Numerical Simulation of Vapour Bubble Ebullition from Discrete Cavity during Pool Boiling

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ABSTRACT

Modification of boiling surface has received a wide acceptance out of different passive techniques to enhance the heat transfer rate. In nucleate boiling artificial nucleation sites of appropriate design can enhance the rate of heat transfer substantially. Therefore in this numerical study a number of artificial single micro cavity surfaces have been developed to visualize nucleate boiling over different shapes as of V, Rectangular and Trapezoidal cavity of same height and width using water as liquid. A constant surface flux is applied at the base and compares the bubble dynamic and heat transfer coefficient for each case modelled in 2D with transient study using multi physics laminar two- phase flow, phase field interface, heat transfer in CFD software COMSOL Multi-physics. Results shows that rectangular and V micro cavity shape have faster bubble ebullition and more enhancement in boiling heat transfer than trapezoidal micro cavity surface.

Keywords: Pool Boiling, Artificial Micro Cavity-V, Rectangular, Trapezoidal.

1. INTRODUCTION

The study of bubble rise characteristics is vital for the design of heat and mass transfer operations in various industries. It is highly important to obtain the knowledge of bubble behaviour because the investigation on bubble motion provides useful information for realising suitable process design and operation. The rate of heat and mass transfer is affected by the bubble size, interaction between bubbles, rise velocity and rising trajectory. A number of numerical and experimental investigations have been done to understand the physics behind boiling heat transfer[1]. Nevertheless, this still remains one of the least understood topics of the thermal engineering due to various complex processes involved. Particularly, the process of nucleation, bubble growth and departure are difficult to model. Nucleation for instance, depends on the topography of the surface[2], properties of the solid and liquid as well as operating parameters. It has further been observed that artificial nucleation sites of appropriate design can enhance the rate of heat transfer substantially in nucleate boiling[3]. Cavity shape is also very sensitive to the increase of heat transfer rate and bubble nucleation.

In order to investigate the effect of various cavity shapes on pool boiling heat transfer three different artificial micro cavity has been analysed of same width of 0.8 mm and 1.5 mm in height and for trapezoidal cavity the angle between adjacent sides is 68.198°. A constant heat flux $10^4 W/m^2$ is provided on the surface of boiling pot where cavity has formed with initially entrapped vapour at the base in order to track the liquid vapour interface and bubble trajectories continuously for visualisation. Bubble dynamics of pool boiling with microstructure cavity is modelled in 2D with transient study using multi physics laminar two-phase flow, phase field interface, heat transfer in CFD software COMSOL Multi-physics over three different cavities with finer meshing (Figure1). The physical behaviour of boiling flow is driven by interface dynamics. The governing equations are standard N-S, convection/conduction equations. Boundary conditions are complicated because of moving interface. With a series of approximation with exact equations and boundary condition problem can be solved on fixed mesh where the interface is tracked by phase field equation.

2. GOVERNING EQUATIONS

For Liquid velocity field and pressure are described by incompressible N-S equation

$$\rho_L \frac{\partial u_L}{\partial t} + \rho_L (u_L \cdot \nabla) u_L = \nabla \cdot \left[-p_L I + \mu_L \left(\nabla u_L + (u_L)^T \right) \right] + \rho_L g \tag{1}$$

$$\nabla \cdot u_L = 0 \tag{2}$$

where ρ_L is fluid density (kg/m^3), u_L is fluid velocity (m/s) and μ_L is viscosity (Pa.s).Subscription L denotes for liquid phase and v denotes for vapour phase. For the vapour phase, the compressible N-S equations are solved:

$$\rho_v \frac{\partial u_v}{\partial t} + \rho_v (u_v \cdot \nabla) u_v = \nabla \cdot \left[-p_v I + \eta_v \left(\nabla u_v + (\nabla u_v)^T \right) - \frac{2}{3} \mu_v (\nabla \cdot u_v) I \right] + \rho_v g \tag{3}$$

$$\frac{\partial \rho_v}{\partial t} + \nabla \cdot (\rho_v u_v) = 0 \tag{4}$$

The heat equation is solved only in vapour phase:

$$\rho_v C_p \frac{\partial T_v}{\partial t} + \rho_v C_p (u_v \cdot \nabla) T = \nabla \cdot \kappa_v \nabla T_v \tag{5}$$

where Cp is the specific heat capacity (J/(kg.K)) and κ_v is the thermal conductivity of the vapour(W/(m.K)). The heat conduction equation is only solved in vapour phase because the temperature at the liquid/vapour interface is set to the saturation temperature. This results in a constant temperature throughout the liquid phase and so it is not necessary to solve heat equation for liquid phase.

3. BOUNDARY CONDITIONS

The boundary condition for a boiling flow model is rather complicated. It's important to realize that interface velocity, liquid velocity and vapour velocity are not necessary equal.

$$u_{\text{int}} = u_L - \frac{\dot{m}}{\rho_L} n$$

where n is unit normal vector to interface directed from the liquid phase to vapour phase and $\dot{m}$ is the rate of vaporization $(kg / m^2 * sec)$ .The natural boundary condition on the interface for vapour phase is:

$$n \bullet \rho_v u_v = \dot{m}\left(1 - \frac{\rho_v}{\rho_L}\right) + \left(n \bullet \rho_v u_L\right) \tag{6}$$

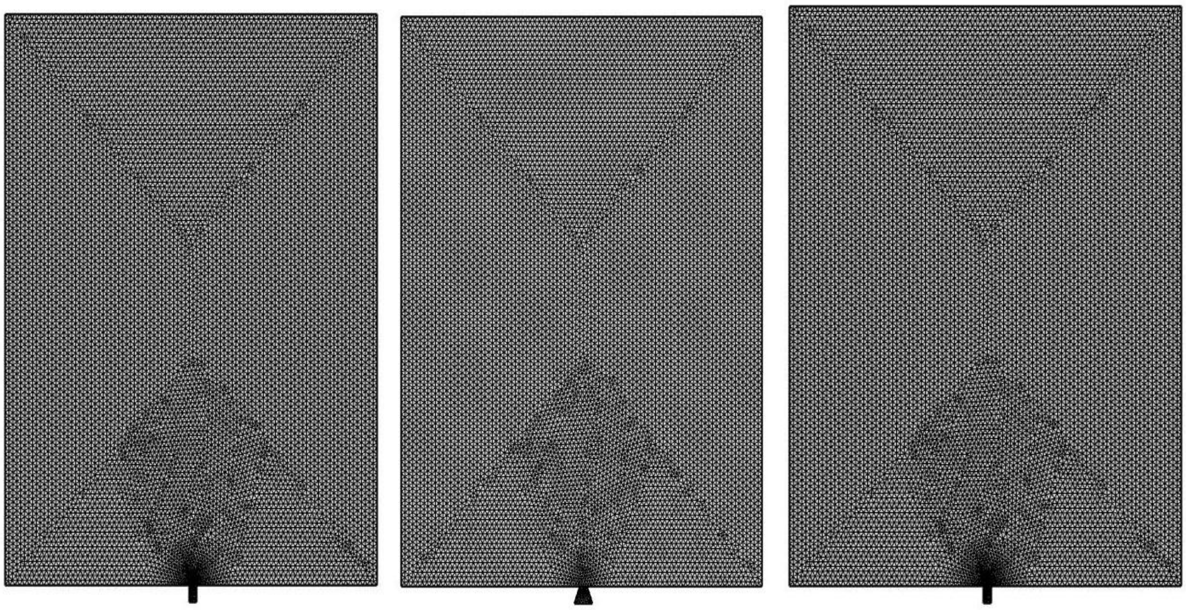
There are three forces that act on the liquid at the interface and so the natural boundary condition for the liquid is:

$$n \bullet \left[-p_L I + \mu_L\left(\nabla u_L + (\nabla u_L)^T\right)\right] = \dot{m}\left(u_L - u_v\right) + \sigma\kappa n + n \bullet \left[-p_v I + \mu_v\left(\nabla u_v + (\nabla u_v)^T\right) - \frac{2}{3}\mu_v(\nabla \bullet u) I\right] \tag{7}$$

which results from a force balance on the interface. The mass flux leaving the interface can then be evaluated from the conductive heat flux:

$$\dot{m} = \left(\frac{M_W}{\Delta H_{vl}}\right) n \bullet \kappa_v \nabla T_v \tag{8}$$

where Mw is the molecular weight of vapour (kg/mol) and ΔH_{vl} is the enthalpy of vaporization (J/mol). This approximation is obtained by neglecting the kinetic energies and work due to viscous forces[4].

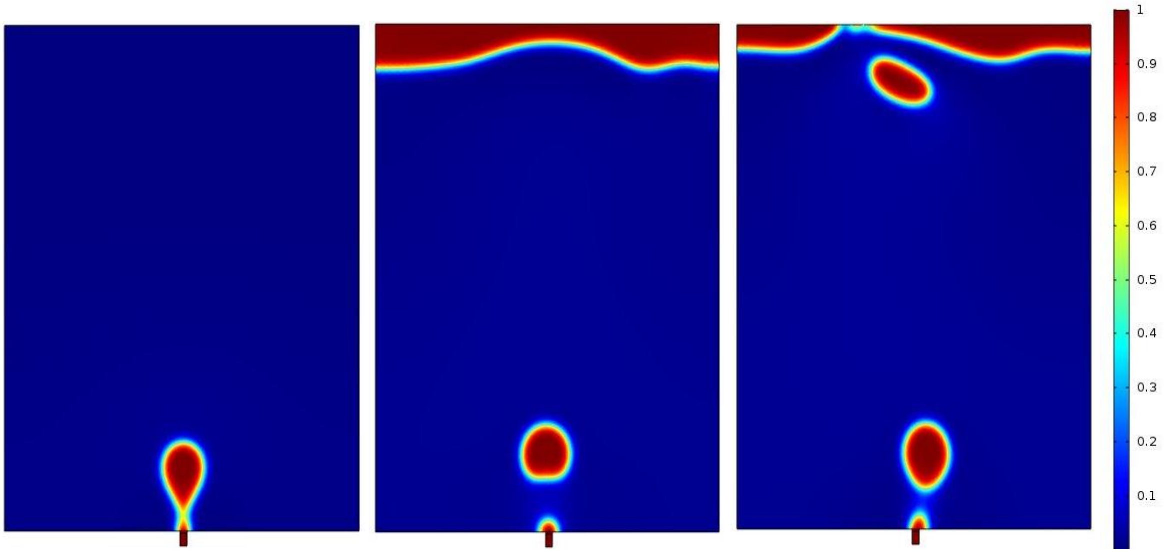


a) b) c)

Figure 1. Mesh for a) V micro cavity b) Trapezoidal micro cavity c) Rectangular micro cavity

4. RESULTS AND DISCUSSION

Vapour is continuously being released and detaching from the surface, the surface area of interface oscillates as pockets of vapour are produced expand and penetrate the surface. The augmentation of vapour is examined at various time steps for Rectangular micro cavity (Figure2), V micro cavity (Figure4), and Trapezoidal micro cavity (Figure6). Temperature variation in respective cavity is also shown in Fig.3,Fig.5, Fig.7 respectively.



a) b) c)

Figure2. Bubble augmentation from Rectangular Cavity at time a) 0.49 s b) 1.04 s c) 1.93 s

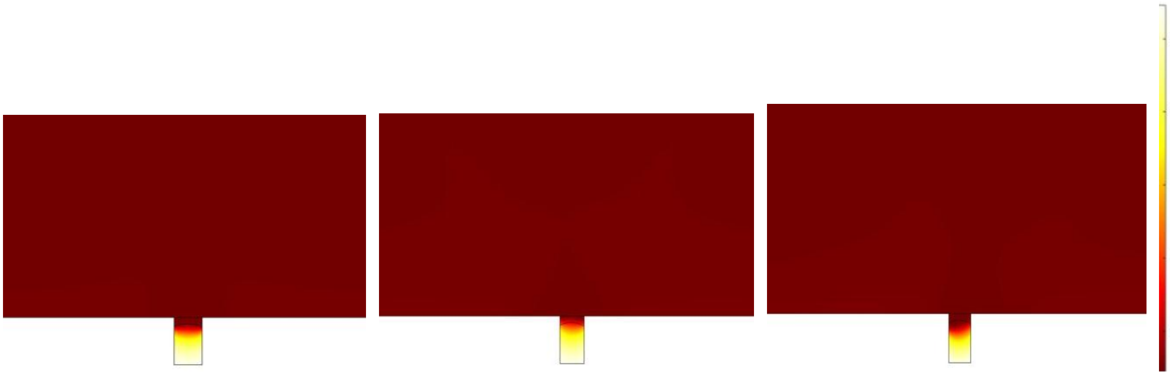


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Figure 3. Temperature variation in Rectangular cavity at a) 0.49 s b) 1.04 s c) 1.93 s

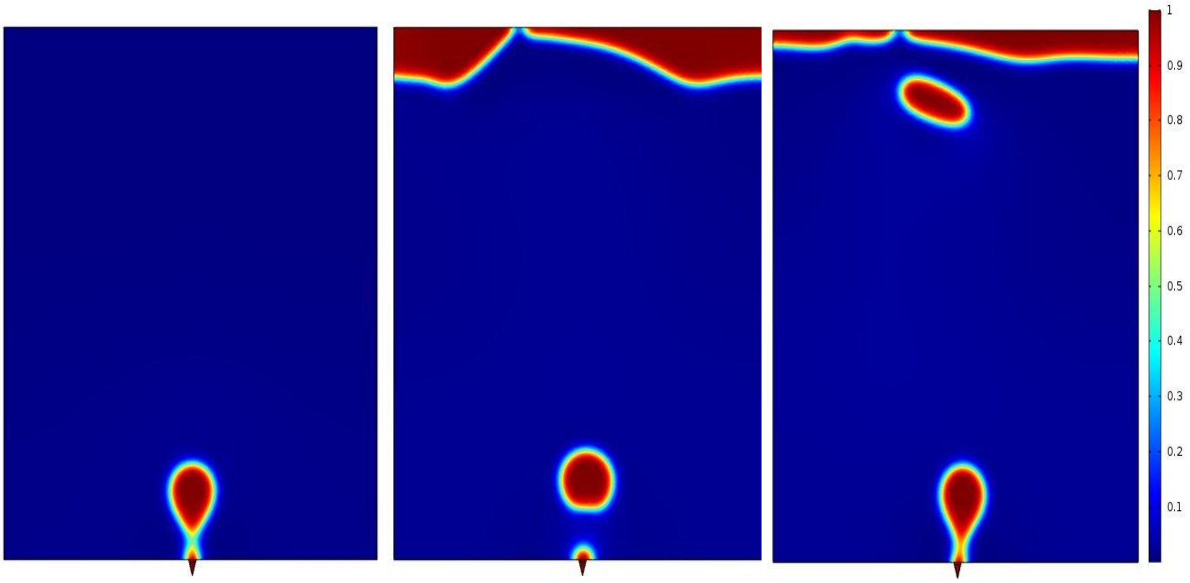

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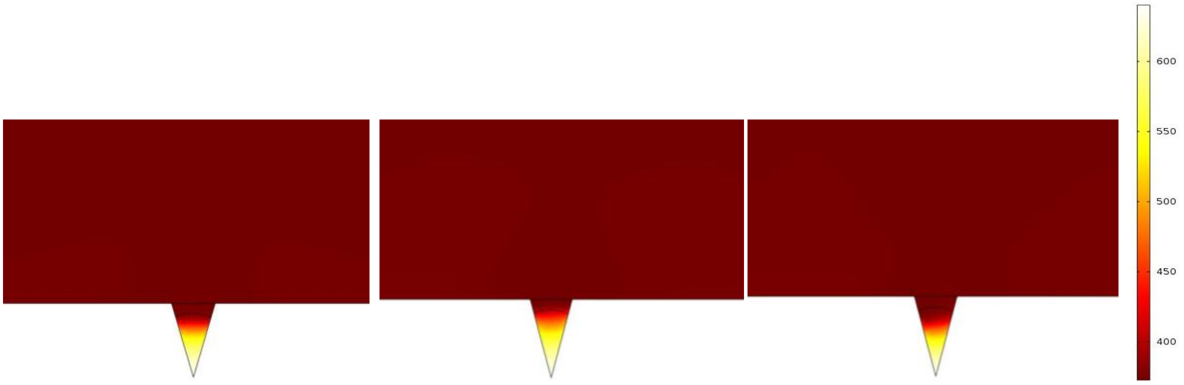
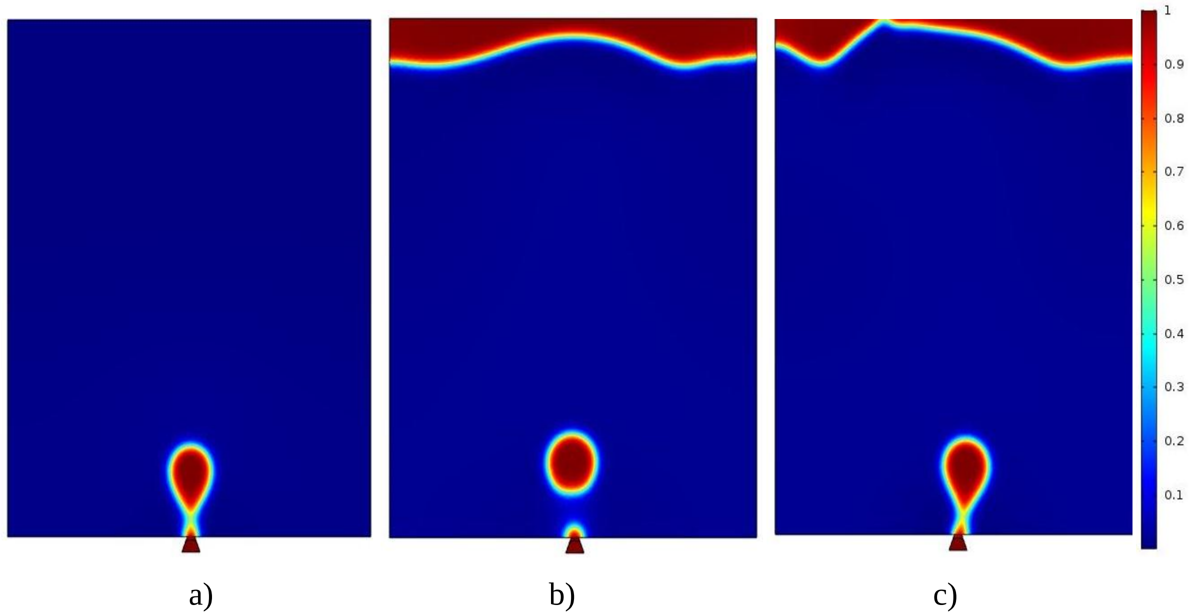
Figure 4. Bubble augmentation from V Cavity at time a) 0.5 s b) 1.28 s c) 1.92 s



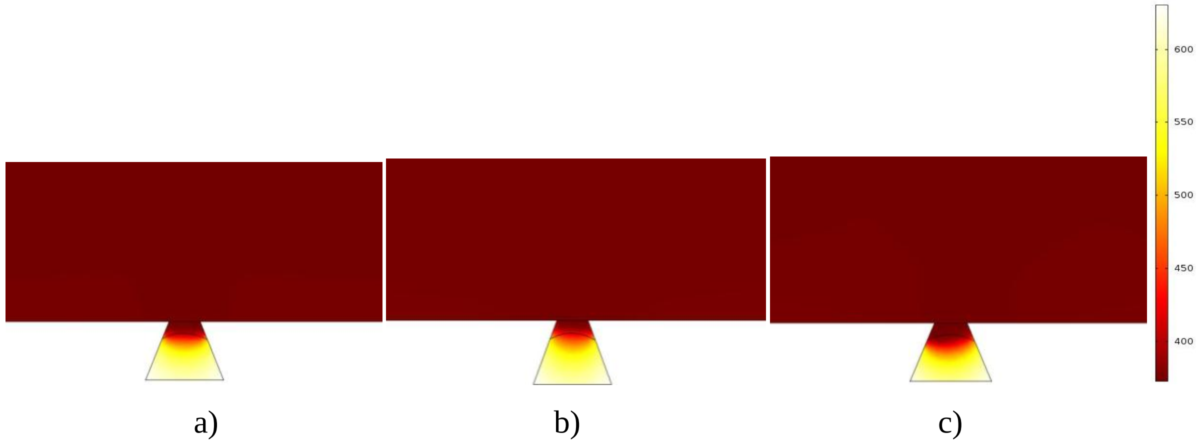
a) b) c)

Figure 5. Temperature variation in V cavity at time a) 0.5 s b) 1.28 s c) 1.92 s



a) b) c)

Figure 6. Bubble augmentation from Trapezoidal Cavity at time a) 0.59 s b) 1.15 s c)1.4 s



a) b) c)

Figure7. Temperature variation in rectangular cavity at time a) 0.59 s b) 1.15 s c)1.4 s

Boiling, by nature is extremely sensitive to the input parameters. For example, lowering the heat flux will not lead to bubble inception and for higher flux will lead to jet formation after some bubble inception. The shedding of vapour bubble for various cavities is shown in Figure 8. For Rectangular and V micro cavity first bubble begin to shed approx after same time about 0.5 seconds while for trapezoidal it begins later . Bubble inception, growth and departure are quite similar for Rectangular and V micro cavity whereas in case of Trapezoidal cavity it occurs later.

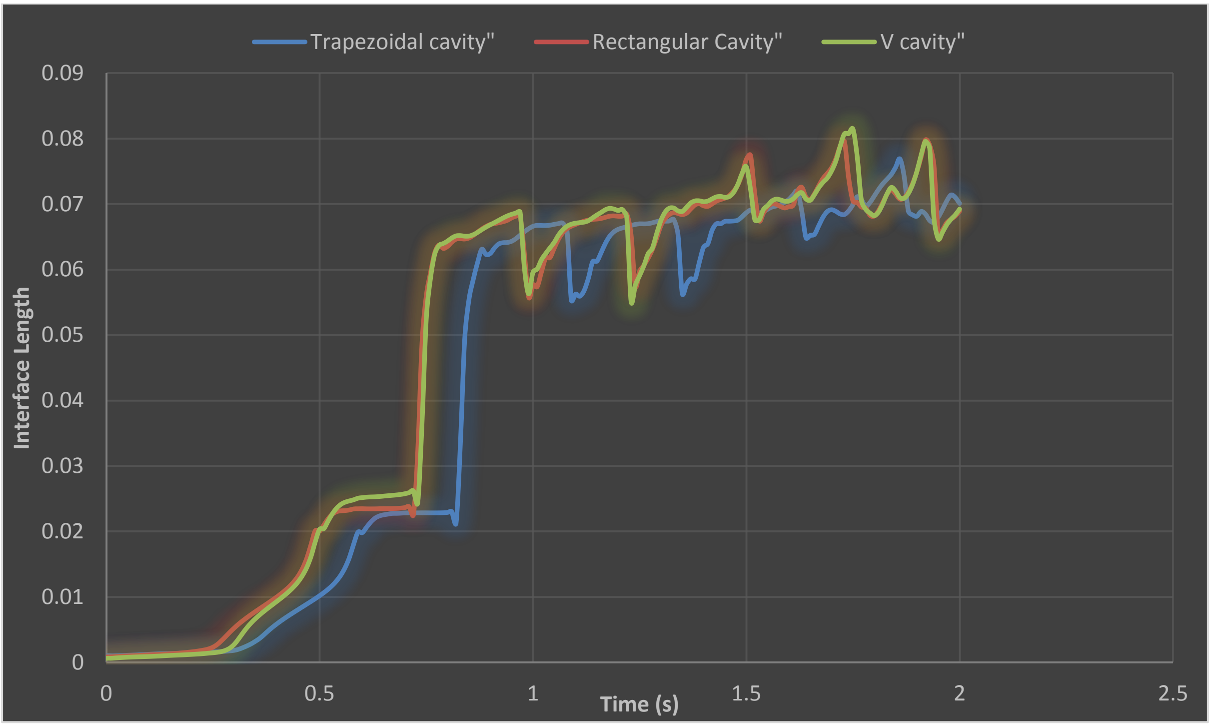


Figure8. Plot of interface length v/s time for comparing shedding frequency of vapour bubble

In this study constant heat flux $10^4 W/m^2$ is provided to the vapour entrapped surface and tried to find out the effect of different surface condition on heat transfer by calculating heat transfer coefficient for each case. We are getting peak for heat transfer coefficient at the time when bubble is getting detached .Figure 9 shows the comparison of heat transfer coefficient for the three cavities. For Trapezoidal cavity bubble departure is quite difficult initially than other two cavity as because it capture more volume of vapour entrapped for the same opening and height .This may be the reason for giving low peaks for initial bubble departure, While for rest two cavity rectangular micro cavity is leads to somewhat faster bubble inception and almost same heat transfer.

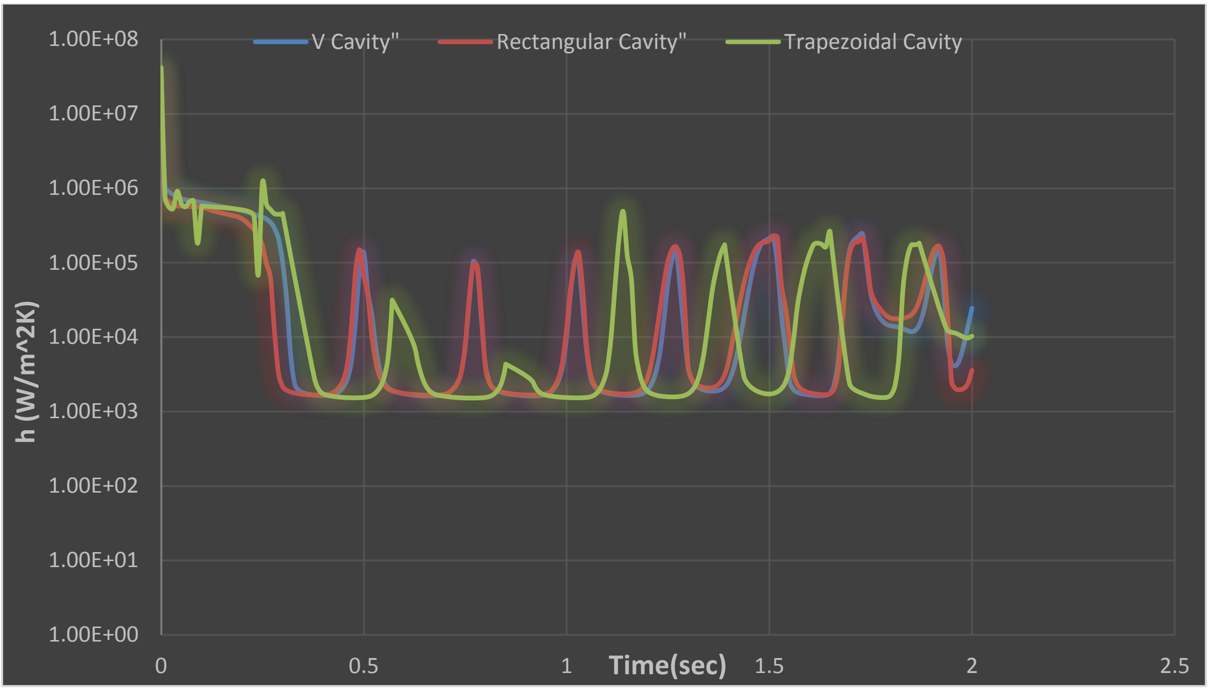


Figure9. Plot for heat transfer coefficient v/s time for different cavity

5. CONCLUSION

In order to investigate the effect of various cavity shapes on pool boiling heat transfer different artificial micro cavity has been analysed of same width and height with constant heat flux is modelled in 2D with transient study using multi physics laminar two- phase flow, phase field interface, heat transfer in CFD software COMSOL and track the liquid vapour interface and bubble trajectories for 2 sec continuously for each modified surface. Along with it temperature variation has been visualised at every time step throughout the domain. Also, study of bubble shedding frequency and variation of heat transfer coefficient with time has been done. On the basis of these analysis following points can be concluded**:**

1. Bubble gets detach faster in rectangular micro cavity than other with same dimensional and heat flux condition. Delay in bubble detachment in Trapezoidal cavity might be because of initially more vapour entrapped in the cavity which is taking time to come out from the cavity.
2. Shedding of bubble is quite similar for V and rectangular micro cavity for same heat flux condition. Also, Trapezoidal cavity can give faster shedding of bubble for higher heat flux as it has more initially vapour volume entrapped. The shedding frequency of vapour bubbles is periodic.

3. Enhancement in heat transfer can be visualise from Figure 9 for all the artificial micro cavity surface. There is sudden increment in heat transfer coefficient for the three cases as the bubble departed which is showing that heat is being transferred by convection with vapour augmentation with lesser value of temperature difference at that time.

4. Rectangular and V cavity is found to be more effective for bubble formation in nucleate boiling compared to the Trapezoidal types of cavity for constant width ,height and heat flux condition.

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