PHASE CHANGE HEAT TRANSFER – A PERSPECTIVE FOR THE FUTURE

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

ABSTRACT

During the last half of the twentieth century, significant advances have been made in developing an understanding of phase change heat transfer (e.g., boiling and condensation). Further advances in phase change heat transfer will continue to take place motivated by new technologies such as micro-electronics, thermal management in space, advanced terrestrial and space power systems and processing of designed materials. In the past, because of the complexity of the processes, very often we have "oversimplified", maybe out of necessity, the modeling of the processes. The resulting weaknesses in our models and correlations have continued to haunt us whenever we have encountered new applications. In order to address the phenomena from basic principles, in my opinion, we need to pay attention to processes occurring at nano to micro to macro scales, capitalizing on recent advances that have been made in experimental and numerical techniques. These phenomena include nucleation, evolution, merger and breakup of vapor-liquid interfaces, contact line behavior; coupling of the bulk and surface features of the solid; and the role of nano and micro inhomogeneties and intermolecular forces between solid and liquid. Prediction of nucleate boiling transfer is taken as an example to demonstrate the value of coupling different scales in meeting the overall objective.

INTRODUCTION

Phase change heat transfer is a broad field that finds applications in almost all of the engineering disciplines. Boiling and condensation are two of the most important phase change processes as they are generally associated with high heat transfer rates. Boiling and condensation (drop wise) are very complex processes as well, and have been investigated extensively over the last half of the twentieth century. Professor Warren Rohsenow, in whose honor this paper is written, was a pioneer in this area of heat transfer. Past studies have lead to an increased understanding of the processes as well as to the development of correlations and semi-theoretical models at the global and subprocess level. These correlations and semi-theoretical models have served us well in their intended application. However, the simplifications we have made in developing correlations or models for the process have haunted us whenever new applications are encountered. Although further advances in phase change heat transfer will continue to occur in the future driven by new technological needs in micro-electronics, thermal management, power systems and material processing, in my view, future research trends in two-phase flow heat transfer will be in developing and solving conservation equations similar to those used for single-phase flows. In obtaining these solutions we must tie the underlying physics from nano to micro to macro scale. A significant effort will be required in relating results from different scales. Of course, advances in new instrumentation techniques [1] such as x-rays, liquid crystal thermography, high-speed infrared thermometry, nuclear magnetic resonance (NMR), neutron tomography, and laser induced fluorescence will play an important role in validating the physical models at various scales. In discussing the future research direction and needs, an example of nucleate boiling is considered. Nucleate boiling involves most of the basic elements of interest in generic two-phase heat transfer problems.

FUTURE RESEARCH DIRECTION

In nucleate boiling, vapor bubbles form on discretely located sites on heater surface. The formation and departure of vapor bubbles leads to enhancement in heat transfer. The interacting physical processes that lead to the enhancement in heat transfer beyond the single phase value are the evaporation at microlayer underneath the bubble, evaporation around the bubble, heat transfer due to bubble created flow field, and convective motion resulting from buoyancy. The contributions of these processes to the total heat transfer rate depend on number density, and bubble merger and breakup processes, including bubble size at departure. Each of these processes involving physics at nano, micro and meso and level and are ill understood and require a concerted effort to achieve the objective defined earlier.

Nucleation and Nucleation Site Density

It is generally accepted that defects (cavities) that trap gas/vapor are the potential nucleation sites on a heated surface. Many parameters affect the volume of gas trapped in a cavity including the magnitude of surface tension, contact angle, the shape of the cavity and the experimental conditions such as system pressure, liquid temperature, temperature of the heated surface, and dissolved gas content. The size of the gas trapping cavity and the temperature distribution in the thermal layer adjacent to the heater surface are believed to influence the superheat at which a given cavity becomes active. In the past, models for gas trapping ability of cavities of various shapes and the superheat at which they nucleate have been developed and some validation of these models with experiments on artificially and naturally formed cavities have been provided. However, the physics of the process of entrapment of gas/vapor in micro cavities of different sizes and shapes during advancing and receding interfaces is still not understood; especially as it relates to the role played by surface wettability. Recently, even the requirement of existence of cavities on the surface for the formation of vapor bubbles has been questioned. Evidence of formation of vapor bubble on a nanometer smooth surface with hydrophobic molecular clusters has been provided. Thus, it appears that we need to address the issue of nucleation at the molecular level. The other ill understood issues that need to be addressed are the effect of dissolved gases in the liquid, the scavenging with time of trapped gases in the cavity, activation or deactivation of nucleation sites because of temperature fluctuations in the solid resulting from advancing and receding liquid-vapor interfaces over the cavities. Coupling of the solid, especially when the conductivity and thickness of the solid are not high, needs to be an essential part of any modeling effort.

Nucleation site density is an extremely important variable that not only influences the rate of heat transfer from the heater surface, but also the structures of the phases near the heated wall and the partitioning of energy from the wall into liquid and vapor phases. Figure 1 shows the dependence of thermal resistance in boiling on the density of active nucleation sites. The upper line is for pool boiling on a vertical plate, whereas the lower two curves are for flow boiling. Boiling heat transfer resistance is seen to strongly decrease with increase in nucleate site density. The flow velocity tends to weaken the functional dependence of the boiling resistance on nucleation site density. The effect of contact angle is small, if any. This is a surprising result considering the fact that number density of active sites depends strongly, aside from wall superheat, on contact angle. Mikic and Rosenhow [2] related the site density of active sites to the diameter of the largest cavity present on the heater. Wang and Dhir [3] developed a mechanistic approach for the prediction of active nucleation site density, excluding well-wetted surfaces, as a function of wall superheat and contact angle. Very recently, Basu *et al* [4], have developed a generalized correlation based on a large variety of data available in literature. However, we are far away from predicting the active site density theoretically. Because surface topography at nano and microlevels will be a prerequisite to any theoretical model, it is uncertain if it will be possible to provide such information for a large commercial surface? If not, what else can be done? Or, should we eliminate such a difficult task by developing designed surfaces having cavities of prescribed size and shape? This will not only allow us to predict a priori the number density of active sites, but also the wall heat flux at a given wall superheat.

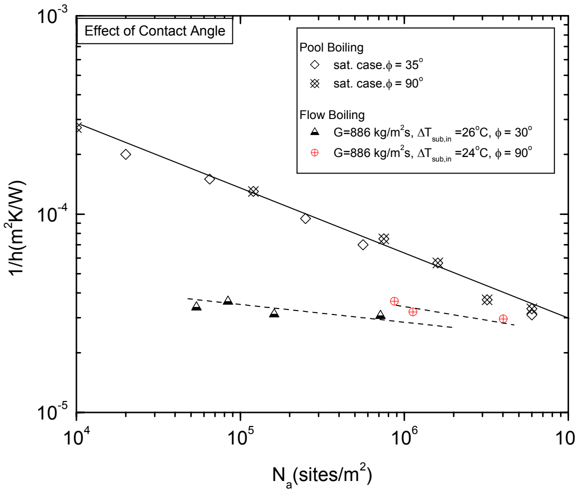

Figure 1: Dependence of boiling resistance on nucleation site density.

Behavior of Contact Lines

As a vapor bubble evolves on a nucleation site, an ultra thin microlayer forms underneath the bubble. The inner edge of the microlayer is marked by the non evaporating liquid molecules absorbed on the surface, whereas at the outer edge the microlayer can be several microns thick. The interline or contact line represents the location of triple interface involving liquid, vapor and solid (with absorbed liquid molecules). Although a number of experimental and analytical studies have been reported in the literature [5] on the behavior of the contact line region, we still have little understanding of the dynamics of the contact line when the interface is advancing or receding underneath a bubble. We know little about the effect of the movement of the interface on advancing and receding underneath a bubble contact angles; the appropriate definition of contact angle (macro vs. micro), the effect of physical non uniformities on the solid surface on the pinning of the interface; and the influence of wettability gradients on the solid surface has on the movement of the interline; and finally on conditions leading to instability of the interface. Maybe it will be more appropriate, at least theoretically, to discard the definition of contact angle and simply obtain the interface shape by modeling inter-molecular forces between solid and liquid.

A good understanding of the behavior of the contact line is not only needed for the bubble dynamics including bubble break-off from the surface and associated heat transfer considerations, but also for the development of our understanding of dryout and rewetting of surfaces, post critical heat flux, and heat transfer post minimum film boiling temperature. Behavior of thin liquid films can also be influenced by the dynamics of the interline region.

Evolution, Merger and Breakup of Vapor-Liquid Interfaces

Vapor-liquid interface evolution, merger, and breakup are important processes that not only determine the phasic structure near the heater surface, but also the rate of heat transfer and partitioning of wall energy between vapor and liquid phases. The phasic structures can also influence the conditions leading to critical heat flux. Merger and breakup processes are affected by inter-molecular forces. These forces take on added importance when additives such as surfactants are present in the liquid.

The growth of a vapor bubble on a nucleation site has been extensively studied in the past both experimentally and analytically. One of the early and successful models is that of Mikic, Rohsenow, and Griffith [6]. In this semi-theoretical model, existence of a microlayer underneath an evolving vapor bubble was not considered and energy for evaporation was assumed to be supplied by transient diffusion from a thermal layer that wrapped around the bubble. Waiting time, shape of the bubble, temperature profile in the thermal layer around the bubble, and neglect of inertia were the other main assumptions. Subsequent studies have included microlayer contribution and have attempted to solve for bubble growth in a time dependent temperature field around the bubble, but by assuming that the bubble shape is invariant in time. As will be discussed later, it is only recently that direct numerical simulations of the bubble evolution process including the shape of the bubble have been performed by solving the conservation equations.

A large number of efforts have been made in the literature to quantify the forces that act on a vapor bubble during its evolution in pool and flow boiling, and to determine the condition at which a bubble lifts off from the surface. The forces are associated with the inertia of liquid and vapor, the liquid drag on the bubble, buoyancy, and surface tension. There is a significant difference in opinions of various investigators with respect to the importance of the various forces, although several of them have been able to match their predictions with the data via use of empirical constants. It is generally accepted that surface tension tends to hold the bubble to the surface, however, Cooper *et al* [7] and more recently Buyevich and Webber [8] have argued that surface tension assists bubble departure by making the bubble spherical. Even almost seventy years after Fritz's [9] correlation, we do not have a comprehensive model for bubble diameter at departure in terms of the independent variables such as fluid properties, flow velocity, wall superheat liquid subcooling, and contact angle. The quantification of the role played by the contact angle (advancing or receding), especially when the surfaces are nearly well wetted, has continued to remain elusive. Another shortcoming of the past efforts is that bubble growth and the evaluation of forces have been treated as disjoint processes.

Recent studies have involved complete numerical simulation of the process, including microlayer, and have eliminated this deficiency. These studies have addressed the bubble merger and breakup processes as well. In simulating the evolution of a vapor bubble at a nucleation site, Son *et al* [10] divided the computational domain into micro and macro regions. The micro-region contained the thin liquid film (microlayer) that forms underneath the bubble. Lubrication theory was employed in analyzing the microlayer. The macro-region consisted of the evolving vapor bubble and the liquid surrounding the bubble. Flow was considered to be laminar, and the fluid properties including density, viscosity, and thermal conductivity were evaluated at the mean temperature in each phase. For numerically analyzing the macro region, finite difference scheme was used and the level set method was employed to capture the interface. Level set method has the key advantage that merger and breakup of bubble interfaces can be easily captured. Other methods such as Volume of Fluid (VOF), Lattice Boltzmann, and Direct Front Tracking have been used in the literature for capturing the interface and the thermal and hydrodynamic processes associated with an evolving interface. As an example, Juric and Tryggvason [11] have used the front tracking method to carry out two-dimensional simulation of the rise and growth of vapor bubbles in a superheated liquid and to simulate the evolution of the vapor-liquid interface during saturated film boiling. In Son *et al's* model, the film thickness at the outer edge of the microlayer and its spatial derivative were matched with those obtained from the macro-solution. The slope of the interface was related to the tangent of the apparent contact angle. Hamakar constant was related to the apparent contact angle by using an iterative procedure. However, no distinction was made between an advancing and receding contact angle. This can be a serious deficiency especially in flow boiling when upstream and downstream contacts can be drastically different. As discussed earlier, the interline behavior can not only affect the heat transfer, but also the bubble dynamics including the size of the vapor bubble at departure from the surface. However, good agreement between experiments and numerical predictions was found for bubble growth history, shape of the evolving interface, and bubble diameter at departure and the growth period. The simulations were used to carryout numerical experiments to study the effect of such variables as apparent contact angle and wall superheat. In a subsequent work, the numerical experiments were extended to investigate the effect of the magnitude of gravity and liquid subcooling. The numerical simulations, for the first time, provided a quantitative evaluation of partitioning of energy between vapor and liquid phases.

The numerical simulations [12] have also been employed to study bubble merger normal to and along the heater surface as would occur in fully developed nucleate boiling (high wall superheats). Vapor bubble merger in the vertical direction occurs when the growth rate of a bubble formed at the nucleation site exceeds the rate at which the lower interface of the preceding bubble moves away from the heater surface. After merger, the combined vapor mass may detach from the heater surface before the process repeats itself. Figures 2a and 2b show the results of visual observations and numerical simulations for one cycle of the merger of three consecutive bubbles in vertical direction. The individual frames in each figure are from left to right and from top to bottom. After merger of the departed bubble with the succeeding bubble, the larger vapor mass causes the vapor bubble at the nucleation site to prematurely depart. Thereafter, the second succeeding bubble merges with the vapor mass hovering over the surface. The combined vapor mass goes through several shape changes and departs as a cylindrical bubble. The departing bubble creates a wall jet which impinges on the lower interface of the bubble and forms a dimple. Thereafter, the vapor mass tries to acquire a spherical shape as it moves away from the wall. The rapid movement of the vapor mass breaks down the merger process before the cycle repeats itself. The bubble shapes as well as the merger behavior predicted from the numerical simulations are in startling agreement with the visual observations.

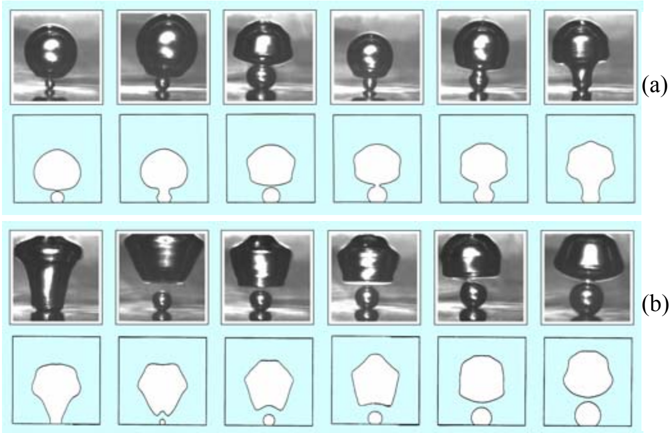

Figure 2. Bubble merger normal to the heater.

Lateral bubble merger, as would occur when nucleation sites are closely spaced, has been analyzed by Mukherjee and Dhir [13]. Figure 3 compares experimentally observed shapes during merger of two bubbles at neighboring sites with those computed from the numerical simulations. Formation of mushroom type of bubble with two stems attached to the solid is clearly evident. The numerical simulations generally capture the observed interfacial behavior with the exception that the region of trapped liquid is generally smaller and disappears rapidly in comparison to the experiments. Interestingly, the numerical simulations capture correctly the formation of vapor ligaments at about 16.8 ms. Large changes in interface shape as a result of surface tension are observed as the vapor mass tries to acquire a spherical shape before departure. Aside from providing the interface shape, the numerical simulations can provide us with time dependent heat heat flux at different locations on the wall. This type of simulations when extended to three or five bubbles in a plane can provide insights to the dryout mechanism when a solid is thermally coupled to the thermal- and hydrodynamic processes taking place in the liquid. Such an approach can also be very valuable when species conservation equations are included in studying the mixture boiling and subcooled boiling with dissolved gases and, in turn, in delineating the flow created by capillary gradients.

Conjugate Problems

Often in experiments or applications, heat flux is controlled, because of the temporal and spatial variations in heat transfer associated with outward and inward movement of the interline during bubble growth and departure phases, respectively. This existence of microlayer underneath an evolving vapor bubble was an area of controversy in the 1960s.

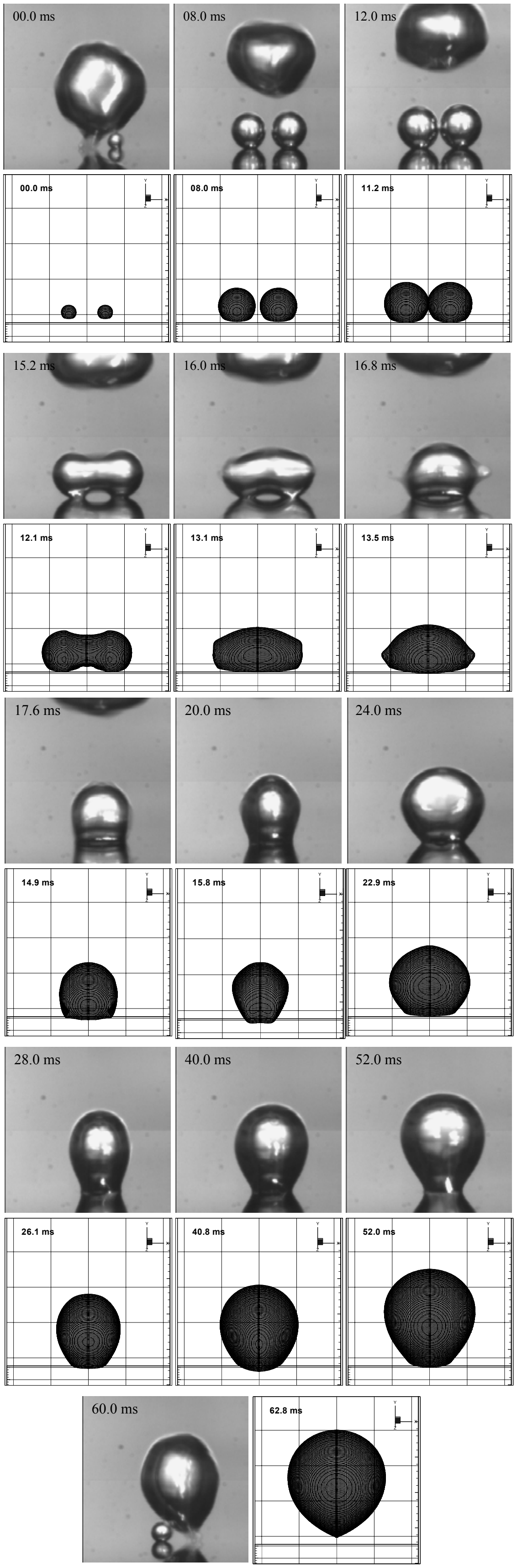

Figure 3: Comparison of experimental observed and numerically predicted bubble shapes.

Figure 4 shows the normalized variation of wall temperature with time at different radial positions from the cavity center predicted from the numerical simulations, when the wall heat flux is fixed. The largest temperature variation occurs at the location nearest to the cavity. In Fig. 4 the data obtained by Moore and Mesler [14] using a microthermocouple are also plotted. The predictions from numerical simulations that include the existence of microlayer underneath the bubble are in good agreement with data. The coupling of the temperature response of the solid with the fluid side heat transfer becomes important when local and spatial variations associated with phase change heat transfer phenomena becomes large. This coupling also inferences the waiting time between consecutive bubble ebullition cycles.

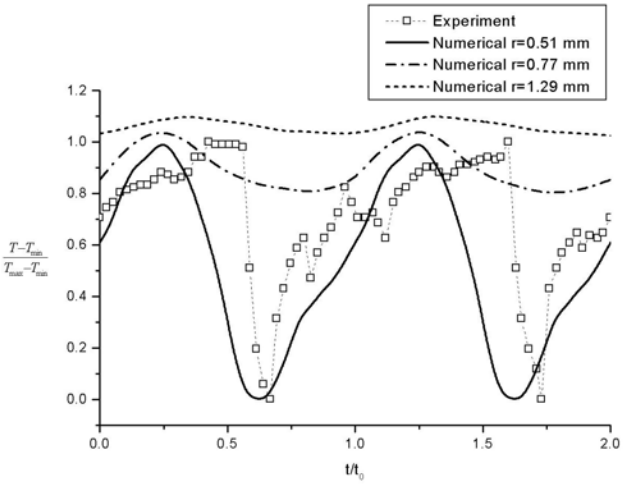

Figure 4: Effect of presence of microlayer on wall temperature.

Prediction of Nucleate Boiling Heat Transfer

Numerical simulations can readily be used to predict not only nucleate boiling heat flux, but also the partitioning of wall heat flux into vapor and liquid phases. Although very successful correlations starting with Rohsenow [15] have been developed, these correlations are rarely validated at the subprocess level and can hardly provide the partitioning of wall heat flux. Partitioning of wall heat flux takes on added importance in flow boiling when one is interested in the void fraction in the bulk which strongly depends on the source term at the wall. Table 1 compares the nucleate boiling heat flux predictions from the numerical simulations with the data obtained on a 40mm x 40mm silicon surface maintained at 6.6K wall superheat. Saturated water at 1 atm. was used as the test liquid. Static contact angle of water with silicon was taken to be 50˚. For these small number of cavities over a large area (partial nucleate boiling), natural convection is the dominant mode of heat transfer. As would be expected, evaporative contribution increases with the increase in the number of nucleation sites. The predicted heat flux is within about 25% of the data. The above exercise represents only a small step in the direction of complete numerical simulation of the process. With further advances in numerical algorithm development and the rate at which computational speed is increasing, it should be possible in the near future to predict the nucleate boiling heat flux, when a very large number of cavities are present on the heater surface and bubble mergers occur both laterally and normal to the surface.

TABLE 1

	Numerical				**Exp.**
No. of Cavities	Q_{nc} (W)	Q_{ev} (W)	Q_{total} (W)	q_{num} (W/cm^2)	q_{exp} (W/cm^2)
3	9.84	0.76	10.14	0.63	0.58
5	9.84	1.26	10.34	0.65	0.87

domain Size = 40 mm × 40 mm, wall superheat = 6.6 K

CONCLUDING REMARKS

1. New technologies including micro-electronics, thermal management and power in space, advanced terrestrial power systems, and processing of designed materials will continue to drive advances in phase change heat transfer.
2. In the past out of necessity, we have oversimplified complex phase change problems. The resulting weaknesses in our models and correlations have continued to haunt us whenever we have encountered new applications.
3. Significant gains are possible in the future if we pay attention to processes occurring at micro and nano levels and by connecting the phenomena of interest from nano to micro to macro scales.
4. Advances in numerical simulations supported by similar advances in instrumentation techniques will play an important role in the future.
5. It is anticipated that, not in the too distant future, we will be able to solve phase change heat transfer problems by solving basic conservation equations in a manner similar to single phase flows.

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