of liquids in microgravity, utilized in the pool boiling studies to date and anticipated to be equally applicable in future "low velocity" flow boiling studies, is the ability to predict with reasonable certainty the temperature distributions in the liquid. This permitted a quantitative description of what is defined as homogeneous nucleation, even though taking place in the immediate vicinity of the heater surface. Figure 2, from [3, 9] show the analytic predictions of homogeneous nucleation in the presence of transient temperature gradients, based on classical homogeneous nucleation theory, as a function of the imposed heat flux and the system pressure, which was varied as a means of conveniently changing the initial bulk liquid subcooling. Measurements from several sets of space experiments are superimposed, and confirm that decreasing the imposed heat flux results in a reduction in the heater surface superheat at nucleation. The measurements from the space experiments at the highest level of heat flux, to the right in Figure 2, are considered to be heterogeneous nucleations, since they all were initiated at precisely the same location on the heater surface, whereas those at the lower levels of heat flux occurred at various apparently random locations.

A tentative conclusion at this time is that it appears that nucleation conforming to the predictions of homogeneous nucleation here also result in the unstable or explosive type of vapor bubble growths characterized by roughened interfaces, described above. Although anticipated, it remains to be demonstrated that corresponding behaviors will take place in the presence of imposed liquid velocities. The nucleation process appears to be governed by local conditions, not in the sense of state functions, and hence should be influenced by the prior history.

Measurements with long term pool boiling in microgravity [3] have demonstrated that the heat transfer is enhanced considerably over that in earth gravity at the lower levels of heat flux, but that the heat flux at which dryout takes place is substantially reduced. This comparison is made in Figure 3, from [10]. The behavior in microgravity in what might normally be termed the film boiling domain is the consequence of a combination of dryout and bubble boiling taking place simultaneously over the heater surface, with the measurements of heat flux and surface temperature representing the spacially integrated mean values. The enhancement in the nucleate boiling domain in Figure 3 is attributed to the steady existence of a "macrolayer" between the heater surface and a large vapor bubble which remains suspended in the vicinity of the heater. This layer serves as a boundary across which evaporation takes place, as well as a mechanism for the efficient removal of vapor bubbles from the heater surface, due to vapor pressure differences arising from surface tension.

It is expected that any bulk liquid motion imposed parallel to the heater surface in microgravity would further enhance the heat transfer process by what has been termed sliding bubbles, in a manner similar to that produced by buoyancy in earth gravity [11] and by forced flow in short term reduced gravity [12]. These result in the continuous renewal of the thin liquid layers beneath the bubbles. The departure size of the vapor bubble is an important constituent in the microlayer evaporation process taking place in such circumstances, and the drag forces in forced convection boiling provide a vehicle for this departure in microgravity. A description of the relation between the buoyancy dominant and inertial dominant regimes for bubble departure has been provided in terms of a "two-phase Richardson number" [13].

Experimental Results to Date

A schematic of a low velocity forced convection boiling loop for proposed studies in microgravity is shown in Fig. 4. Velocities can be varied from 0.5 cm/s to 60 cm/s by pump speed control combined with changes in test section height, from 2.54 cm (1 inch) to 0.318 cm (0.125 inch). The use of a flow loop permits the study of boiling under steady conditions as well as under transients, and thus can accommodate the use of metallic surfaces which, while representative of engineering surfaces, also introduce complications with transients, associated with heat capacity effects. The flow loop proper occupies a volume of about 1.22 x .61 x .46 m (48 x 24 x 18 inches). The flat heater surface used is rectangular in shape, 1.91 cm by 3.81 cm (0.75 x 1.5 inches), consisting of a 400 Angstrom thick semi-tranparent gold film sputtered either on a quartz substrate which serves simultaneously as a heater and a resistance thermometer, or a copper substrate of the same size. The heater substrate is a disc which can be rotated so that the heated length in the flow direction can be changed from 1.91 to 3.81 cm (0.75 to 1.5 inches). Variable buoyancy normal to the heater surface is achieved by rotation of the entire loop relative to earth gravity. Of course, this is at the expense of varying the buoyance parallel to the heater surface. The 0° reference for orientation is taken with the flat heater surface horizontal facing upward, while the angle increases such that 90° implies a vertical heater surface with the fluid flow direction upward.

The enhancement of the boiling process taking place with low velocities for those orientations, producing the "sliding" vapor bubbles described above, has been demonstrated and presented previously [14, 15]. A further confirmation of this effect is seen in Figure 5, from [16], in which the heated length in the flow direction was changed from 1.91 cm (0.75 inches) to 3.81 cm (1.50 inches). The orientation angle is $\theta = 180°$, with the heater horizontal facing downward, so that buoyancy holds the vapor bubbles against the surface as they slide along with the higher velocity of 32.4 cm/sec here. Both polished quartz and copper heater surfaces of identical sizes were used, with similar enhancements as noted.

It was noted in Figure 3 that heater surface dryout takes place at a considerably lower heat flux with pool boiling in microgravity, as compared to earth gravity. With the imposition of fluid flow it can be anticipated that this dryout (CHF-Critical Heat Flux) will increase, depending, of course, on the velocity. The onset of the dryout depends on the ability of the liquid to make contact with the heater surface which depends, in turn, on the circumstances under which the vapor departs from the vicinity of the heater surface. Results of the influence of both heater surface orientation and velocity were reported previously [14, 17], for the flow loop in Figure 4. Recent work, in which void fraction measurements were made in the vicinity of the heater surface with the various orientations which tend to keep the vapor near the heater, indicate that a distinct relationship exists between the CHF and the vapor bubble residence time at the heater. The residence times were measured with hot wire anemometry, with the comparisons shown in Figure 6, from [18]. The residence time is related to the mechanisms producing departure of the vapor from the heater surface, as well as the geometry of the heater, including the heated length along the flow direction. It is anticipated that the description of the residence time will provide the analytical basis for predicting the flow boiling heat transfer in microgravity.

References

1. Bergles, A. E., and Rohsenow, W. M., "The Determination of Forced-Convection Surface Boiling Heat Transfer," J. Heat Transfer, 86, 1964, 365-382.
2. Bartolini, R. et al, "Experimental Study on Nucleate Boiling of Water in Vertical Upflow and Downflow," *Int. J. Multiphase Flow*, 9, 1983, 161-165.
3. Merte, H., Jr., Lee, H. S., and Keller, R. B., "Report on Pool Boiling Experiment Flown on STS-47 (PBE-IA), STS-57 (PBE-IB), and STS-60 (PBE-IC). NASA CR 198465 prepared for Lewis Research Center under Contract NAS3-25812. March, 1996.
4. Hahne, E., et al, "Fully Developed Nucleate Boiling in Upflow and Downflow," *Int. J. Heat Mass Transfer*, 32, 1989, 1799-1808.
5. Lee, H. S., and Merte, H., Jr., "The Origin of the Dynamic Growth of Vapor Bubbles Associated with Vapor Explosions," submitted for presentation at session on "Heat Transfer in Microgravity Systems," to be held at the ASME-IMECE in Atlanta, GA on Nov. 17-22, 1996.
6. Ervin, J. S., Merte, H., Jr., Keller, R. B., and Kirk, K., "Transient Pool Boiling in Microgravity," *Int. J. Heat Mass Trans.*, 35, March, 1992, pp. 659-674.
7. Lee, H. S., and Merte, H., Jr., "Spherical Vapor Bubble Growth in Uniformly Superheated Liquids," accepted for publication in *Int. J. Heat Mass Transfer*, 1996.
8. Lee, H. S., and Merte, H., Jr., "Hemispherical Vapor Bubble Growth in Microgravity: Experiments and Model," accepted for publication in *Int. J. Heat Mass Transfer*, 1996.
9. Merte, H., Jr., and Lee, H. S., "Homogeneous Nucleation in Microgravity at Low Heat Flux: Experiments and Theory," ASME Paper 95-WA/HT-41 presented at Session "Heat Transfer in Microgravity Systems at the ASME-IMECE in San Francisco, CA on Nov. 12-17, 1995.

10. Lee, H. S., Merte, H., Jr., and Chiaramonte, F., "The Pool Boiling Curve in Microgravity," AIAA Paper 96-0499 presented at 10th Annual Symposium on Microgravity Science and Space Processing, AIAA 34th Aerospace Science Meeting, Jan. 15-18, 1996, Reno, NV.
11. Cornwell, K., "The Role of Sliding Bubbles in Boiling on Tube Bundles," Heat Transfer 1990 - Vol. 3, *Proc. 9th Int. Heat Transfer Conf.*, Jerusalem, Israel, Aug. 19-24, 1990, 455-460.
12. Cooper, M., et al, "Behavior of Vapour Bubbles Growing at a Wall with Forced Flow," *Int. J. Heat Mass Transfer*, 26, 1983, 1489-1507.
13. Kirk, K. M., and Merte, H., Jr., "A Mixed Natural/Forced Convection Nucleate Boiling Heat Transfer Criteria," Heat Transfer 1994, Vol. 7, pp. 479-484. *Proceedings of the 10th International Heat Transfer Conference*, Brighton, England, August 14-18, 1994.
14. Merte, H., Jr., "Pool and Flow Boiling in Variable and Microgravity," *2nd Microgravity Fluid Physics Conference*, June 21-23, 1994, NASA-Lewis, Cleveland, OH.
15. Kirk, K. M., Merte, H., Jr., and Keller, R. B., "Low Velocity Subcooled Nucleate Flow Boiling at Various Orientations," *ASME J. of Heat Trans.*, Vol. 117, 2, pp. 380-386, May, 1995.
16. Nestel, S. U., and Merte, H., Jr., "The Effects of Heater Surface Length in Forced Convection Nucleate Boiling," Report No. UM-MEAM-95-07, University of Michigan, Department of Mechanical Engineering and Applied Mechanics conducted under NASA Grant NAG3-1310, July 1995.
17. Brusstar, M. J., and Merte, H., Jr., "The Effects of Buoyancy on the Critical Heat Flux in Forced Convection," *AIAA J. of Thermo-physics and Heat Transfer*, 8, April - June 1994, pp. 322-328.
18. Brusstar, M. J., and Merte, H., Jr., Keller, R. B., "The Role of Buoyancy Orientation on Bubble Residence Times and the Related Critical Heat Flux," 1995 *National Heat Transfer Conference, Proc. of Symposium "Heat Transfer in Microgravity Systems,"* ASME HTD-Vol. 305, pp. 15-27. Portland, Oregon, August 5-9, 1995.

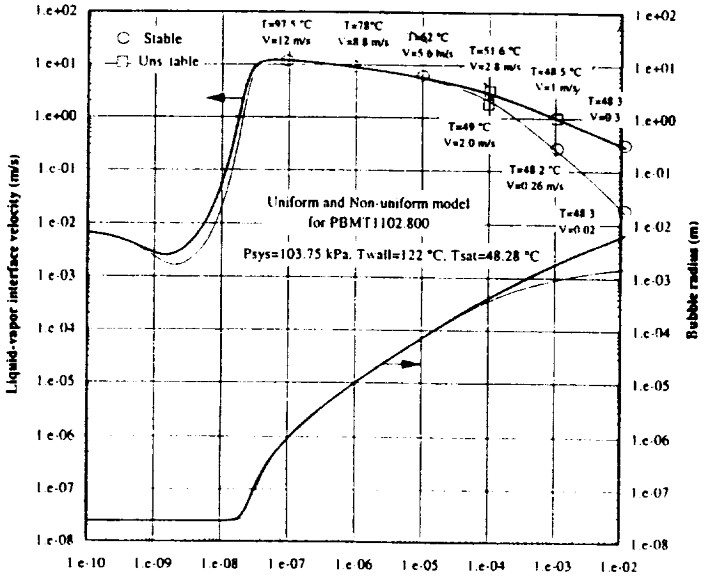

Figure 1. Prediction of onset of unstable vapor bubble growths in microgravity [5].

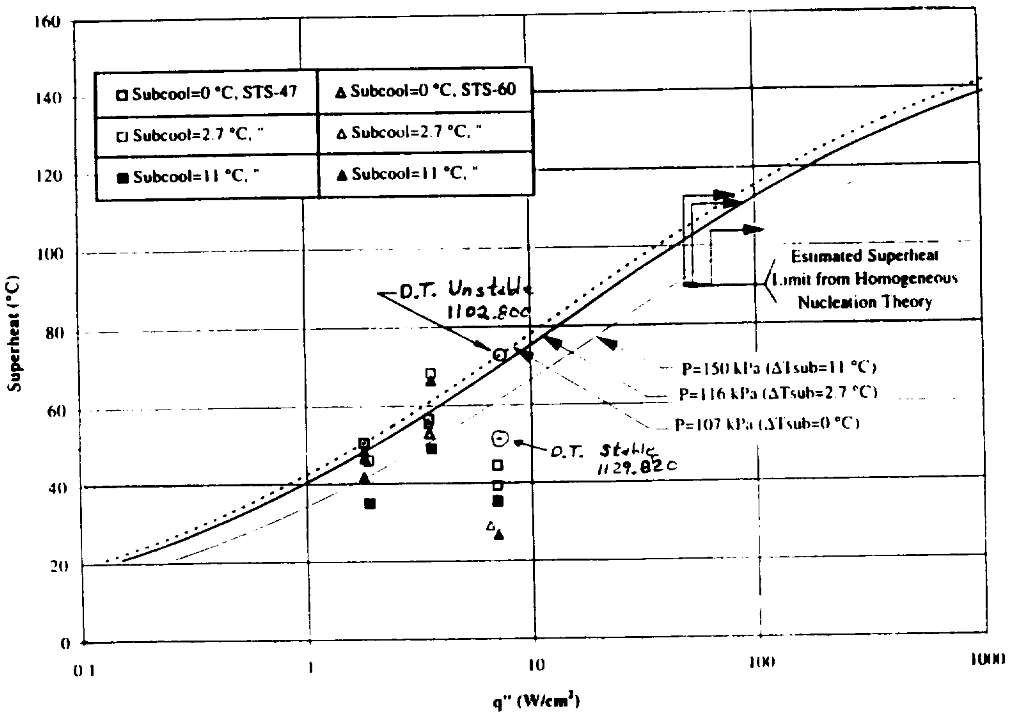

Figure 2. Homogeneous nucleationmodel for R-113 with transient heating in microgravity. Measurements with PBE-IA - IC (STS-47-60) $K^* = 2.57 \times 10^6$ evaluated for PBE-IA: Run No. 9.

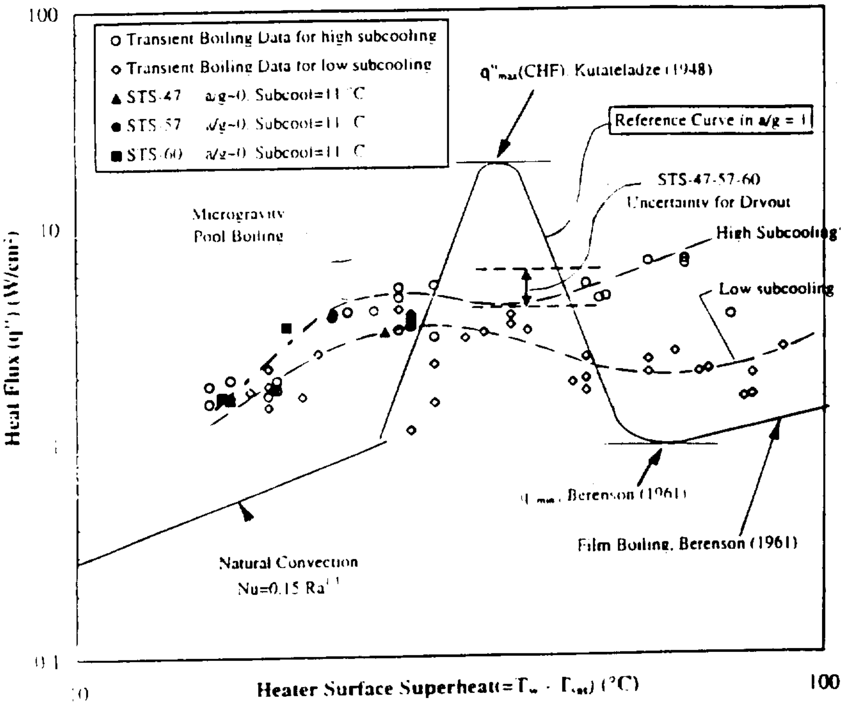

Figure 3. Composite microgravity pool boiling curves for R-113 from PBE-GAS space experiments compared with Reference Curve for a/g = 1. From [10].

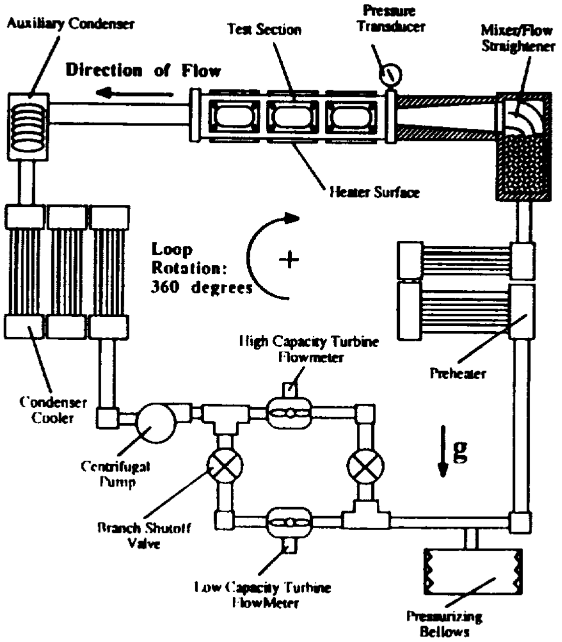

Figure 4. Schematic of flow loop for study of boiling in microgravity.

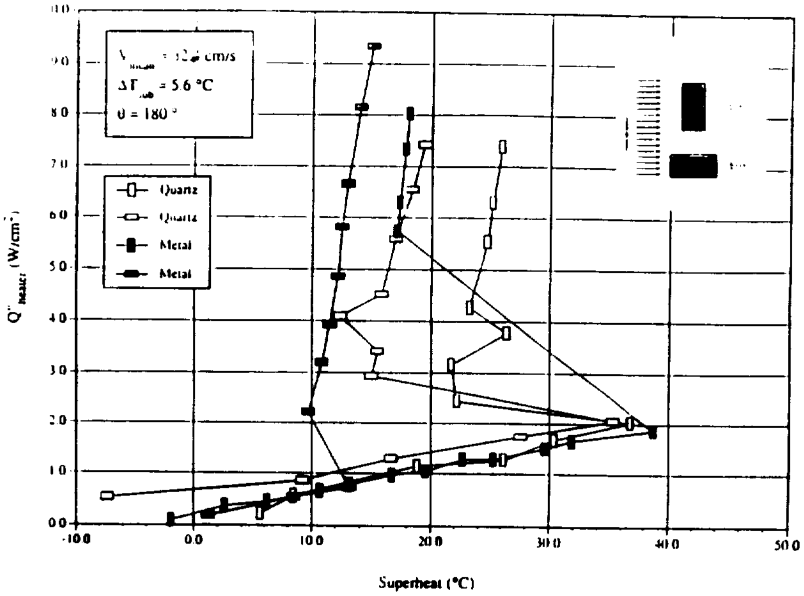

Figure 5. Steady forced convection nucleate boiling on flat heater surfaces. Horizontal down. R-113. $\Delta T_{sub} = 5.6°C$.

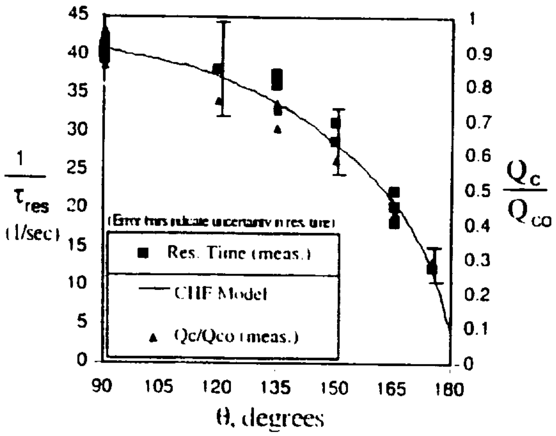

Figure 6. Comparison of Flow Boiling Measurements of Vapor Bubble Residence Time and Critical Heat Flux with Model Predictions at Various Orientation Angles. From [18].