24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM2017-2191
NUMERICAL STUDY OF A SINGLE BUBBLE DYNAMIC IN NUCLEATE POOL BOILING

Mateus Faria de Andrade Paschoal
Elaine Maria Cardoso
UNESP- São Paulo State University, School of Natural Sciences and Engineering, Department of Mechanical Engineering, Ilha Solteira, SP, Brazil.
mateus.f.a.p@gmail.com
elainemaria@dem.feis.unesp.br
João Batista Campos Silva
UNESP- São Paulo State University, School of Natural Sciences and Engineering, Department of Mechanical Engineering, Ilha Solteira, SP, Brazil.
jbcampos.silva@gmail.com

Abstract. *A better understanding of the mechanisms governing the nucleate boiling is required in order to intensify its use in thermal systems. Although intensive research on pool boiling processes has been undertaken for decades, the physical phenomena are still not sufficiently understood. Most of analytical studies in this area are based on empirical correlations to predict the boiling phenomenon, and numerical studies, generally, do not consider the transient phenomenon in the heating surface. The aim of this study is to solve numerically the axis symmetrical Navier-Stokes equations for a single bubble considering the time dependence of the temperature in the heating surface. The simulation takes into account the bubble growth period and the liquid-phase flow close to the vapor bubble. Initially, an axially hemispherical bubble shape is assumed and, also, the axis-symmetry about ψ coordinate of the liquid-phase flow. The bubble radius growth, temperature, pressure and velocity fields in the vicinity of the growing bubble are compared with results from the literature. It was observed that the results considering constant or non-constant surface temperature are similar, i.e., the simulations for vapor bubble growth considering constant wall temperature gives values similar to the situation in which the wall temperature varies.*

Keywords: *Pool boiling, numerical simulation, vapor bubble dynamics.*

1. INTRODUCTION

In the nucleate boiling regime, vapor bubbles are generated from active cavities, growing up to a critical diameter, and departing from the heating surface (Yeoma, Sridharana e Corradinia, 2014). To understand the boiling phenomena during this regime, the knowledge of vapor bubble detachment from a solid heating surface is important.

The mechanisms associated with the vapor bubble nucleation are not fully understood due to the high number and the variety of the physical mechanisms involved simultaneously. Various models have been developed during the last decades to analyze the vapor bubble dynamic and its effects on boiling heat transfer (Van der Geld, 2004; Siedel, Cioulachtjian and Bonjour, 2008; Afzal and Kang, 2012). However, sometimes the results predicted by these models are far from the experimental results due to the fast changes in the temperature and flow fields, bubbles interaction, material properties and physical parameters not always well defined. Thus, boiling phenomena needs to be simplified in order to identify the role of the different mechanisms involved.

To simplify these studies, Stephan and Hammer (1994), and Son, Dhir and Ramanujapu (1999) minimized the variation and non-homogeneity of the heating surface temperature in their formulation. Thus, the surface temperature was assumed to be constant and homogeneous in their models.

The present work aims to predict the departure time of a single vapor bubble, as well as, the fields of velocity, pressure, liquid phase temperature and heating surface temperature. In a first moment, the effect of the microlayer evaporation was considered negligible and the transient phenomenon in the heating surface was taken into account based on the second generation model developed by Patil (1991).

2. NUMERICAL FORMULATION

In order to study the detachment phenomena, it was considered a single vapor bubble attached to a heating surface as shown in Fig 1. According to Patil (1991), to formulate this problem the following assumptions must be taken:

- An hemispherical bubble shape is assumed;
- The heating surface temperature is time dependent;
- The vapor phase is assumed as perfect gas and at atmospheric pressure for saturated condition;
- 2D axial geometry for bubble is considered;
- Newtonian fluid with constant properties;
- Negligible convection inside the vapor bubble;
- Thermodynamic equilibrium at bubble interface;
- Semi-infinity pool fulfilled with saturared or subcooled liquid.

In this formulation, shown in Patil (1991), two steps are considered: first, an analysis is done inside the vapor bubble to find the rate of radius growth; second, the governing equations across the bubble interface are considered to relate the state of vapor to that of liquid. Figure 1 shows the coordinate system used for the numerical formulation.

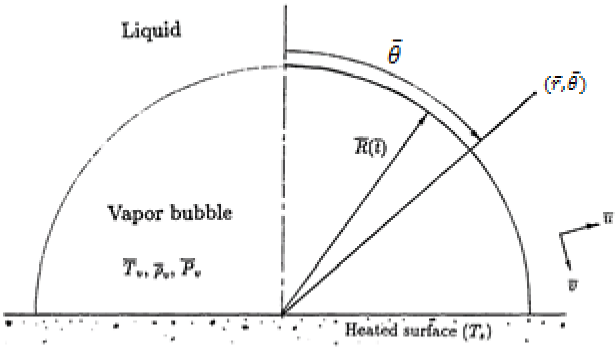

Figure 1. Coordinate system to analyze a bubble growth in pool boiling (Patil, 1991).

To formulate this problem was used the continuity, flow and thermal energy equations in spherical coordinates. The resulting system of equations is as follow:

- *continuity equation*

$$\frac{1}{\bar{r}^2}\frac{\partial\left(\bar{r}^2\bar{u}\right)}{\partial\bar{r}}+\frac{1}{\bar{r}sen\theta}\frac{\partial\left(\bar{v}sen\theta\right)}{\partial\theta}=0 \tag{1}$$

- *momentum equations*

$$\bar{\rho}\left[\frac{\partial\bar{u}}{\partial\bar{t}}+\bar{u}\frac{\partial\bar{u}}{\partial\bar{r}}+\frac{\bar{v}}{\bar{r}}\frac{\partial\bar{u}}{\partial\theta}-\frac{\bar{v}^2}{\bar{r}}\right]=-\frac{\partial\bar{p}}{\partial\bar{r}}+\bar{\mu}\left(\nabla^2\bar{u}-\frac{2\bar{u}}{\bar{r}^2}-\frac{2}{\bar{r}^2}\frac{\partial\bar{v}}{\partial\theta}-\frac{2\bar{v}\cot\theta}{\bar{r}^2}\right) \tag{2}$$

$$\bar{\rho}\left[\frac{\partial\bar{v}}{\partial\bar{t}}+\bar{u}\frac{\partial\bar{v}}{\partial\bar{r}}+\frac{\bar{v}}{\bar{r}}\frac{\partial\bar{v}}{\partial\theta}-\frac{\bar{u}\bar{v}}{\bar{r}}\right]=-\frac{1}{\bar{r}}\frac{\partial\bar{p}}{\partial\theta}+\bar{\mu}\left(\nabla^2\bar{v}+\frac{2}{\bar{r}^2}\frac{\partial\bar{u}}{\partial\theta}-\frac{\bar{v}}{\bar{r}^2sen^2\theta}\right) \tag{3}$$

- *thermal energy equation*

$$\frac{\partial\bar{T}}{\partial\bar{t}}+\bar{u}\frac{\partial\bar{T}}{\partial\bar{r}}+\frac{\bar{v}}{\bar{r}}\frac{\partial\bar{T}}{\partial\theta}=\bar{\alpha}\nabla^2\bar{T} \tag{4}$$

where: $\overline{p}$ is the pressure, $\overline{u}$ and $\overline{v}$ are the velocity components in $\overline{r}$ and θ coordinates respectively, and $\overline{T}$ is the temperature field. The Laplacian operator is $\nabla^2 = \frac{1}{\overline{r}^2}\frac{\partial}{\partial \overline{r}}\left(\overline{r}^2\frac{\partial}{\partial \overline{r}}\right) + \frac{1}{\overline{r}^2 sen\theta}\frac{\partial}{\partial\theta}\left(sen\theta\frac{\partial}{\partial\theta}\right)$. An over bar indicates dimensional variables.

The pressure field is obtained from the solution of the Poisson equation

$$\nabla^2\overline{p} = -\overline{\rho}\left\{\begin{array}{l}\frac{1}{\overline{r}^2}\frac{\partial}{\partial\overline{r}}\left[\overline{r}^2\left(\overline{u}\frac{\partial\overline{u}}{\partial\overline{r}} + \frac{\overline{v}}{\overline{r}}\frac{\partial\overline{u}}{\partial\theta} - \frac{\overline{v}^2}{\overline{r}}\right)\right] + \\ + \frac{1}{\overline{r}sen\theta}\frac{\partial}{\partial\theta}\left[sen\theta\left(\overline{u}\frac{\partial\overline{v}}{\partial\overline{r}} + \frac{\overline{v}}{\overline{r}}\frac{\partial\overline{v}}{\partial\theta} + \frac{\overline{u}\overline{v}}{\overline{r}}\right)\right]\end{array}\right\} \tag{5}$$

The initial and boundary conditions for solving Equations (2) – (6) are

$$\begin{aligned}&\overline{v} = \frac{\partial\overline{u}}{\partial\theta} = 0, \quad \text{at } \theta = 0\\ &\overline{v} = \overline{u} = 0, \quad \text{at } \theta = \pi/2\\ &\overline{u} = \overline{u}_b, \overline{v} = 0, \text{ at } \overline{r} = \overline{R}\\ &\overline{v} = \overline{u} = 0, \quad \text{at } \overline{r} = \overline{R} + \overline{\delta}\\ &\overline{v} = \overline{u} = 0, \quad \text{at } \overline{t} = 0\end{aligned} \tag{6}$$

$$\begin{aligned}&\overline{p} = p_{sat}, \text{ at } \overline{r} = \overline{R}, \overline{r} = \overline{R} + \overline{\delta} \text{ and } \theta = \pi/2\\ &\frac{\partial\overline{p}}{\partial\theta} = 0, \text{at } \theta = 0\end{aligned} \tag{7}$$

$$\begin{aligned}&\overline{T} = T_v, \text{ at } \overline{r} = \overline{R}\\ &\overline{T} = T_\infty, \text{ at } \overline{r} = \overline{R} + \overline{\delta}\\ &\overline{T} = T_s, \text{at } \theta = \pi/2\\ &\frac{\partial\overline{T}}{\partial\theta} = 0, \text{at } \theta = 0\end{aligned} \tag{8}$$

The velocity of the moving boundary in according to Collier and Thome (1994) is governed by the equation:

$$\bar{R}\frac{d^2\bar{R}}{dt^2} + \frac{3}{2}\frac{d\bar{R}}{dt} = -\frac{1}{\rho_f}\left[P_f - P_g + \frac{2\sigma}{R}\right] \tag{9}$$

Where P_f is the bulk liquid pressure and P_g is the vapor inside the bubble.
The following dimensionless variables are defined:

$$\begin{aligned}&r = \frac{\overline{r} - \overline{R}}{\overline{\delta}}; R = \frac{\overline{R}}{R_0}; t = \frac{\alpha\overline{t}}{R_0^2}; \gamma = \delta r + R\\ &u_i = \frac{R_0\overline{u}_i}{\alpha}; \; p = \frac{\overline{p} - p_\infty}{\rho\left(\frac{\alpha}{R_0}\right)}; T = \frac{\overline{T} - T_{sat}}{T_{s,0} - T_{sat}}\end{aligned} \tag{10}$$

The following system of non-dimensionalized equations is obtained:

$$\frac{\partial^2 p}{\partial r^2}+\frac{\delta^2}{\gamma^2}\frac{\partial^2 p}{\partial \theta^2}+\frac{2\delta}{\gamma}\frac{\partial p}{\partial r}+\frac{\delta^2}{\gamma^2}\cot\theta\frac{\partial p}{\partial \theta}=S_P \tag{11a}$$

$$S_P=-\begin{Bmatrix}\frac{1}{\gamma^2}\frac{\partial}{\partial r}\left[\gamma^2\left(u\frac{\partial u}{\partial r}+\frac{\delta}{\gamma}v\frac{\partial u}{\partial \theta}-\frac{\delta}{\gamma}v^2\right)\right]+\\ +\frac{\delta}{\gamma}\frac{1}{sen\theta}\frac{\partial}{\partial\theta}\left[sen\theta\left(u\frac{\partial v}{\partial r}+\frac{\delta}{\gamma}v\frac{\partial v}{\partial\theta}+\frac{\delta}{\gamma}uv\right)\right]\end{Bmatrix} \tag{11b}$$

$$\delta^2\frac{\partial u}{\partial t}-U\frac{\partial u}{\partial r}-V\frac{\partial u}{\partial\theta}-Pr\frac{\partial^2 u}{\partial r^2}-Pr\frac{\delta^2}{\gamma^2}\frac{\partial^2 u}{\partial\theta^2}=-\delta\frac{\partial p}{\partial r}+S_u \tag{12a}$$

$$U=\delta\left[\left(\frac{d\delta}{dt}r+\frac{dR}{dt}\right)+\frac{2\,\mathrm{Pr}}{\gamma}-u\right]\ ;\ V=\frac{\delta^2}{\gamma^2}\left[\mathrm{Pr}\cot\theta-\gamma v\right] \tag{12b, c}$$

$$S_u=\frac{\delta^2}{\gamma^2}\left[\gamma v^2-\mathrm{Pr}\left(2u+2\frac{\partial v}{\partial\theta}+v\cot\theta\right)\right] \tag{12d}$$

$$\delta^2\frac{\partial v}{\partial t}-U\frac{\partial v}{\partial r}-V\frac{\partial v}{\partial\theta}-Pr\frac{\partial^2 v}{\partial r^2}-Pr\frac{\delta^2}{\gamma^2}\frac{\partial^2 v}{\partial\theta^2}=-\frac{\delta^2}{\gamma}\frac{\partial p}{\partial\theta}+S_v \tag{13a}$$

$$S_v=\frac{\delta^2}{\gamma^2}\left[Pr\left(2\frac{\partial u}{\partial\theta}-\frac{v}{sen^2\theta}\right)-\gamma uv\right] \tag{13b}$$

$$\delta^2\frac{\partial T}{\partial t}-U^*\frac{\partial T}{\partial r}-V^*\frac{\partial T}{\partial\theta}-\frac{\partial^2 T}{\partial r^2}-\frac{\delta^2}{\gamma^2}\frac{\partial^2 T}{\partial\theta^2}=0 \tag{14a}$$

$$U^*=\delta\left[\left(\frac{dR}{dt}+r\frac{d\delta}{dt}\right)+\frac{2}{\gamma}-u\right]\ ;\ V^*=\frac{\delta^2}{\gamma^2}\left(\cot\theta-\gamma v\right) \tag{14b, c}$$

3. NUMERICAL PROCEDURE

The formulation of the problem is solved numerically using an implicit, point-iterative, finite difference method. The discretization is shown below:

$$\frac{\partial\zeta}{\partial x_i}\approx\frac{\zeta^{x_i+h}-\zeta^{x_i}}{h} \tag{15a}$$

$$\frac{\partial^2 \zeta}{\partial x_i \partial x_i} \approx \frac{\zeta^{x_i+h} - 2\zeta^{x_i} + \zeta^{x_i-h}}{h^2} \tag{15b}$$

The system resulted by discretization was solved by Gauss-Siedel method.

4. RESULTS

In this section, we present some results from the simulations. The conditions to run the problem are set as follows:

- Water is used as a model liquid
- Saturation temperature: 99 °C
- Saturation pressure: 97.85 kPa
- Superheating wall degree: 8 °C
- Fluid initial temperature: 99 °C
- Wall initial temperature: 107 °C
- Wall thickness: 2 cm
- The heated surface is assumed to be plain copper
- Mesh length (radius, angular, wall thickness and time, respectively): 50 x 50 x 500 x 430
- Fluid at saturation state, in which state physical the proprieties are obtained.

The results were analyzed for 4.3 ms, time predicted by Carey (1992) in which the bubble departure occurs. A solver has been developed in Fortran 90 language to simulate the velocity, pressure and the temperature fields in the region corresponding to liquid adjacent to the bubble, as shown in the Figure 1. Due to symmetry, only one quarter of the bubble is considered.

In Figures 2 to 5 are shown the results of the simulations. The temperature at the interface of the heated surface liquid is considered time dependent, since the solution to the temperature field in the heater is also obtained and imposed as boundary condition for the solution of the temperature in liquid layer adjacent to the vapor bubble.

Figure 2 and 3 show the u and v components of velocity field, respectively. One may observe that velocities in the liquid layer are almost zero in all domains. Figure 4 shows the pressure field, while in Figure 5 it is shown the temperature field. A simulation considering a constant temperature at the interface of the heated surface-liquid has been also performed, in order to compare with the results for time dependent temperature of the heater. The temperature field for the case with temperature constant at the heater surface is shown in Figure 6.

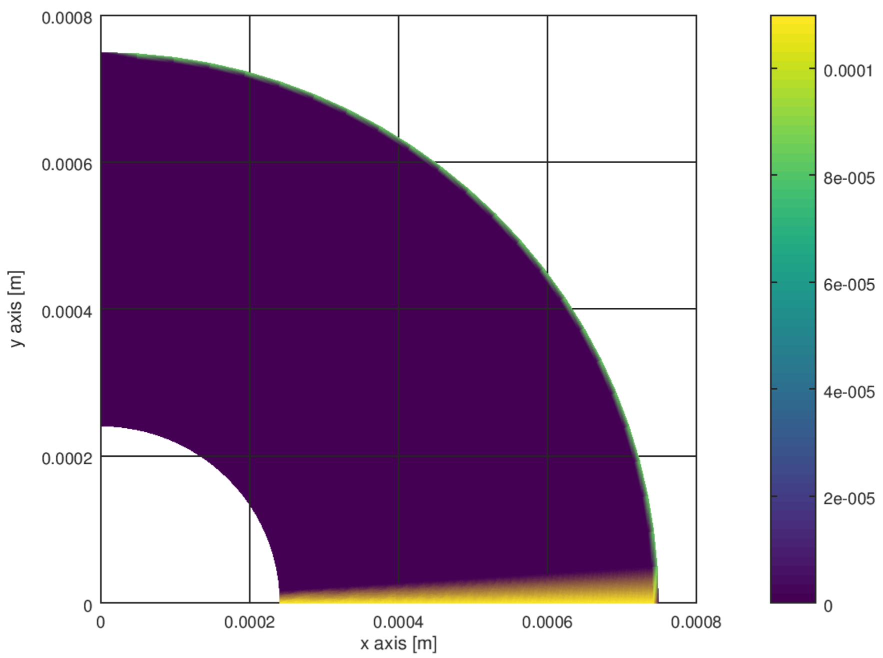

Figure 2. u component of velocity (in r direction and SI units) field inside bubble phase layer considering time dependent wall temperature.

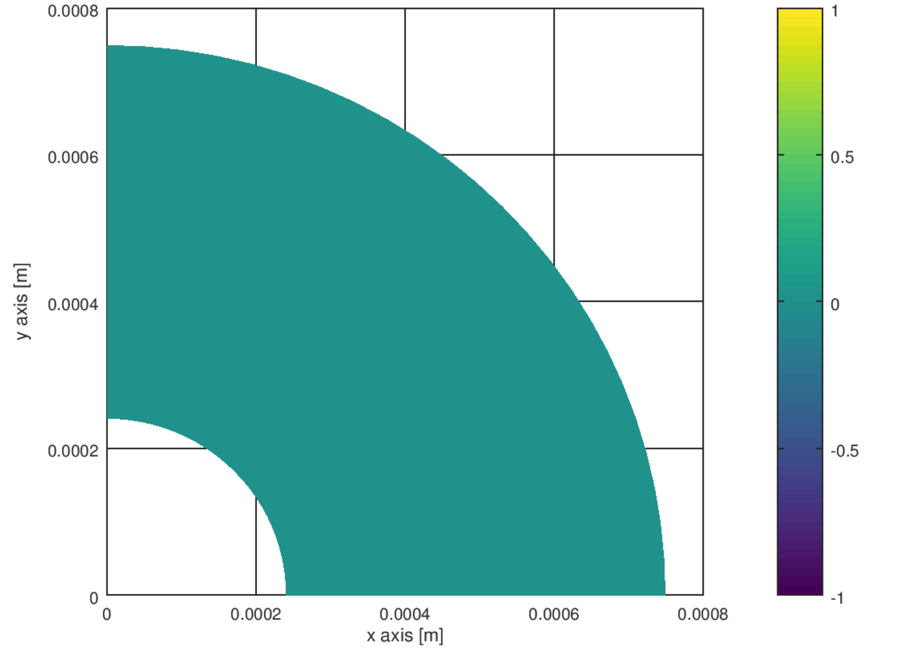

Figure 3. v component of velocity (in direction and SI units) field inside bubble phase layer considering time dependent wall temperature.

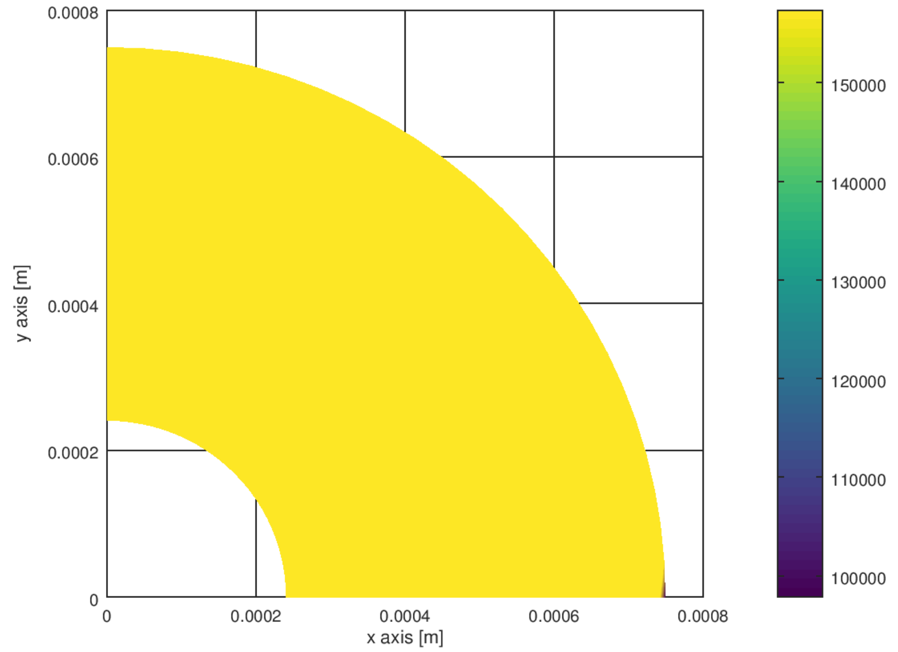

Figure 4. Pressure (presented in Pa) field inside bubble phase layer considering time dependent wall temperature.

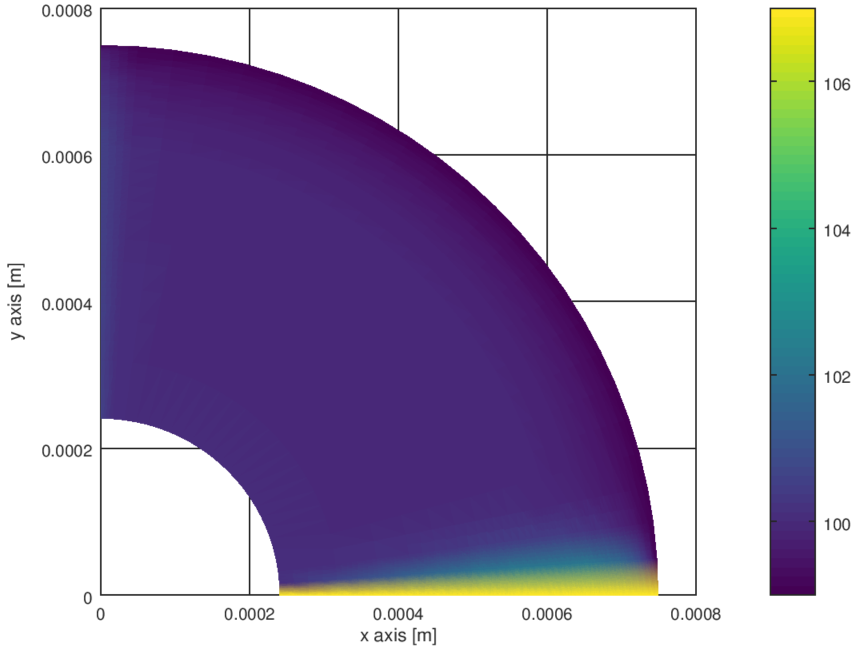

Figure 5. Temperature (presented in °C) field inside bubble phase layer considering time dependent wall temperature.

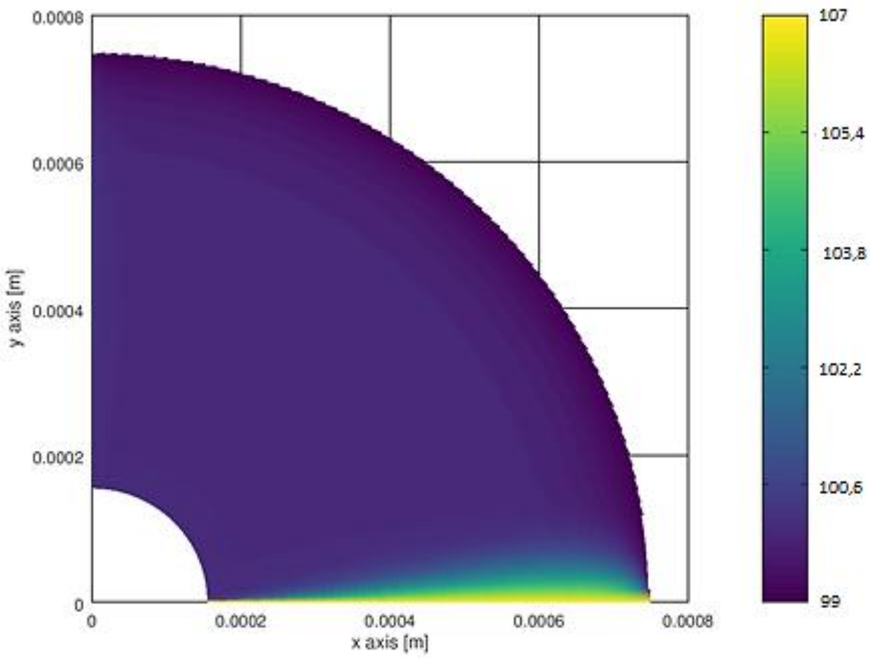

Figure 6. Temperature field inside bubble phase change considering constant wall temperature.

The code implemented has good stability and has a quick convergence; it was necessary 20 iterations to achieve errors values in the order of 10^{-7}. It also showed independence in terms of mesh with too few elements (50 x 50 elements). Finally, it took less than 1 hour to obtain the results showed above.

5. CONCLUSION

The results show that there is an insignificant difference between considering the wall temperature constant or not in the vapor bubble growth simulation. This result is consistent with those reported in Aktinol and Dhir (2012) and Tanguy et al. (2014). Thus, to solve numerically the vapor bubble growth on a heating surface, it is not necessary to consider the time dependence of the temperature in the heating surface, and the problem can be treated as a simple problem, with less computational resources and time.

6. ACKNOWLEDGEMENTS

The authors are grateful for the financial support of FAPESP (grant numbers 2013/15431-7 and 2016/13685-0).

7. REFERENCES

Afzal, M.U., Kang, I.S. A Numerical Study on Bubble Detachment from Solid Wall and Formation of Jet inside Detached Bubble. International Journal of Chemical Engineering and Applications, Vol. 3, No. 1, February 2012.

Aktinol, E. and Dhir, V.K., Numerical simulation of nucleate boiling phenomenon coupled with thermal response of the solid, Microgravity Science and Technology, 2012, 24, 255–265.

Carey, Van P. Liquid Vapor phase Change Phenomena, Taylor & Rancis, 1992.

Collier, J. G.; Thome, J. R.. Convective Boiling and Condensation. 3. ed. New York: Oxford University Press, 1994.

Mobli, M., Li, C. On the Heat Transfer Characteristics of a Single Bubble Growth and Departure During Pool Boling, 2016.

Patil, R.K., A numerical model for a bubble in nucleate pool boiling, PhD Thesis, Iowa State University, 1991.

Siedel, S., Cioulachtjian, S., Bonjour, J. Experimental analysis of bubble growth, departure and interactions during pool boiling on artificial nucleation sites. Experimental Thermal And Fluid Science, Elsevier, 2008, 32 (8), pp.1504-1511.

Son, G., Dhir, V.K. and Ramanujapu, N., Dynamics and heat transfer associated with a single bubble during nucleate boiling on a horizontal surface, Journal of Heat Transfer, 1999, 121, 623–631.

Stephan, P. and Hammer, J., A new model for nucleate boiling heat transfer, Heat and Mass Transfer, 1994, 30 (2),119–125.

Tanguy, S.; Sagan, M.; Lalanne, B.; Couderc, F.; Colin, C., Benchmarks and numerical methods for the simulation of boiling flows. (2014) Journal of Computational Physics, vol. 264, pp. 1-22.SS

Van Der Geld, C.W.M., Prediction of dynamic contact angle histories of a bubble growing at a wall, International Journal of Heat and Fluid Flow 25 (2004) 74-80.

Yeoma, H., Sridharan, K., Corradinia, M., Bubble dynamics in pool boiling on nanoparticle coated surfaces. Heat Transfer Engineering. London, p. 37-41, 2014.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.