Journal of Advances in Science and Technology
Vol. 13, Issue No. 1, (Special Issue) March-2017, ISSN 2230-9659

Review on Numerical Simulations of Heat Transfer of Single Bubble in Nucleate Pool Boiling

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Abstract – Nucleate boiling phenomenon is subdivided into three parts: a small ring-shaped zone between heating wall and bubble, called as micro-region, the bubble itself, and liquid surrounding the bubble, which is referred to as macro-region. As micro-region is most important area for heat transfer therefore recently developed models put special emphasis on this region, and predicted heat transfer, bubble growth, and departure diameters of vapor bubbles for low to moderate heat fluxes as well. Due to development of numerical methods and computer technology, they provides a powerful tool to predict vapor bubble behavior.so, the literature was reviewed for different numerical simulation methods, which were very effective for more understanding of bubble behavior in pool boiling.

Keywords— Heat Transfer, Nucleate Boiling, Single Bubble, Numerical Simulation, Micro-Scale

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INTRODUCTION

Nucleate boiling heat transfer is utilized in many applications where large amount of heat has to be transferred in comparatively very small areas such as in nuclear reactors or rocket engines. In addition, it is an efficient mode of heat transfer with a wide variety of applications including refrigerators, steam boilers, electronic cooling, etc. However, fully theoretical description and numerical investigation of nucleate boiling were still face big challenges, which are due to the difficulties of inclusion of many aspects of nucleate boiling. The single vapor bubble growing at a horizontal heating wall which considered by all researchers is shown in figure 1 and figure 2.This single bubble is subdivided into three parts namely a small, ring-shaped zone between heating wall and bubble, called micro-region, the bubble itself, and its surrounding liquid, referred as macro-region. The small spatial scales and the rapidity of the phase change process both of which make it very difficult to obtain the necessary experimental measurements hinder a more basic understanding. Analytical and numerical efforts to understand boiling have mainly focused on simple models of vapor bubble dynamics.

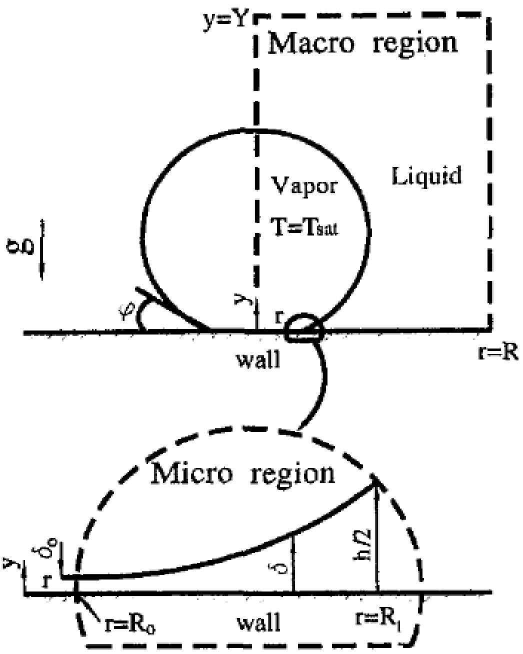


Fig.1- Macro and microregions in numerical simulation [3]

The multiphase flows are very complicated problems as it involves thermodynamics (co-existing phase), kinetics (nucleation, phase transitions) and hydrodynamics (inertial effects). For vapor bubble, the vapor–liquid interface becomes extraordinary complicated because of its nonlinearity and time-dependence behavior induced by phase-change with heat and mass transfer. Therefore, tracking of the interface is a key problem in the simulation of bubbly flows.

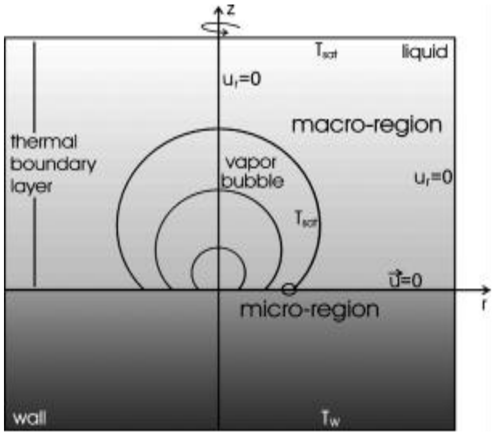


Fig.2- Vapour bubble, surrounding liquid and adjacent wall with boundary conditions [8]

LITERATURE REVIEWED

Lee and Nydahl [1] conducted numerical study of a bubble growth by considering a micro-layer model. However, they did not investigate the departing bubble phenomenon on the wall. The first attempt to simulate boiling using a CFD technique was done by Welch [2]. He investigated two-dimensional boiling flow, and the moving grid technique was implemented in the study, where a deformation of bubble using a semi-implicit moving mesh during nucleate boiling was studied. However, due to limited capabilities of restructured grids, which can't handle a topological change, the full boiling process including a bubble departure was not investigated. For the purpose of capture large deformation of the liquid-vapor interface, interface-tracking methods were introduced to phase-change investigations.

Son et al. [3] introduced a level set (LS) method, while a Front Tracking method (FT) by Juric and Tryggvason [4], and a Volume of Fluid (VOF) method by Welch and Wilson [5]. The work presented by Stephan and Hammer [6] was, one of the first numerical investigations of heat transfer in the so-called 'micro-layer'. By the numerical analysis, the liquid film thickness and heat flux distribution near to the contact line in micro-region had been obtained. The phase change model coupled with Level Set method has been continuously improved mainly due to the extraordinary efforts of Dhir's group [7]. Son et al.[3] have performed an entire numerical study of a growing and departing bubble in nucleate boiling using the level set method which was modified to include the Phase change and micro-layer evaporation. But, the drawback of the phase-change model coupled with LS method is that the mass conservation did not guaranteed, because LS is a non-conservative approach. Genske and Stephan [8] gave their time to improve the existing model. The figure 2 shows the geometry of modelled bubble with boundary conditions. They modelled the fluid flow around and within the bubble is now modeled and its influence on bubble growth and heat transfer in more detail by using moving mesh model. Mukherjee and kandlikar [9] presented the numerical calculations performed to study the effect of the dynamic contact angle at the bubble base as compared to a static contact angle. Figure 3 shows a nucleating bubble at the wall during nucleate pool boiling. Sato and Niceno [10] developed a mass-conservative interface tracking method based on LS method in which the mass transfer rate was directly calculated from the heat flux at the liquid-vapor interface.

Lattice Boltzmann method (LBM) which was based on a kinetic Boltzmann equation has been proposed since the 1980s. Yang et al. [11], Hazi and Markus [12], and Dong et al. [13] have conducted the study of nucleate boiling by lattice Boltzmann method. Hazi and Markus [12] developed a lattice Boltzmann model and investigated boiling phenomenon on a horizontal surface in a stagnant fluid. However, the result shows independency of the bubble departure diameter on contact angle, which was contrary to the studies of Dong et al. [13]. Recently, Gong and Cheng [14] have studied the bubble growth on and departure from a superheated wall using an improved hybrid lattice Boltzmann method, which was based on the free energy two-phase model combined with the thermal hybrid model. Chen and Utaka [15] studied the contribution of micro-layer evaporation in nucleate pool boiling and numerical simulations were performed for two- phase vapor–liquid flow induced by the growth of a single bubble using the volume of fluid method. They were proposed a special model to combine the micro-layer and bulk liquid regions.

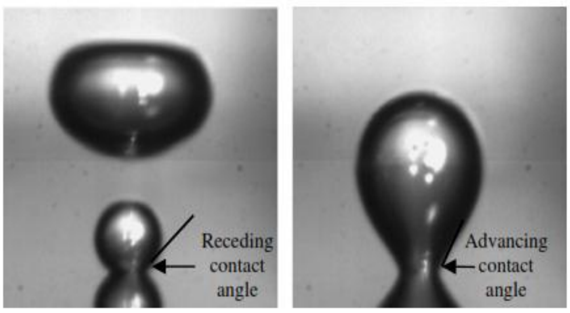


Fig.3-Dynamic contact angle at bubble base during nucleate pool boiling [9]

RESULTS AND DISCUSSION

The major purpose of the numerical simulations was to present a self-consistent formulation that would enable both a qualitative indication of the thermal and fluid fields during bubble growth and departure, and a quantitative comparison of the contributions of the micro-mechanisms to bubble growth and overall wall heat transfer.

For the conditions simulated [1], the micro-layer proved to be the dominant micro-mechanism. It provided 90 percent of the energy for bubble growth, and 87 percent of the overall enhanced heat transfer. The enhanced convective heat transfer effects during growth (micro-convection) proved to be essentially nonexistent, while the enhanced heat transfer following departure (a combination of enhanced convective effects and transient conduction) provided only 13 percent of the excess heat transfer. The method developed [2] addresses difficulties of discontinuity of the normal component of velocity and the pressure by tracking the phase interface and by moving the computational grid in such a way as to keep a high grid resolution near the interface.. From the numerical simulation [3], the location where the vapor-liquid interface contacts the wall is observed to move outwards and then inwards as the bubble grows and departs. The local wall heat flux is seen to vary cyclically during the bubble growth. The contribution of micro-layer to the total heat flux is found to be about 20 percent.   The departing bubble becomes larger with the increase in contact angle and wall superheat. A numerical method for direct numerical simulation of film boiling and an approach to computing boiling flows based on Young's enhancement of the VOF method has been presented in [4] & [5] resp.

The developed model [6] clearly demonstrates that the phenomena in the micro region had significant influence on the overall heat flow. The heat flux reaches a high maximum in the micro region, which is about 100 times larger than the burnout heat flux. A numerical procedure, coupling the level-set function with the moving mesh method [7], has been employed to simulate sub-cooled nucleate boiling under various gravity levels. The effect of sub-cooling on bubble size is more pronounced under microgravity than under earth-normal gravity, which is shown in figure-4.

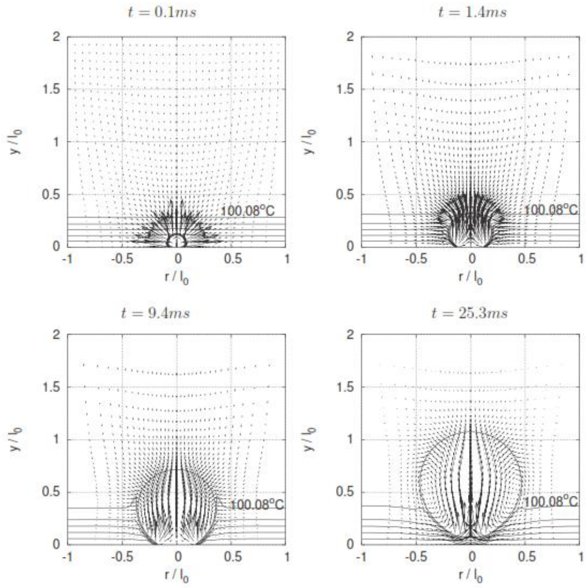


Fig.4-Temperature distribution and velocity field for wall superheat=8°C, liquid sub-cooling=0°C, contact angle=38deg, Pressure = 1.013*10^{5}Pa, and g/g_e=0.01 [7]

During bubble growth, velocities and temperature distribution in both vapor and liquid were determined [8].They showed that, a smaller area close to the bubble, in which forced convection flow has a strong influence on heat transfer, and an area farther away from the bubble in which heat conduction prevails as shown in figure 5 while bubble growth counters in figure 6 for R114 fluid. The size of this area depends on bubble site density.

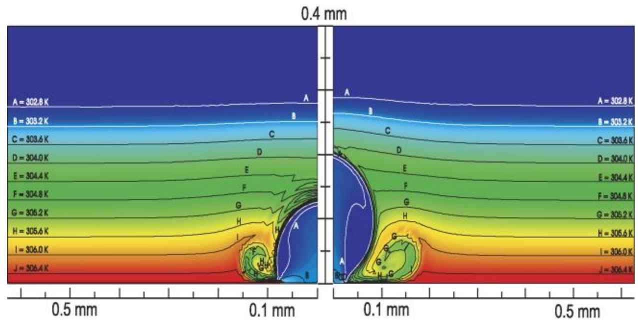


Fig.5- Temperature field around and inside a growing vapor bubble after 3 m-s (left) and 4 m-s (right). R114, p = 0.247 MPa, T = 4K, N_B= 81 cm^{-2} [8]

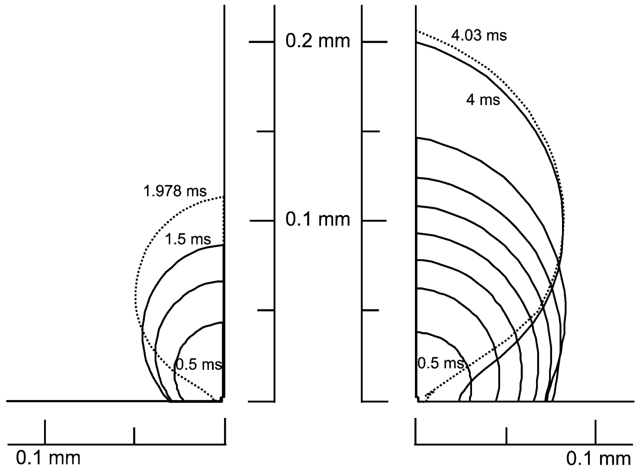
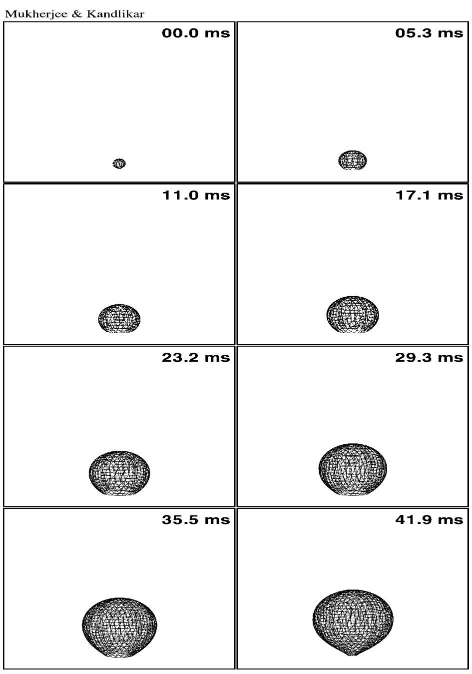


Fig.6- Bubble growth contours and departure diameter (dashed line) for two different apparent contact angles. Left: 55, right: 75. R114, p = 0.247 MPa, T = 4K [8]

Numerical simulation [9] carried out of single nucleating vapor bubble on a heated wall with different contact angle models at the bubble base, concluded that Dynamic contact angle model based on the sign of the contact line velocity causes the bubble base to exhibit a stick/slip pattern during bubble growth whereas the base exhibits a smooth behavior when the static contact angle model is used. In addition, the vapor volume growth rate is found to primarily increase with increase in the advancing contact angle as shown in figure 7.



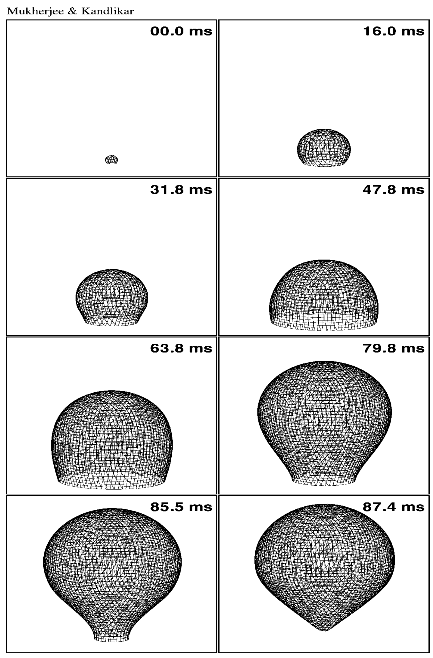


Fig.7-Bubble shapes (a) receding contact angle 20˚, advancing contact angle 54˚; (b) receding contact angle 54˚, advancing contact angle 90˚[9]

From sharp-interface phase change model, coupled with a mass-conservative, interface-tracking method employing the color function to determine the interface location [10], it is noted that the temperature distribution becomes severely distorted for the low Jakob number simulation using a coarse grid as shown in figure 8. The computed bubble shape remained spherical throughout the simulation as shown in figure 9.

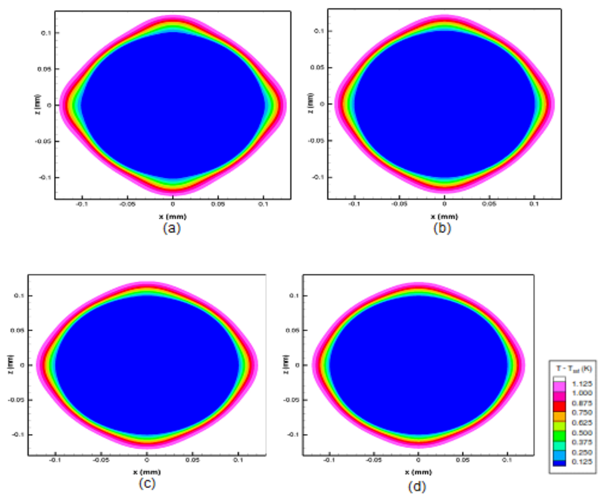


Fig.8-Distribution of temperature difference of the growing bubble for ΔT =1.25 K: (a) the coarsest grid Δx =1.95 lm; (b) Δx =1.30 lm; (c) Δx =0.98 lm; and (d) the finest grid Δx =0.65 lm [10]

The results of the LB simulation [11] clearly demonstrate that the bubble nucleation site density (related to the heater surface condition and heat fluxes), and the surface position have a profound effect on the flow regime (pool boiling) characteristics. The results of the LB simulation of hydrodynamics of two-phase flow on the horizontal surface provide the pictures quite similar to the experimental observation for saturated pool boiling. It was found that this approach provides realistic physical pictures of the single and multiple bubble growth, detachment and coalescence behavior under partial nucleate boiling condition as shown in figure 10.

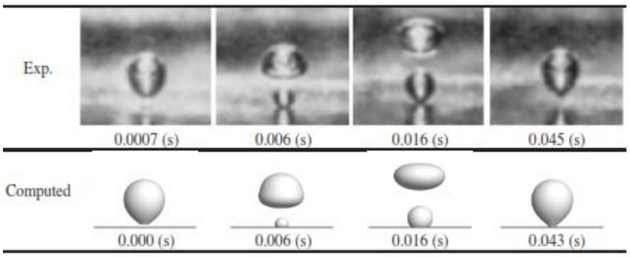


Fig.9-Comparison of bubble shape between experiment and computation [10]

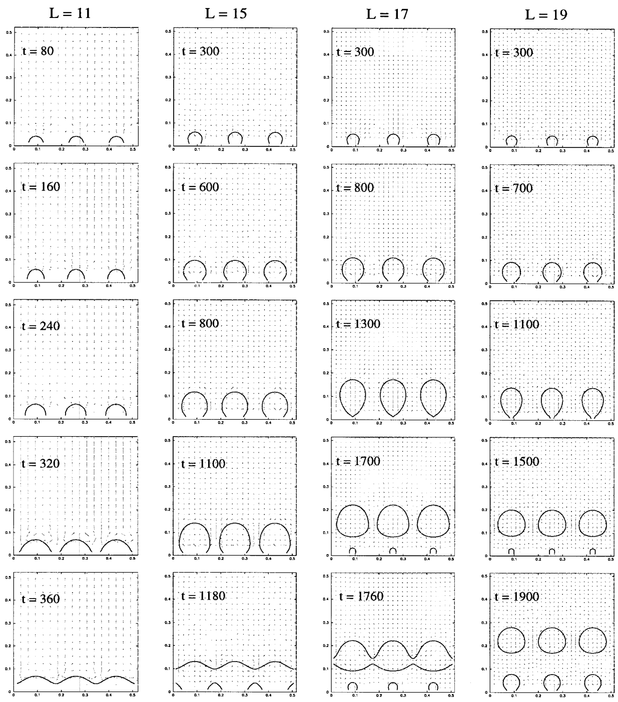


Fig.10-The lateral bubble coalescence behavior for different distances between neighboring bubble generation sites on the horizontal surface [11]

From the simulations [12] it can be concluded that, both the departure diameter and release period depend strongly on the width and weakly on the depth of the cavity. Increasing the width of the cavity both the departure diameter and the release period increases. In spite of the gradual increase of the distance between cavities, the departure diameter can increase in a discontinuous manner. Increasing the distance between cavities the release period decreases significantly reaching a minimum and then it starts increasing slightly. At low heat fluxes, the deformations occur even horizontally, while vertical deformation can be observed at high heat fluxes as shown in figure11. At low heat fluxes, neighboring nucleation sites can inhibit the nucleation of the other site. Neighboring nucleation sites can decrease their bubble growth rates mutually or even a nucleation site can deactivate nucleation in another site. This process is called deactivation and observed in experiments. At high heat fluxes, the deactivation does not take place.

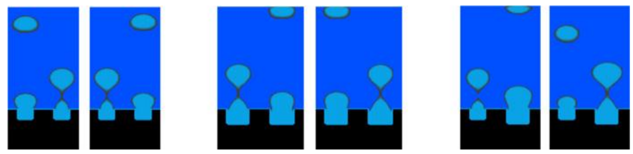


Fig.11-Interaction of bubbles at high heat flux using two cavities of the size 20× 20 (left); 30× 30 (middle) and finally the combination of a 20× 20 lattices and 30× 30 lattices size cavities (right). The spacing between cavities is 31 lattices [12]

The LBM multiphase model with a large ratio of density, combining with the LBM thermal model [13] is extended and developed into a hybrid model, which is able to predict the phase change process. The temperature fields in nucleate pool boiling are directly simulated by means of the present hybrid model so that the heat transfer is quantitatively analyzed as shown in figure 12.

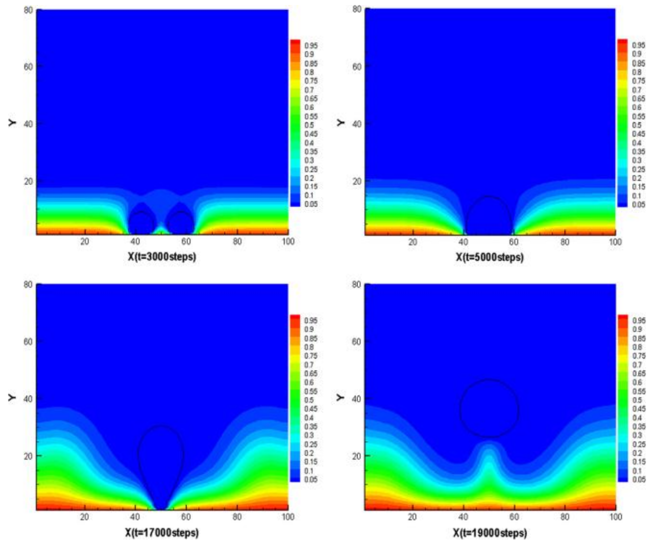


Fig.12-Propagation of temperature fields with time [13]

In a newly developed phase-change, lattice Boltzmann method [14], there is no need to specify a small vapor bubble at the beginning of computation like previous methods. From this simulation they can concluded that the vapor bubble departure diameter is proportional to $g^{-0.5}$ and the bubble release period is proportional to $g^{-0.75}$. With the increase of contact angle, bubble release period increases and heat flux decreases as shown in figure13. Also with the increase of superheat, bubble departure diameter increases and bubble release period decreases as shown in figure 14. It is concluded that the nucleation waiting time decreases with increasing heat flux at the same contact angle, and decreases with increasing contact angle for the same heat flux. The nucleation temperature increases with the increasing heat flux for the same contact angle, and decreases with increasing contact angle for the same heat flux. During the bubble growth period, the vapor bubble is at superheated condition with non-uniform temperature distribution, and the degree of the superheat decreases after the bubble departs from the micro-heater. Using this method, they calculated the specific latent heat for water over a wide temperature range. Table 1 shows that calculated results based on a method more agree with experimental results.

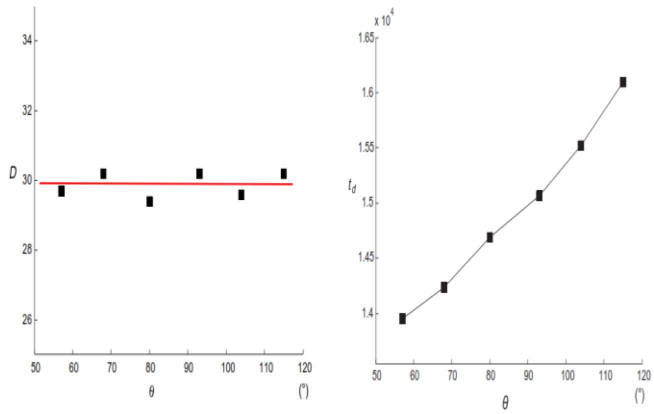
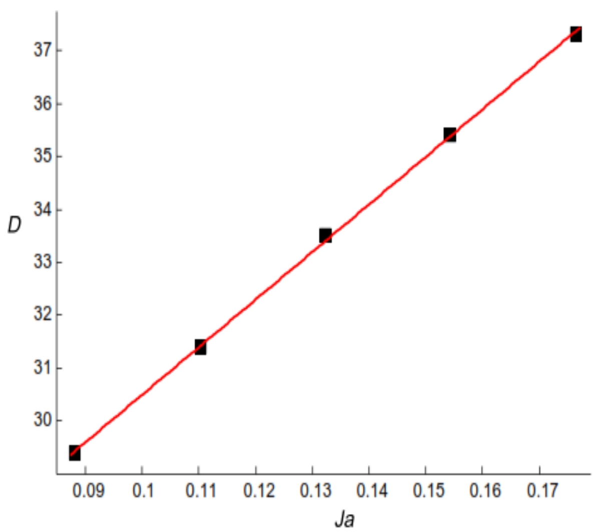


Fig.13-Effect of contact angle on bubble departure diameter and bubble release period at θ=93˚[14]



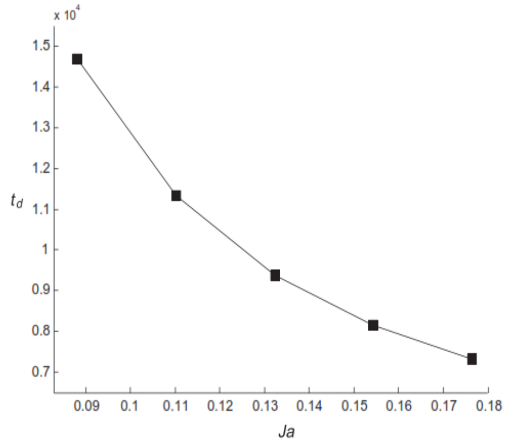


Fig.14-Effect of super heat on bubble departure diameter and bubble release period at θ=93˚[14]

Table 1-Comparison of the calculated latent heat of water by hybrid method with experimental results [14]

T/°C	80	100	120	140	160	180	200
Ref. [32]/kJ/kg	2307.7	2256.3	2201.4	2142.8	2080.0	2012.2	1937.3
Eq. (A-6)/kJ/kg	2392.9	2337.4	2279.8	2219.0	2154.1	2083.9	2006.9
Error (%)	3.7	3.6	3.6	3.6	3.6	3.6	3.6
T/°C	220	240	260	280	300	320	340
Ref. [32]/(kJ/kg)	1854.7	1762.2	1653.9	1528.4	1386.2	1222.1	1014.3
Eq. (A-6)/(kJ/kg)	1921.3	1825.1	1715.4	1588.2	1437.7	1253.8	1016.6
Error (%)	3.6	3.6	3.7	3.9	3.7	2.6	0.23

Finally numerical simulations [15] conducted for the growth of a single bubble during nucleate pool boiling of water concluded that, the bubble growth was affected by the temperature distribution in the superheated liquid layer. There is a higher temperature gradient at the vapor–liquid interface, which is closer to the heat transfer surface. In addition the micro-layer becomes thinner and dry-out occurs initially at the center of the micro-layer, and then extends to the outer region with the development of evaporation. The heat flux for micro-layer evaporation increases with the micro-layer radius and has a maximum in the periphery of the micro-layer as shown in figure 15.

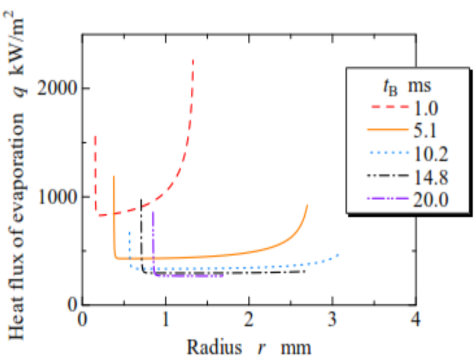


Fig.15-Distributions of heat flux for micro-layer evaporation as a function of radius for various bubble times [15]

Using this method, they calculated the specific latent heat for water over a wide temperature range. Table 1 shows that calculated results based on this method more agree with experimental results.

CONCLUSION

This paper is a review of some papers published on numerical simulation of heat transfer of single bubble in nucleate pool boiling from development of first model to recent developed models. Following conclusions are drawn after this review:

- The researchers had started investigations from earlier available models.
- Due to developments in mathematical treatments newer models were developed and newer researchers modifies existing one.
- By reviewing all these papers, we got idea regarding numerical investigation of heat transfer enhancement by breaking a single bubble by mechanistic approach.

REFERENCES

1) R.C. Lee, J.E. Nydahl, Numerical calculation of bubble growth in nucleate boiling from inception through departure, J. Heat. Transf. 111 (1989), 474-479.

2) S. Welch, Direct simulation of vapor bubble growth, Int. J. Heat. Mass Transf.41 (1998), 1655-1666.

3) G. Son, V.K. Dhir, N. Ramanujapu, Dynamics and heat transfer associated with a single bubble during nucleate boiling on a horizontal surface, J. Heat. Transf.121 (1999), 623-631.

4) D. Juric, G. Tryggvason, Computations of boiling flows, Int. Journal on Multiphase Flow. 24(1997), 387-410.

5) S.W.J. Welch, J. Wilson, A volume of fluid based method for fluid flows with phase change, J. Computer. Phys. 160, (2000), 662-682.

6) P. Stephan, J. Hammer, A new model for nucleate boiling heat transfer, J. Heat Mass Transf. 30 (1994), 119-125.

7) V.K.Dhir, Mechanistic prediction of nucleate boiling heat transfer achievable or a hopeless task? J. Heat. Transf. 128 (2006), 1-12.

8) P. Genske, K. Stephan, Numerical simulation of heat transfer during growth of single vapour bubble in nucleate boiling, Int. Jour. Of Sci. 45(2006), 299-309.

9) Mukharjee, S. G. Kandlikar, Numerical study of single bubble with dynamic contact angle during nucleate pool boiling, Int. Jou. Heat and Mass Transf. 50(2005), 127-138.

10) Y. Sato, B. Niceno, A sharp-interface phase change model for a mass-conservative interface tracking method Journal of Comput. Physics 249 (2013), 127–161.

11) Z.L.Yang, T.N. Dinh, R.R. Nourgaliev, B.R. Sehgal, Numerical investigation of boiling regime transition mechanism by a Lattice-Boltzmann model, Nucl. Eng.Des. 248 (2012), 263-269.

12) G. Hazi, A. Markus, Numerical simulation of detachment of bubble from a rough surface at micro-scale level, Int. J. Heat. Mass Transf. 52 (2008), 1472-1480.

13) Z. Dong, W. Li, Y. Song, A numerical investigation of bubble growth on and departure from a superheated wall by lattice Boltzmann method, Int. J. Heat. Mass Transf. 53 (2010), 4908-4916.

14) S. Gong, P. Cheng, Lattice Boltzmann simulation of periodic bubble nucleation, growth and departure from a heated surface in pool boiling, Int. J. Heat. Mass Transf. 64 (2013), 122-132.

15) Z. Chen, Y. Utaka, Numerical simulation on heat transfer and evaporation characteristics in the growth process of a bubble with microlayer structure during nucleate boiling, Inter. Jour. Heat and Mass Transfer 81 (2015), 750–759.

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