

NUMERICAL ANALYSIS OF FILM BOILING AROUND HORIZONTAL CYLINDRICAL SURFACES

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ABSTRACT:

Stability of vapor film over a horizontal heater drags attention due to its wide spread applications in nuclear reactors, metal processing, manufacturing and chemical refineries. Existence of vapor film around the heater can cause advantages as well as disadvantages for various applications in industry and daily life. Hence understanding the film formation and its subsequent release in the form of bubble are dealt carefully by researchers in heat transfer community. Critical vapor thickness and average heat flux are the essential parameters which govern the release of vapor mass in the form of isolated bubbles from the surface. Experimental evidences have been reported in order to find out film dynamics for some specific fluids. However understanding it from the fundamental physics is still due and becomes a major challenge for heat transfer community. In this paper, numerical analysis of the film boiling heat transfer on a horizontal cylinder is presented to determine the effect of superheating on the heat transfer coefficient and film thickness in a pool. Findings from the present study will develop knowhow about the film formation and its role in enhancing the boiling heat transfer coefficient.

INTRODUCTION

Film boiling is often encountered in day to day life in experiments, industries, nuclear reactors and other places. In this type of boiling, rate of vaporization is such that the surface is always covered with vapor. This results in very inefficient heat transfer which further results in varying heat flux from the horizontal surface after the critical heat flux is reached and vapor film covers the surface.

To understand the heat transfer by film boiling different relationships have been established for different conditions and geometries. Bromley [1] was the first to study heat transfer in detail around horizontal cylinders and gave the famous equation for calculating Nusselt number as

$$Nu = 0.62[GrPr_v/(1+0.34Ja)]^{1/4} \quad (1)$$

However this equation is only valid for film thickness much lower than the cylinder diameter.

NOMENCLATURE

C_p	[J/kgK]	specific heat
D	[m]	diameter of cylinder
E	[J]	energy
g	[m/s ²]	acceleration due to gravity
Gr	[-]	Grashof Number, $\rho_v(\rho_l - \rho_v)gD^3/\mu_v^2$
h	[W/(m ² K)]	heat transfer coefficient
h_{lv}	[J/kg]	latent heat of vaporization
Ja	[-]	Jakob's number
k	[W/(mK)]	thermal conductivity
L	[m]	reference length, $\sqrt{\sigma/g(\rho_l - \rho_v)}$
Nu	[-]	Nusselt number given by Bromley's correlation
Nu'	[-]	Nusselt Number corrected by Breen and Westwater
P	[Pa]	Pressure
Pr	[-]	Prandtl Number
q	[W/m ²]	heat flux
t	[s]	time
T	[K]	Temperature
ΔT_{sup}	[K]	superheat
\vec{U}	[m/s]	local velocity vector
<i>Special symbols</i>		
α	[-]	volume fraction
μ	[kg/(ms)]	dynamic viscosity
ρ	[kg/m ³]	density
σ	[N/m]	surface tension
<i>Subscripts</i>		
l		liquid
t		total
v		vapor

Breen and Westwater [2] experimentally found that Bromley's equation did not work for smaller diameters or diameters larger

than the critical Taylor wavelength for a flat plate. They considered surface forces and proposed a new correlation which is applicable to larger set of diameters

$$Nu' = (0.601(D/L)^{1/4} + 0.442(L/D)^{3/4})Nu \quad (2)$$

Sakurai et al. [3-4] have done numerical simulations for film boiling by considering the radiation effects under subcooled liquid pool. They have shown that numerical simulation agrees quiet well with Bromley's correlation [1] for a wide range of operating parameters.

Though there are isolated efforts to understand the physical phenomenon behind the film formation, phase change around a cylindrical heater is not yet understood from fundamental physics. Numerical simulations of the phenomenon can throw light in the gray areas of film boiling heat transfer over cylinder. Researchers have tried various interface capturing techniques to express the formation and detachment of vapor phase but a systematic study of film boiling is still due. Welch [5] used triangular grids to simulate the two-dimensional film boiling which was advanced by Son and Dhir [6-7]. However their techniques could not tackle properties variation at interface effectively. Juric and Tryggvason [8] presented a modified numerical formulation by including the source terms in continuity equation and energy equation to Eulerian approach of Unverdi and Tryggvason [9] which gave promising results for heat transfer rates (and wall temperatures) but their model could not approve interfacial geometry from what seen in experiments. Welch and Wilson [10] used Volume of Fluid (VOF) method and their simulations showed that VOF method can be used to track liquid-vapor interface. Present effort targets finite volume simulations of film formation and its subsequent growth by using interface capturing via Volume of Fluid methodology.

The aim of this paper is to simulate the boiling phenomenon at different superheats around horizontal cylinder and to develop the idea of variation in heat flux with change in surface temperatures. The computation is also directed to study the variation of formation of bubble mushroom over the surface with change in superheat.

NUMERICAL ANALYSIS

MODEL DESCRIPTION

The basic assumptions made for model are: uniform surface temperature, pool containing water at saturated conditions, smooth liquid-vapor interface, pure and incompressible fluid phases and constant physical properties. The simulations were carried out in a pool keeping initial velocity of vapor zero also their effect were found to be negligible as reported by Bromley et al. [11]. Son and Dhir [6] reported in their work that for lower

superheats radiation effect on calculating surface heat flux can be neglected hence for cases presented here influence of radiation was not taken into account.

Numerical simulations were done under the VOF framework of ANSYS FLUENT 15. In VOF model, tracking of interface is accomplished by solving the continuity equation for volume fraction of all phases in each cell. For each cell, the volume fraction of primary phase is computed using following constraint

$$\sum_{i=1}^n \alpha_i = 1 \quad (3)$$

Since density of phases are same, the general continuity equation solved for i^{th} phase involving mass source term

$$\frac{\partial \alpha_i}{\partial t} + \vec{U} \nabla \alpha_i = \frac{S_{\alpha_i}}{\rho_i} \quad (4)$$

where S_{α_i} is mass source term, and

$$S_{\alpha_i} = \sum_{i=l,v} \frac{k_i \alpha_i (\nabla T \cdot \nabla \alpha_i)}{h_{lv}} = S_h / h_{lv} \quad (5)$$

where S_h is volumetric heat source term is initialized using a User Defined Function (UDF).

In VOF modelling, a single set of momentum equation is solved for all phases and the equation is described as

$$\frac{\partial (\rho \vec{U})}{\partial t} + \nabla \cdot (\rho \vec{U} \vec{U}) = -\nabla P + \nabla \cdot (\tau) + \rho \vec{g} + \vec{F}_s \quad (6)$$

where F_s represents forces due to surface tension and τ is tensor.

Following energy equation for laminar flow is solved

$$\frac{\partial (\rho E)}{\partial t} + \nabla \cdot (\vec{U} (\rho E + P)) = \nabla \cdot (k \nabla T) + S_h \quad (7)$$

The various schemes or models involved in discretization are as follows:

Table 1: Discretization schemes or models used

Pressure- Velocity coupling	PISO
Pressure	PRESTO
Volume fraction interpolation	Geo-Reconstruct
Momentum	QUICK
Energy	QUICK

DOMAIN DESCRIPTION

For study, cylinder of diameter (D) 0.01 m was taken in a pool having dimensions 5D X 10D and the cylinder was placed at center of pool at a height of 3D from the bottom. Since the

domain was symmetric in nature its advantage was taken for grid preparation. A thin vapor layer of thickness $0.2D$ was initialized around cylinder with the help of UDF. All other walls were kept adiabatic and the top was made as pressure-outlet. The geometry and boundary conditions are as shown in Fig 1.

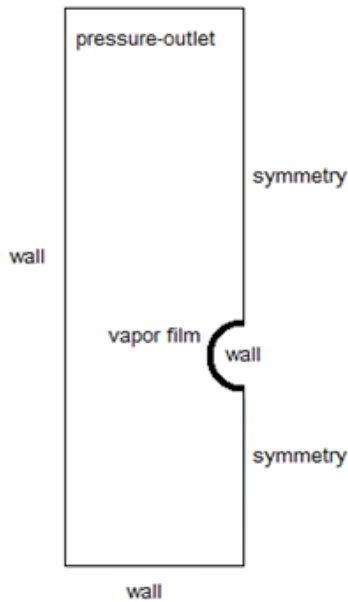


Figure 1. Geometry along with boundary conditions.

GRID INDEPENDENCE STUDY

Quadrilateral grids were used for simulation, and refinement was done near the cylinder as well as on upper portion of domain where bubble growth will take place. Three grids of cell sizes 4080, 12913 and 24304 cells were created. Total surface heat flux at $170\text{ }^{\circ}\text{C}$ around cylinder up to certain flow time was plotted for comparison of grids.

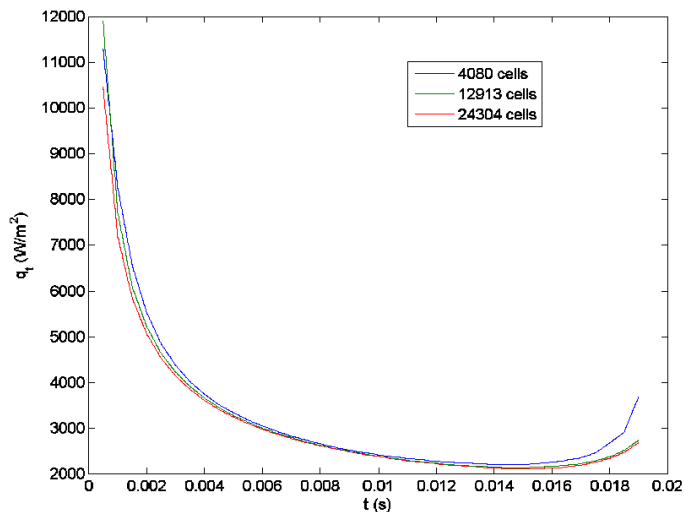


Figure 2. Comparison of grids using total surface heat flux

It was seen that the maximum difference in heat flux for grid with 4080 cells and 12913 cells was 15% where it was approximately 1% for grids with 12913 and 24304 cells. The study established that grid with 12913 cells are good to carry out the computations, however the grid scheme with 24304 cells was chosen to capture the vapor-liquid interface more efficiently.

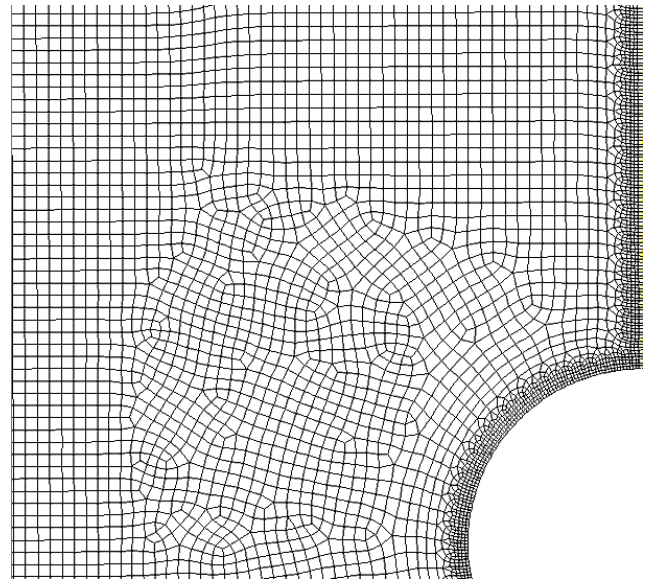


Figure 3. Refined grid structure near cylinder

CASE STUDIES

To determine the effect of superheat on surface heat flux four different surface temperatures were taken were 110, 125, 140 and $170\text{ }^{\circ}\text{C}$. Properties of liquid water are set at saturated conditions of 1 atmospheric pressure and $100\text{ }^{\circ}\text{C}$, as: $\rho = 958.4\text{ kg/m}^3$, $\mu = 2.819 \times 10^{-4}\text{ kg/m s}$, $C_p = 4217\text{ J/kg K}$, $k = 0.6651\text{ W/m K}$, $h_{lv} = 2.257 \times 10^6\text{ J/kg}$ and surface tension between liquid and water vapor, $\sigma = 0.05891\text{ N/m}$. Temperature of water vapor in film varies from surface temperature to saturated conditions, but as superheat in considered cases are less varying, the properties of water vapor are found not change much at different temperatures. So properties of vapor is set at $100\text{ }^{\circ}\text{C}$ and they are: $\rho = 0.597\text{ kg/m}^3$, $\mu = 1.2228 \times 10^{-5}\text{ kg/m s}$, $C_p = 2026\text{ J/kg K}$, $k = 0.02478\text{ W/m K}$.

RESULTS AND DISCUSSIONS

Evolution of bubble

The bubble formation, growth and release at superheat of 40 K was captured as shown in Fig 4. It has been observed that symmetrical vapor mass across the cylinder first becomes asymmetric due to gravity and subsequently gives rise bubble like formation at the top of the cylinder. Finally, due to effect of surface tension bubble pinches off and gets released.

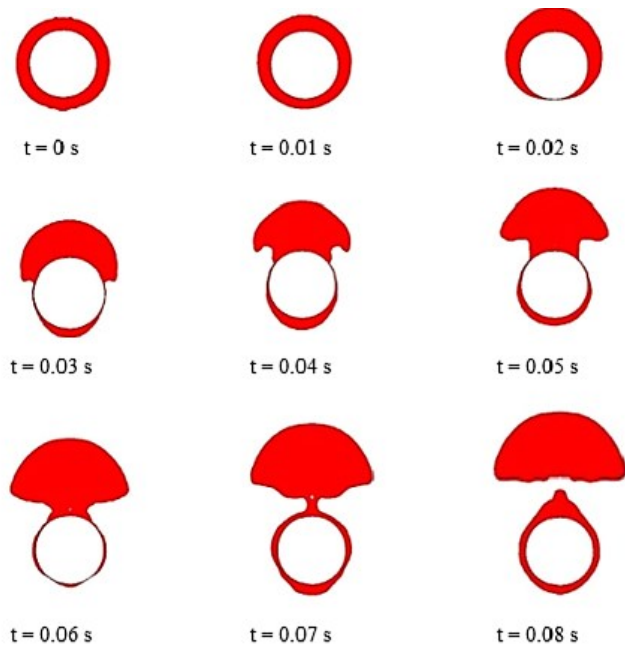


Figure 4. Evolution of vapor mushroom at $\Delta T_{\text{sup}} = 40$ K

At 40 K rate of vapor generation is higher compared to 10 K as a result we are observing the vapor mass over the cylinder is bigger in case of Fig 4 as compared to Fig 5. Also in case of higher superheat faster rate of vapor generation is not allowing the surface tension force to work properly in making the smooth interface of the bubble whereas in case of low superheat surface tension force is dominant and shape of the departing bubble becomes similar to static bubble.

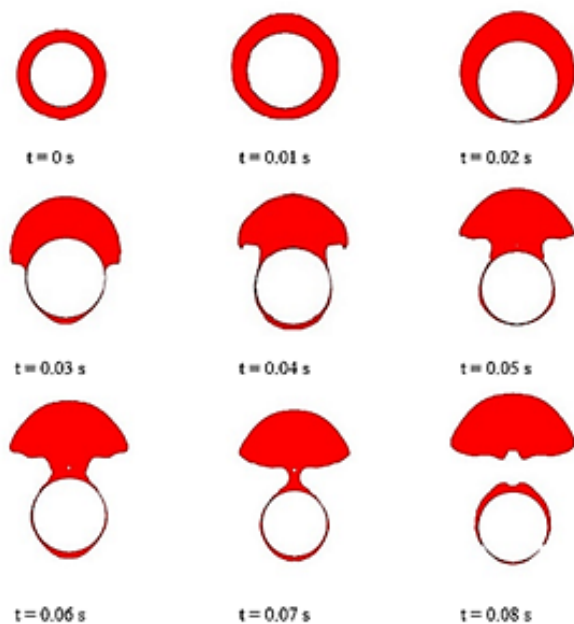


Figure 5. Evolution of vapor mushroom at $\Delta T_{\text{sup}} = 10$ K

Bubble departure with superheat

At higher superheat like 70 K we are observing vapor mushroom above the solid highest whereas the size decreases monotonically with the decrease of superheat.

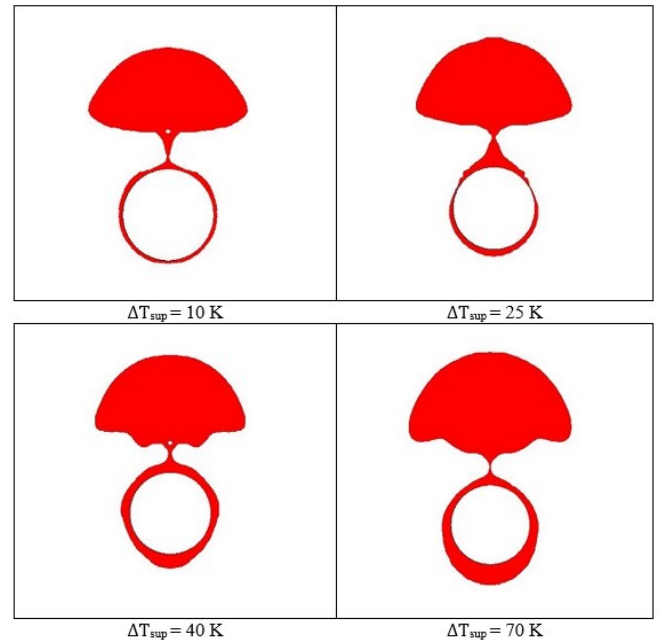


Figure 6. Variation in release of bubble with superheat

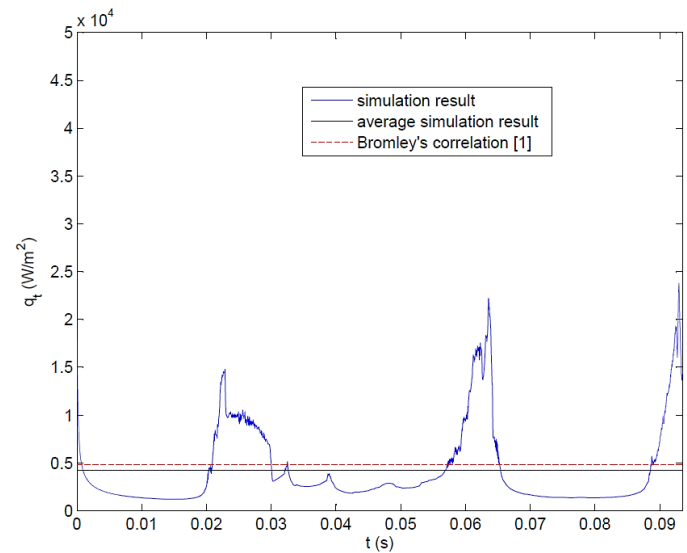


Figure 7. Heat flux at $\Delta T_{\text{sup}} = 40$ K

Heat flux

Surface heat flux of cylinder was plotted and it was found that heat flux varies intermittently with time, this has also been reported by Son and Dhir [12]. It was also confirmed that heat flux variation depended on shape of bubble around cylinder. From Fig 4 it can be seen that between time interval of 0.02 s

to 0.03 s and 0.06 s to 0.07 s we get relatively thin vapor layer around cylinder and hence in those interval heat flux increases as shown in Fig 7. The numerical results are in agreement to Bromley's correlation [1] with an average difference of 12.3%.

Velocity vectors

Velocity field in the vicinity of cylinder at $\Delta T_{\text{sup}} = 40$ K was also studied and it was found that surface tension and gravity leads to accumulation of vapor at upper region of cylinder and forming a mushroom kind of shape before pinching off from cylinder as shown in Fig 8. Initially film has zero velocity which then due to gravity starts growing upwards. When the vapor bubble is developing, curling of velocity vectors is found to occur which effects the shape of bubble. After the detachment from surface it was found that the circular motion dampens and only upward velocity is left which further lifts the bubble.

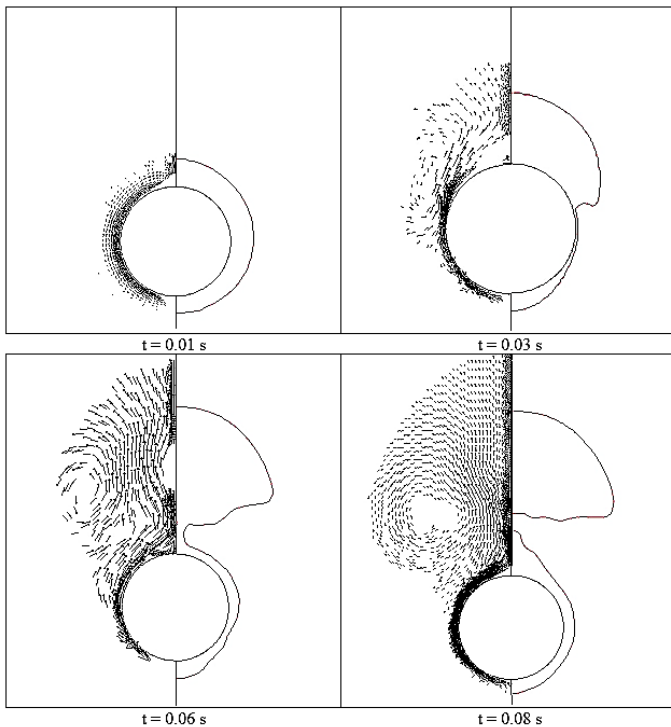


Figure 8. Velocity vectors of bubble formation with time for $\Delta T_{\text{sup}} = 40$ K

Temperature profile

Temperature distribution for surface temperature 140 °C was reported as in Fig 9. At $t = 0$ s only cylindrical surface has the excess temperature which then spreads to the layer of vapor film. With surface temperature remaining constant, heat is dispersed to nearby saturated liquid and hence increasing the vapor mass around surface. After the vapor leaves the cylinder

source of heat is lost and decrease in temperature of bubble is found to occur as can be seen from Fig 9.

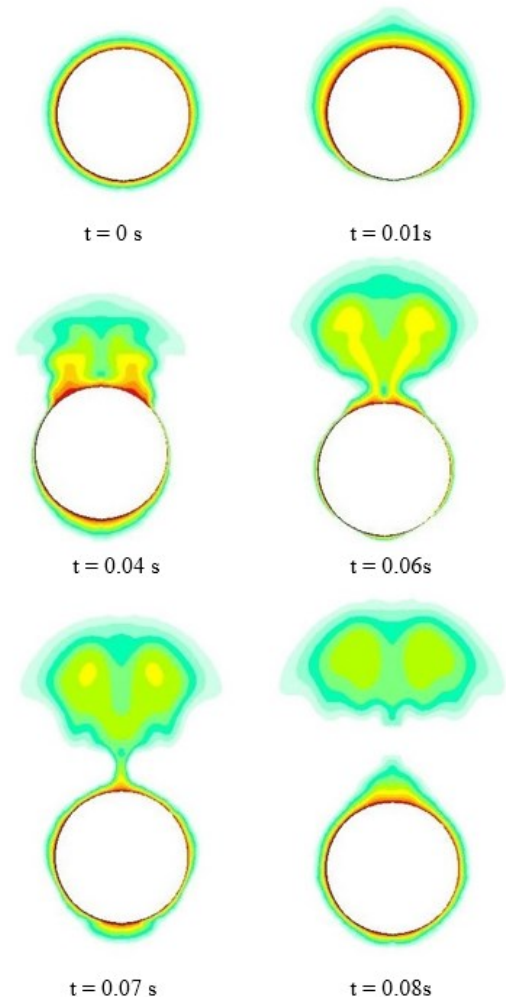


Figure 9. Temperature profile for $\Delta T_{\text{sup}} = 40$ K

CONCLUSION

Numerical simulations of film boiling for different superheats around a horizontal cylinder have been carried out. Finite volume based discretization has been done for coupled mass, momentum and energy equations along with Volume of Fluid based interface tracking. Credibility of the developed code has been tested first using proper grid independence test and validation with famous correlation of Bromley [1]. Efforts have been made to study the dynamics of vapor mushroom around a superheated cylinder in a pool of saturated liquid water. It has been observed that due to effect of gravity vapor mass becomes asymmetric and evolves as a bubble release pump at the top of the cylinder. By varying the degree of superheat we have observed that shape and size of the departing bubble increases as degree of superheat goes up. By studying the velocity vector around the bubble and temperature contours, efforts have been

made to understand the underlined physics behind the phenomenon. The model developed can be extrapolated further for 2D/3D phase change procedures for real life and industrial applications.

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