An M-Tech research report

on

PREDICTION OF BUBBLES AND DROP DYNAMICS UNDER DIFFERENT FLOW SITUATIONS AND PHASE CHANGE: LATTICE BOLTZMANN STUDY

In partial fulfilment of the requirement for the degree

of

Master of Technology

in

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(Thermal Engineering Specialization)

by

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National Institute of Technology Rourkela

CERTIFICATE

This is to certify that the report entitled "PREDICTION OF BUBBLE AND DROP DYNAMICS UNDER DIFFERENT FLOW SITUATIONS AND PHASE CHANGE: LATTICE BOLTZMANN STUDY" submitted to the National Institute of Technology, Rourkela by Shahnawaz Ahmed, Roll No. 211ME3195 in partial fulfillment of the requirement for the degree of Master of Technology in Department of Mechanical Engineering with specialization in Thermal Engineering is a record of bona fide work carried out by him under my supervision and guidance.

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Date: 3 June 2013 **Place: Rourkela** **Shahnawaz Ahmed**

Contents

List of Symbols and Abbreviations

Symbols	Description
ρ	Density
u	Velocity
t	Time
Ω	Collision operator
τ	Relaxation parameter
f	Distribution function
e	Lattice velocity
w	Weights associated with direction
n	Total number density
φ	Number density difference
θ_m	Mobility
μ_φ	Chemical potential
$\dot{\varphi}$	Phase change parameter
C_{pl}	Specific heat at constant pressure
h_{fg}	Latent heat
λ	Thermal conductivity
d_e	Initial diameter
U_2	Velocity of the bubble
U_c	Velocity of the surrounding fluid
U_t	Terminal Velocity
H	Breadth of the rectangular domain
ΔV	Change in Volume
V_0	Original Volume
T_h	Boiling temperature
T_l	Saturation temperature
LBM	Lattice Boltzmann Method
FVM	Finite Volume Method
VOF	Volume of Fluid

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Abstract

This paper deals with a numerical investigation about the bubble and drop dynamics under different flow situation and phase change process. Lattice Boltzmann Method (LBM) is used to discretize the governing equations for each of the flow situation related to drop or bubble. Three different cases are simulated related to bubble dynamics. Among them two are about the deformation of bubble in liquid medium with different flow conditions. In the 1st case, the bubble is subjected to flow parabolic velocity profile and in the 2nd case, the bubble is subjected to flow with linear velocity profile. The third one is related to the phase changes. In this case, a superheated bubble is placed in a surrounding of saturated liquid. Only one case is studied about the drop dynamics in which a water drop is placed in a rectangular horizontal channel with air medium subjected to parabolic velocity profile at inlet. In the present investigation, three separate probability distribution functions are used in LBM to handle continuity, momentum and energy equations separately. The interface between the two phasesis considered to be diffused within a narrow zone and it has been modelledwith convective Cahn-Hillard equation. Combined diffused interface-LBM framework is adapted accordingly to handle complex interface separating two phases having high density ratio.

Keywords:- Lattice Boltzmann Method (LBM), Deformation Angle, Shear Rate, Jacob Number, Peclet Number.

Chapter 1 INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

Multiphase flow plays a crucial role in many areas of technical importance. A lot of numerical works have been reported to study the interfacial dynamics of the bubble in liquid ambient. But still a proper description of interfacial behaviour of a gaseous bubble under different magnitudes of superheats is not clearly established.

Association of two different phases is very common to us in daily life and different industrial processes. Its range starts from sloshing in the naïve kitchen sink to filling of oil tank in sophisticated racing cars. Few applications of two phase flow are depicted in Figure 1. Amidst of wide range of application of two phase flow, simplest but frequently observed forms are gaseous bubbles and liquid drops. Behavior of such elemental assemblage of two different phases can also be difficult to predict under the action of different influences. Researchers (Bhaga and Weber, 1981; Bozanno and Dente, 2001) are continuously trying to analyze the underlying physics behind the dynamics of drops and bubbles. Influences like pressure driven flow, shear flow and buoyancy over the shape and mobility of bubbles and drops are pretty interesting to investigate.

Experimental observation is the best way to study the interfacial shape of bubble and drop. But as the instrumentation for measurement of two phase flow parameters are not well developed and standardized, experimental effort is a costly affair. On the other hand, analytical solution of complex interfacial behavior is quite difficult starting from the first principle of fluid mechanics.

As an alternative, numerical efforts are becoming very popular in research on bubbles and drops. Researchers have made efforts to address bubble/drop behavior using numerical tool and developed algorithms in order to predict instantaneous interface locations. In recent years computational fluid dynamics has gained importance in the field of two phase simulations saving lots of resources and time which otherwise would have been wasted on destructive testing. Software packages like *Fluent, Gerris, Blender, Flow-3d etc* has accommodated two phase flow as a subject. These packages use finite volume method to solve *Navier-Stokes* Equation and continuity Equation. Interfaces are treated either as homogeneous mixture model or well defined volume of fluid methodology. Both the methodologies are successful in predicting the dynamics of the interfaces in their respective periphery. However two phase finite volume method has its own disadvantage as irregular geometries and complex interfaces takes up considerable computing resources.

Researchers continued their search for alternate methodologies that can tackle the interfacial physics properly. Two separate branches evolve subsequently as mesoscopic and microscopic two phase flow. Sophisticated technologies like molecular dynamics and dissipative particle dynamics gained reputation in predicting small scale bubble and drop behavior. On the other hand, bulk mobility of drops are bubbles attracted attention of different researchers who used smoothed particle hydrodynamics and lattice Boltzmann methodologies as tool. Out of different methodologies, lattice Boltzmann technique seems to be most robust and showed fair predictability in different two phase thermo-physical problems.

(a)

(b)

(c)

Figure 1.1: Different multiphase flow a) dam on Krishna river b) swimmer in a pool c) sand storm

Lattice Boltzmann method has been developed by different researchers over the past fifteen years for the computer simulation of two phase fluid dynamics. This method does not involve the complexities of ‘microscopic’ molecular dynamics method nor does have to overlook the small scale physics with the simplicity of ‘macroscopic’ finite volume method. Lattice Boltzmann thus is ‘mesoscopic’ in nature and has the advantage of both but disadvantage of none. In a lattice gas model the `particles' are restricted to move on the links of a regular underlying grid and the motion evolves in discrete time-steps. The conservation laws are incorporated into update rules which are applied at each discrete time. The lattice gas model thus requires very less ‘space’ in terms of computational resources and also allows parallel computing. The Lattice Boltzmann method has been incorporated in many complex applications such as turbulence, multi-component and multi-phase flows as well as additional applications, including simulations of the Schrödinger equation. Hence it is needless to mention that dynamics of bubbles and drops can be well tackled using the versatile lattice Boltzmann methodology.

The lattice Boltzmann method (LBM) is derived from classical Lattice gas cellular automata scheme. The term “lattice gas cellular automata” was first coined by Frisch et al. in 1986. Development of such a model originated from the fact that due to its inherent microscopic origin, the model is expected to have a broader and complex range of applications than the macroscopic Navier Stokes equations. The microscopic simulation can essentially provide more detailed information about the interfacial configuration that is important to reveal the underlying physics behind complex two phase flow behavior. Although a direct solution of the full Boltzmann transport equation will provide highest order microscopic details, it would be a rather mathematically cumbersome task, due to large number of dimensions of the distribution functions and complexities in the collision integral. As a compromising alternative, it has been assumed that the movements of two phase fluid particles are restricted only in few assigned directions depending on the lattice structure. This leads to the concept of discrete velocity in lattice directions and subsequently lattice Boltzmann method evolves. The idea behind lattice Boltzmann method is to amplify the macroscopic picture of the Navier–Stokes framework by utilizing discrete sets of probability distribution functions along the prescribed lattice directions.

The Lattice Boltzmann Model considers a typical volume element of fluid to be composed of a collection of particles that are represented by a particle velocity distribution function for each fluid component at each grid point. The time is counted in discrete time steps and the fluid particles can collide with each other as they move, possibly under applied forces. The rules governing the collisions are designed such that the time-average motion of the particles is consistent with the *Navier-Stokes* equation. During the propagation of information local collision, translation and reaction rules between the lattices will come into picture. Eventually these interactions effectively simulate many microscopic effects occurring in a real two phase fluid flow in the basis of mesoscopic configurations.

To replicate the interfacial behavior lattice Boltzmann adopts different methodologies like color method, free energy method and potential method depending on the nature of the interfacial behavior. In the next section brief review of all the methodologies of two phase lattice Boltzmann method is described. Recently, to represent complex dynamics, the interface is considered to be a thin but diffused region where properties shifts from one phase to the other smoothly without causing discontinuities across. Applications of diffused interface based lattice Boltzmann method are mainly towards the upcoming technological fields like microfluidics, atmospheric research etc. Hence, it can be commented that for simulation of two phase drop/bubble dynamics diffuse interface based lattice Boltzmann methodology is the best possible option. In the next section, a brief literature review about different drop and drop related phenomena are reported. A brief history of the computational methodologies for two phase flow is also documented. Stresses are given to mention different interfacial options for lattice Boltzmann method in replicating two phase flow simulations.

1.2 Literature Review

Nowadays bubble dynamics has garnered considerable attention due to the fact that it is encountered in many industrial applications especially in the pipelines of oil refinery and nuclear reactors. Many researchers have contributed substantial literature pertaining to its study for the past fifty years both on experimental and theoretical basis.

As early as 1981, Bentley and Leal studied the deformation of fluid droplets in steady linear, two-dimensional motion of a second immiscible fluid using a computer controlled, four-roll mill. In recent past, Guido et al. (2003) used video-enhanced microscopy and image analysis on drop deformation under shear flow and found that drop orientation towards the shear direction is directly linked to normal stresses in the matrix fluid. Experimental efforts for different drop and bubble related dynamics are still on and fetch important information related to the underlying physics behind the complex interfacial dynamics. On the other hand, numerical results were obtained for upto twelve drops using a three-dimensional computer simulation of a concentrated emulsion in shear flow under low Reynolds number and finite capillary number conditions by Loewenberg and Hinch in 1996. Their numerical observations reveal a complex rheology with pronounced shear thinning and large normal stresses that is associated with an anisotropic microstructure that results from the alignment of deformed drops in the flow direction. Badalassi and Ceniceros (2003) developed a time-split scheme to solve the coupled Cahn-Hilliard/Navier-Stokes system, known as Model H to study drop deformation under shear flow.

However, the numerical scheme used by the researchers mostly were singular interface model in which the grid was limited so as not to be fit to bubble large deformation in topology, such as coalescence and breakup of the model. In such a situation the diffuse interface model or phase field method were proposed to recover the defect in interfacial configuration. Renardy and Cristini (2001) applied Volume of Fluid method to study the effect of inertia on drop break up by shear. As per their study, a drop initially oscillates, then elongates and finally experiences a higher shear which divides it into two daughters.

But Volume of Fluid method is quite complicated in 3D and also little information were provided about the vapor bubbles behavior with phase change and propagations of physical fields around a growing and deforming vapor bubble. Researchers likewise developed new algorithm which would tackle the multiphase flow and heat transfer simultaneously. Griggs et al. (2007) developed a boundary-integral algorithm that employs the Green's function for the domain between two infinite plane walls, which incorporates the wall effects without discretization of the walls in 2006 and concluded that with increasing capillary number, the drops become more deformed and have larger steady velocities due to larger drop-to-wall clearances.

The demerits of Volume of Fluid method in predicting complex interfaces are eliminated in mesoscopic lattice Boltzmann method. Several approaches from Shan and Chen (1993); Swift et al. (1995); Gunstensen and Rothman (1998) have been proposed to model interfacial dynamics in two-phase flow using LBM. One of the earliest multi component model is developed by Rothman and Keller (1988) using color method. They have used two different particle distribution functions to represent two phases. Later Shan and Chen (1993) have used potential method to simulate two-phase flow. However, these are phenomenological models. Swift et al. (1996) made an improvement in the model by suggesting a free energy approach. In this model, the equilibrium distribution is defined based on thermodynamics and conservation of energy is satisfied. Lee and Lin (2005) developed a stabilized scheme of discrete Boltzmann equation for multiphase flows with large density ratio. However, it does not completely recover the lattice Boltzmann equation for interface to Cahn–Hilliard equation. On the other hand, large density ratio between the fluids can cause numerical instability. To overcome this difficulty, Inamuro et al. (2002) proposed a model, based on the free energy method for multiphase flows with large density ratio. In a recent study by Zheng et al. (2006), another model for large density ratio of two fluids has been proposed. In their model the lattice Boltzmann equation for interface recovers Cahn-Hilliard equation. They have modeled bubble dynamics for different range of associated non-dimensional parameters.

The change of phase introduces additional intricacy in two phase hydrodynamics. Firstly, the mass of an individual phase is not conserved. Secondly, the evolution of the interface depends on the conjugate effect of local hydrodynamics and the process of phase change. The computational simulation of the two phase flow with phase change poses a significant challenge. Lattice Boltzmann method is also capable of tracking heat transfer phenomena successfully. Dong et al. (2010) developed an improved hybrid Lattice Boltzmann method to study the bubble growth from a superheated wall. To discretize the heat transfer equation they have introduced a third probability distribution function in accordance with the source term due to phase change. Hence, lattice Boltzmann method shows a wide range of application in the field of bubble and drop dynamics. A summary of the survey of literature is presented next.

1.3 Gaps in the Literature

Though the volume of the literature on the computational modeling of two phase flow is growing very rapidly, one can readily identify a number of shortcomings in the existing literature which need immediate attention from the researchers. The following points are worth mentioning which highlights the reviewed literature:

1. Study of bubble dynamics, even a single bubble is complex and the complexity increases exponentially if we consider phase change and deformation.
2. Numerical Schemes developed like volume of fluid and FVM had their own demerits like uneconomical computational resources, low accuracy and inability to handle complex interfaces.

Lattice Boltzmann Method can overcome all the problems mentioned above. Combined with the diffused interface concept, the hybrid methodology can well tackle the bubble and drop deformations. Lattice Boltzmann model can also tackle phase change processes. Thermal lattice Boltzmann method tracks the combined mode heat transfer problem along with the heat transfer problems.

1.4 Aim and objectives

Taking queue from the observed shortcomings, few topics have been selected for the present project. Lattice Boltzmann Method is used to study bubble and drop dynamics under different case scenario which includes phase change. The following points describe the objectives of the present work:

1. Study of drop/bubble deformation with parabolic velocity profile between two plates.
2. Investigation of bubble deformation under shear flow.
3. Study of bubble dynamics under phase change.
4. Deformation of drop placed over a surface due to incoming stream

1.5 Organization of Thesis

The present dissertation is organized using five different chapters. In Chapter 1 (the present chapter), at first an introductory knowledge and brief history about LBM have been given. The importance of the selected problems have been described and then an extensive literature review on the earlier work done about bubble dynamics under different slow situations with and without heat transfer have been performed. Chapter 2 contains the detailed mathematical formulation of LBM together with the physics involved in LBM. Explanations of the governing equations and its formulation under different conditions have also been mentioned here. Chapter 3 concentrates on the description/formulation of different problems that have been solved using Lattice Boltzmann method in the present thesis. Chapter 4 focuses on the obtained results. It also includes the important discussions behind obtained results. Chapter 5 summarizes the important findings and main conclusions drawn from the present study. Future scopes for the present work have also been mentioned in this chapter.

Chapter 2 Mathematical Formulation of LBM

This section explains the basic principle behind Lattice Boltzmann Method Formulation. The Lattice Boltzmann Model considers a typical volume element of fluid to be composed of a collection of particles that are represented by a particle velocity distribution function for each fluid component at each grid point. The time is counted in discrete time steps and the fluid particles can collide with each other as they move, possibly under applied forces. The rules governing the collisions are designed such that the time-average motion of the particles is consistent with the *Navier-Stokes* equation.

2.1 Basic Model

Here a distribution function f(x, ξ, t) is used to describe the macroscopic variables like density (ρ), velocity (u) and internal energy (ε) as follows:

$$\rho = \int f \, d\xi \tag{1}$$

$$\rho u = \int f \;\; \xi \, d\xi \tag{2}$$

$$\rho\varepsilon = \frac{1}{2}\int (\xi - u)^2 \, f \, d\xi \tag{3}$$

f(x, ξ, t) is defined such that f(x, ξ, t)dxdξ is the number of molecules at time t positioned between x and x+dx which have velocities in the range ξ→ ξ+dξ. The collision operator Ω*(f)* is designed based on the assumption that the gas has low density so that only binary collisions can be considered. Its expression is given below:

$$\Omega(f) = -\frac{f(x,\xi,t) - f^{eq}(x,\xi,t)}{\tau} \tag{4}$$

Where τ is the relaxation time and $f^{eq}(x, \xi, t)$ is the Maxwell-Boltzmann equilibrium distribution function. This model is commonly known as *Bhatnagar-Gross-Krook* model or BGK model. The Lattice Boltzmann Equation (LBE) is directly derived from equation (4) and is written in the form of an ordinary differential equation as follows:

$$\frac{df}{dt} + \frac{1}{\tau} f = \frac{1}{\tau} f^{eq} \tag{5}$$

Where $\frac{d}{dt} \equiv \frac{\partial}{\partial t} + \xi \cdot \Delta$

In this paper we have used 2 dimensional 9 directional LBE model (d2q9) with the following set of discrete velocities and weight coefficients (refer to the figure below).

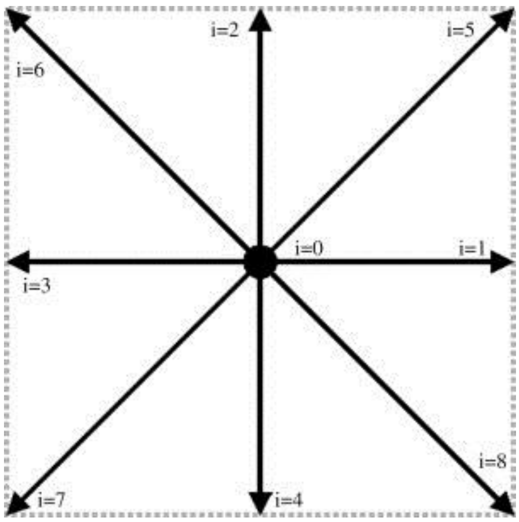


Figure 2.1: D2Q9 Model

Lattice Velocities:

$e_0 = 0$

$e_{1,3} = (\pm 1, 0).c$

$e_{2,4} = (0, \pm 1).c$

$e_{5,6,7,8} = (\pm 1, \pm 1).c$

(where $c = \sqrt{3RT}$ R = Universal Gas Constant and T = Temperature)

Weights associated with direction:

$w_0 = \frac{4}{9}$

$w_{1,2,3,4} = \frac{1}{9}$

$w_{5,6,7,8} = \frac{1}{36}$

It is clear that $\sum_0^8 w_i = 1$

2.1.1 Dynamic Model

Zheng *et al*, defined two independent macroscopic parameters n and φ for modeling the two distinct phase as follows:

$n = \frac{\rho_{h+}\rho_l}{2}$ and $\varphi = \frac{\rho_{h-}\rho_l}{2}$

n is approximately constant throughout the flow field and φ becomes positive in the region where $\rho_h > \rho_l$ and negative where $\rho_h < \rho_l$ representing the two phase effectively.

The governing equations of the flow are suitably modified to fit in different phases:

- Continuity Equation

$$\frac{\partial n}{\partial t} + \nabla(nu) = 0 \tag{6}$$

- Navier-stokes Equation

$$\frac{\partial n}{\partial t} + \nabla(nuu) = -\nabla P + \mu\nabla^2 u + F_b \tag{7}$$

Where u is the velocity of the fluid, P is the pressure tensor and F_b is the body force. Another equation is introduced to describe the physics involved in the interfaces of the two components.

- Cahn-hillliard Equation

$$\frac{\partial \varphi}{\partial t} + \nabla(\varphi u) = \theta_m \nabla^2 \mu_\varphi \tag{8}$$

Where μ_φ and θ_m is the chemical potential and mobility respectively and is given by-

$$\mu_\varphi = A\left(4\varphi^3 - 4\overline{\varphi^2}\cdot\varphi\right) - K\nabla^2\varphi$$

$$\theta_m = q\left(\tau_\varphi q - 0.5\right)\delta\Gamma$$

$$q = \frac{1}{\tau_\varphi + 0.5}$$

Two distribution function f_i and g_i are introduced where f_i is used to model the mass and momentum transfer and g_i is used to track the interface such that

$n = \sum f_i^{eq}$ and $\varphi = \sum g_i^{eq}$

The expressions of the distribution functions are given as following:

$$f_i(x + e_i\Delta t, t + \Delta t) - f_i(x,t)$$

$$= \frac{1}{\tau_n}[f_i(x,t) - f_i^{eq}(x,t)] + \left(1 - \frac{1}{2\tau_n}\right)\frac{w_i}{c_s^2}\left[(e_i - u) + \frac{e_i \cdot u}{c_s^2}e_i\right]\left(\mu_\varphi + F_b\right)\delta_t \tag{9}$$

$$g_i(x + e_i\Delta t, t + \Delta t) - g_i(x,t)$$

$$=(1-q)[g_i(x + e_i\Delta t, t) - g_i(x,t)] - \frac{1}{\tau_\varphi}[g_i(x,t) - g_i^{eq}(x,t)] \tag{10}$$

The equilibrium condition of the distribution function is described below:

$$f_i^{eq} = w_i\rho\left[1 + \frac{3(e_i \cdot u)}{c^2} + \frac{9(e_i \cdot u)^2}{2c^4} - \frac{3u^2}{2c^2}\right]$$

$g_i^{eq} = A_i + B_i\varphi + C_i\varphi e_i \cdot u$ (Based on D2Q5)

τ_n and τ_φ are the dimensionless relaxation parameter and depends on the properties of the material used.

$A_1 = -2\Gamma\mu_\varphi$

$B_1 = 1$, $B_i = 0$ $(i \neq 1)$

$C_i = \frac{1}{2q}$

2.1.2 Thermal Model

Inamuro et al. introduced another distribution function h which models the temperature variation based on energy equation.

$$h_i(x + e_i\Delta t, t + \Delta t) - h_i(x,t) = -\frac{1}{\tau_t}[h_i(x,t) - h_i^{eq}(x,t)] \quad (11)$$

Where $h_i^{eq}(x,t) = w_i T(1 + 3e_i \cdot u)$

Another parameter, $\dot{\varphi}$ is introduced which captures the phase change dynamics. It can be derived from the energy equation and its expression is given below:

$$\frac{\rho_h}{\rho_l}\frac{Ja}{Pe}\left(\frac{\partial^2 T}{\partial x^2}\right) = -\frac{\dot{\varphi}}{\rho_h - \rho_l}$$

To include the phase change, equation-10 is rewritten as

$$g_i(x + e_i\Delta t, t + \Delta t) - g_i(x,t)$$
$$= (1-q)[g_i(x + e_i\Delta t, t) - g_i(x,t)] - \frac{1}{\tau_\varphi}[g_i(x,t) - g_i^{eq}(x,t)] + w_i\dot{\varphi} \quad (12)$$

$$h_i(x + e_i\Delta t, t + \Delta t) - h_i(x,t) = -\frac{1}{\tau_t}[h_i(x,t) - h_i^{eq}(x,t)] + w_i \frac{\rho_l}{\rho_h(\rho_h - \rho_l)}\frac{\dot{\varphi}}{Ja} \quad (13)$$

Here Ja and Pe are Jacob Number and Peclet Number respectively and are given as follows:

$$Ja = \frac{C_{pl} \cdot \Delta T}{h_{fg}}$$

$$Pe = \frac{\rho_h U_t d_e C_{pl}}{\lambda}$$

Where C_{pl} is the specific heat at constant pressure, h_{fg} is the latent heat, U_t is the terminal velocity, λ is the thermal conductivity and d_e is the initial diameter of the bubble.

Chapter 3 Problem Description

This chapter describes the different problems (related to bubble and drop dynamics under different flow situation and phase change process) that have been solved using Lattice Boltzmann method in the present thesis. Three different cases are simulated related to bubble dynamics. Among them two are about the deformation of bubble in liquid medium with different flow conditions. In the first case, the bubble is subjected to flow with parabolic velocity profile and in the second case, the bubble is subjected to flow with linear velocity profile. The third one is related to the phase change process. In this case, a superheated bubble is placed in a surrounding of saturated liquid. The fourth case is about the drop dynamics in which a water drop is placed in a rectangular horizontal channel with air medium subjected to parabolic velocity profile at inlet.

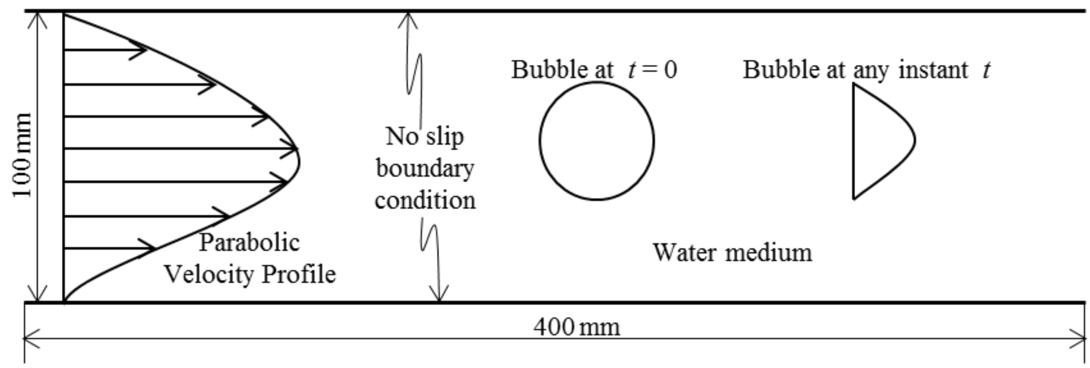


Figure 3.1: Bubble under parabolic velocity

3.1 Study of bubble deformation with parabolic velocity profile

The schematic diagram of this problem is shown in Figure 3.1. In this problem the dynamics of bubble is studied when its surrounding medium is subjected to a parabolic velocity profile at inlet. The surrounding medium between two plates is taken as water where lengths of the plates are 400 mm and distance between two plates is 100 mm. Size of bubble and velocity of the medium are varied and numerical snapshots is taken at uniform time interval.

3.2 Investigation of bubble deformation under shear flow

The schematic diagram of the problem is shown in Figure 3.2. In this case, the dynamics of bubble subjected to opposite but equal shear force on either side of the mid plane (parallel to plates) is studied where the length of each plate is 320 mm and distance between the plates is 120 mm. The velocity profile of the medium is such that the velocity of surrounding water is zero at the centre point between the plates and its magnitude varies linearly attaining maximum value near the plate. The direction of flow on either side of the centre point (between two plate) is opposite in direction. Both velocity of the medium and size of the bubble are varied to study their effect on the dynamics of bubble.

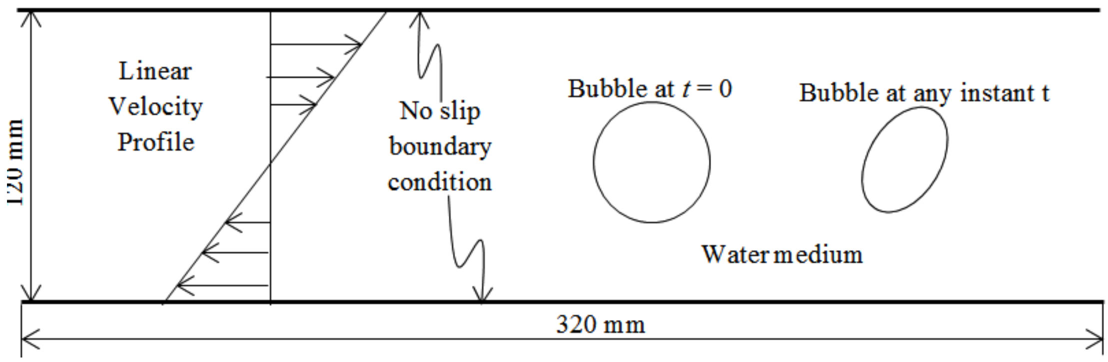
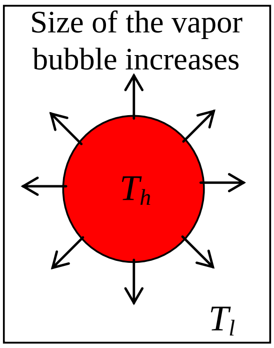


Figure 3.2: Bubble subject to shear force

3.3 Study of bubble dynamics under phase change process

The schematic representation of the present problem is shown in Figure 3.3. Here the dynamics of vapour bubble is studied under phase change process without considering the effect of buoyancy. The bubble is kept in a square channel (120 × 120 mm square domain) containing water at saturation temperature (100^{0}C). The temperature of the bubble is greater than that of the surrounding water. Both temperature of the bubble and its size is varied and numerical snapshots is taken at regular interval.



T_h > Boiling Temperature
T_l = Saturation Temperature
Figure 3.3: Bubble deformation due to phase change

3.4 Deformation of drop on a solid surface due to incoming stream:

The schematic diagram of the problem is shown in Figure 3.4. In this problem the dynamics of drop (placed on solid surface) is studied subjected to an incoming stream having parabolic velocity profile between two plates. The length of each of the plates is 400 mm and distance between them is 75 mm. Both size of the drop and velocity of the medium are varied and numerical snapshot is taken at uniform time interval.

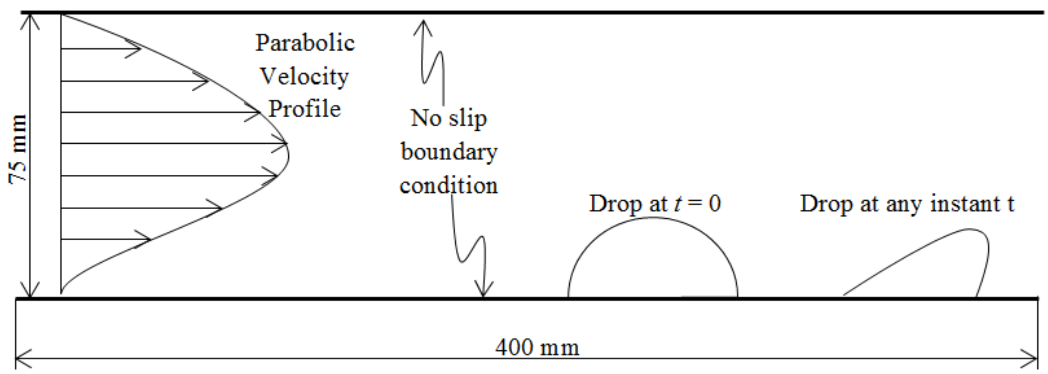


Figure 3.4: A drop placed on a solid surface subject to flow with parabolic velocity.

Chapter 4 Results and Discussion

This chapter explains the various results obtained by solving the problems explained in the previous chapter using Lattice Boltzmann Method. Various parameters such as radius of the bubble or drop as well as velocity of the surrounding medium are varied to study their effect on the respective dynamics. Numerical Snapshots have been extracted at uniform time intervals and have been tabulated as shown in the upcoming Figures. Obtained results and corresponding explanation are given below for each of the case study separately.

4.1 Study of bubble deformation with parabolic velocity profile

The problem is simulated taking the radius of the bubble as 15 mm, 25 mm and 35 mm. The velocity of the surrounding medium (water) is varied as 0.15 m/s, 0.3 m/s and 0.5 m/s. Numerical snapshots is taken at an uniform time interval of 0.4 seconds and are shown in Figure 4.1, 4.2 and 4.3 for the radius 15 mm, 25 mm and 35 mm, respectively.

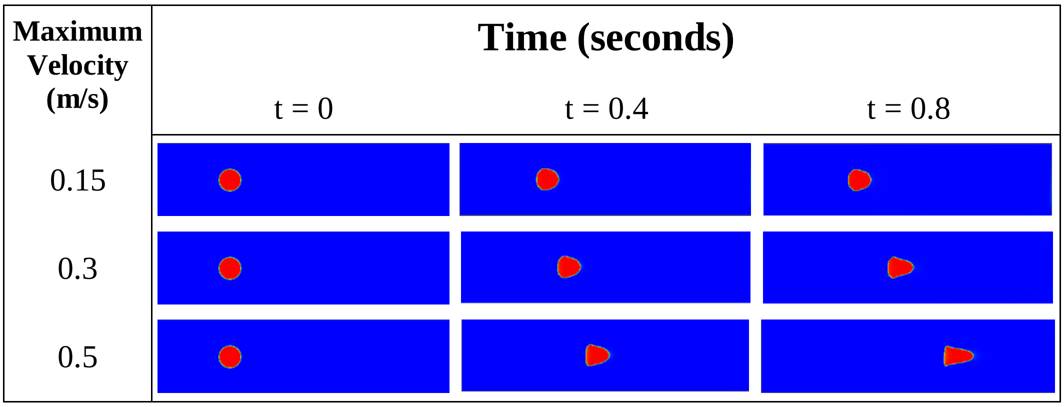


Figure 4.1: Deformation of bubble with radius 15 mm

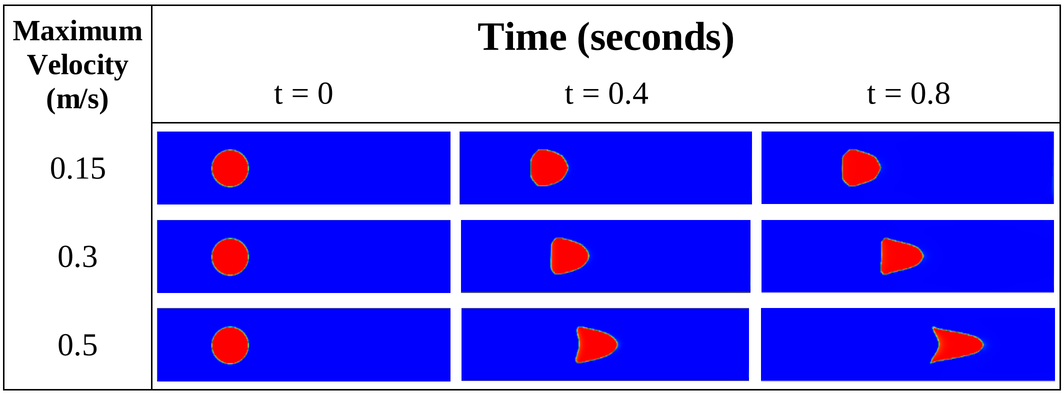


Figure 4.2: Deformation of bubble with radius 25 mm

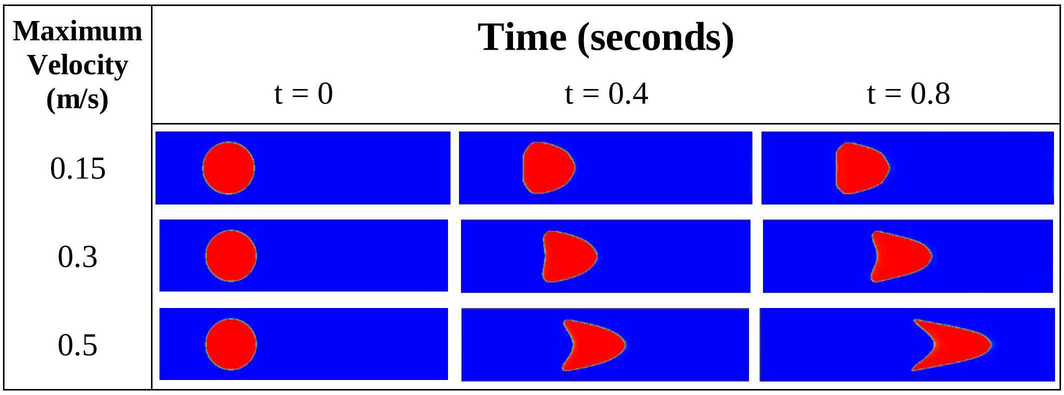


Figure 4.3: Deformation of bubble with radius 35 mm

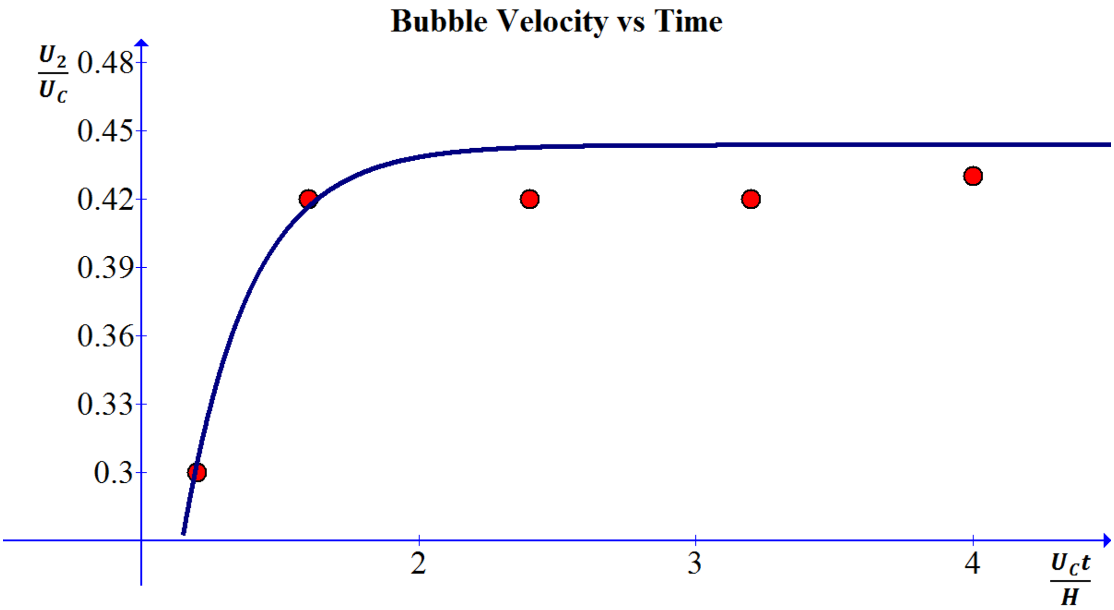


Figure 4.4: Velocity of bubble vs time for the bubble with radius 15 mm.

The variation of velocity of the bubble (with radius 15 mm) with time is shown in Figure 4.4. Here U_2/U_c is plotted along y-axis and $U_c t/H$ is ploted along *x*-axis where U_2 is the velocity with which the bubble moves in the medium, U_c is the maximum velocity of the surrounding medium, *t* is the time interval and *H* is the distance between the two plates.

4.2 Investigation of bubble deformation due to shear flow

In this case the problem is again simulated taking radius of the bubble as 15 mm, 25 mm and 35 mm. The maximum velocity of the surrounding medium (water) is varied as 0.15 m/s, 0.3 m/s and 0.5 m/s. Numerical snapshots is taken at an uniform time interval of 0.4 seconds and is tabulated as shown in Figure 4.5, 4.6 and 4.7 for radius 15 mm, 25 mm and 35 mm, respectively.

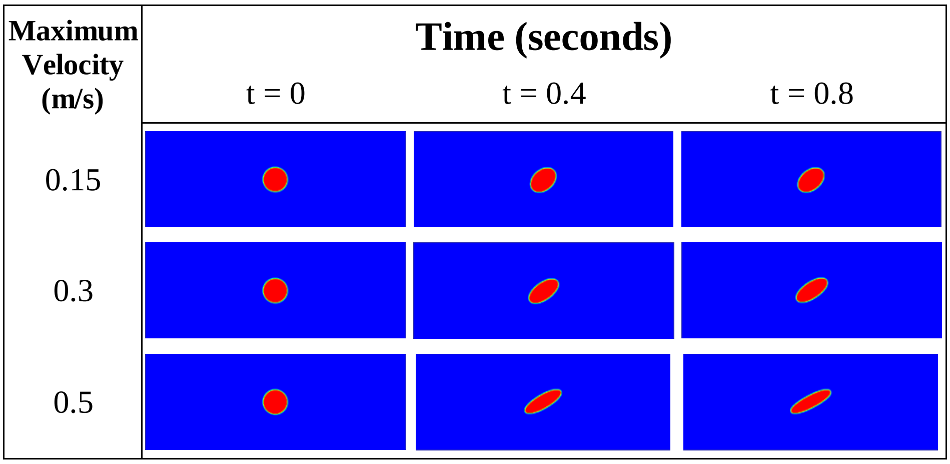


Figure 4.5: Shear deformation of a bubble with radius 15 mm

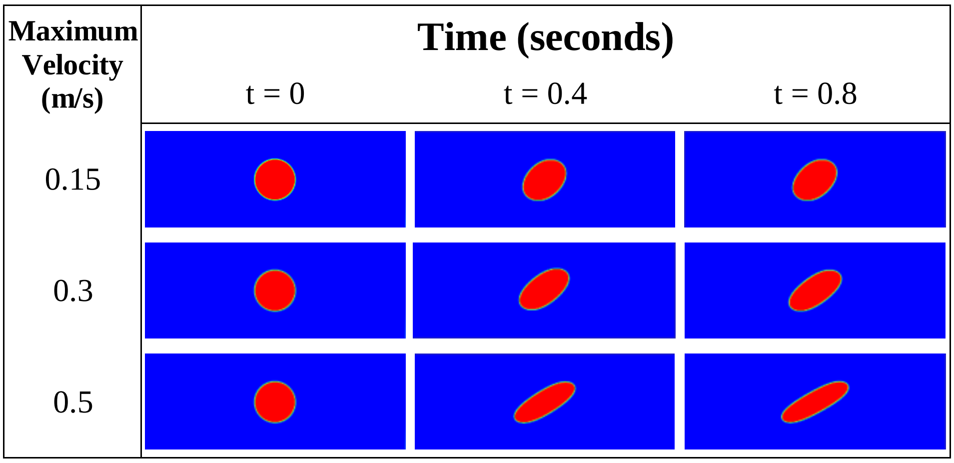


Figure 4.6: Shear deformation of a bubble with radius 25 mm

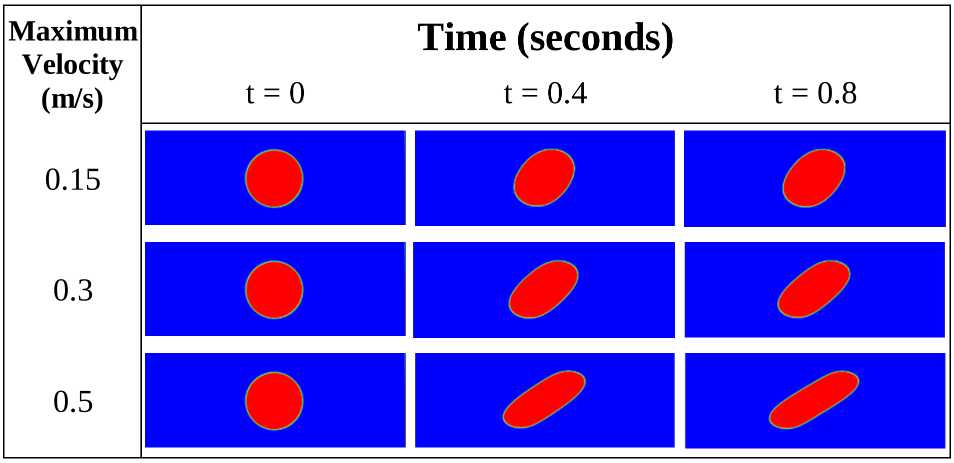


Figure 4.7: Shear deformation of a bubble with radius 35 mm

4.3 Study of bubble dynamics under phase change process

In this problem the radius of the bubble is varied as 15 mm, 25 mm and 35 mm. The temperature of surrounding water is taken as saturated temperature (100^0C) and temperature of the bubble is taken as superheated temperature. Three different case studies have been considered by varying as 150^0C (degree of superheat = 50^0C), 170^0C (degree of superheat = 70^0C) and 190^0C (degree of superheat = 90^0C). Numerical snapshots are taken at a uniform time interval of 0.8 seconds and are tabulated as shown in the Figure 4.8, 4.9 and 4.10 for the degree of super heat 50^0C, 70^0C and 90^0C, respectively.

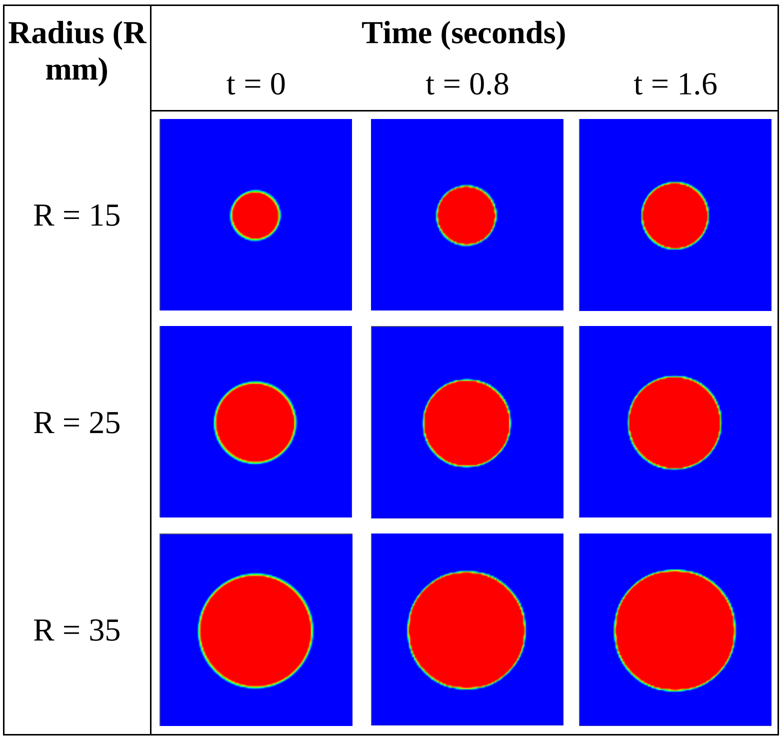


Figure 4.8: Dynamics of superheated bubble with degree of superheat 50^0C

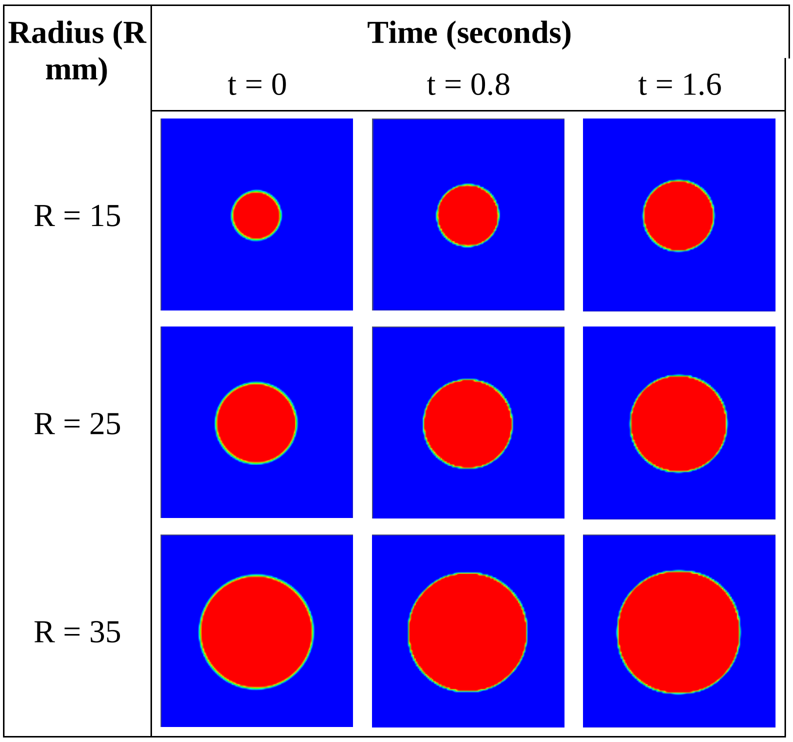


Figure 4.9: Dynamics of superheated bubble with degree of superheat 70^0C

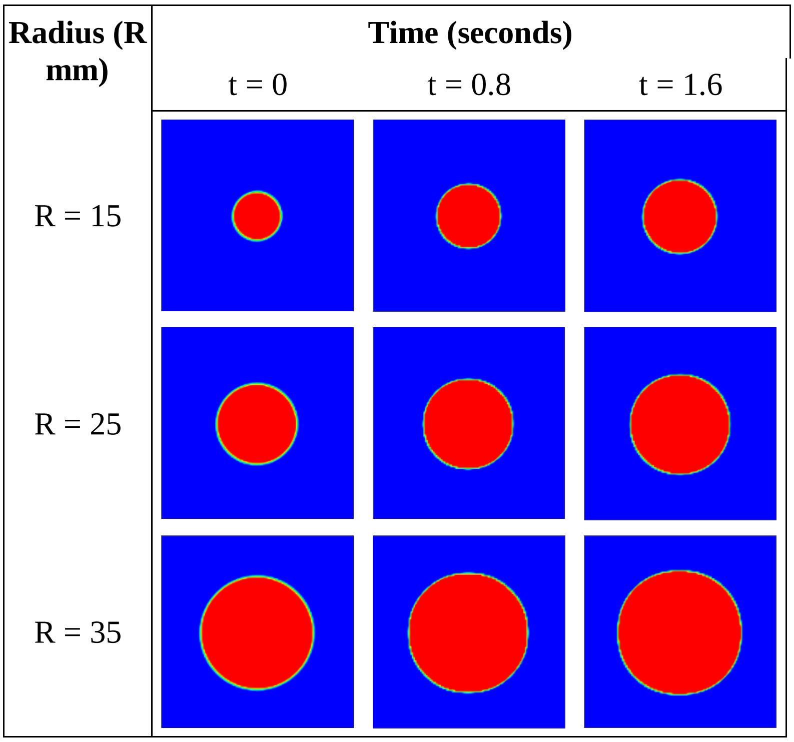
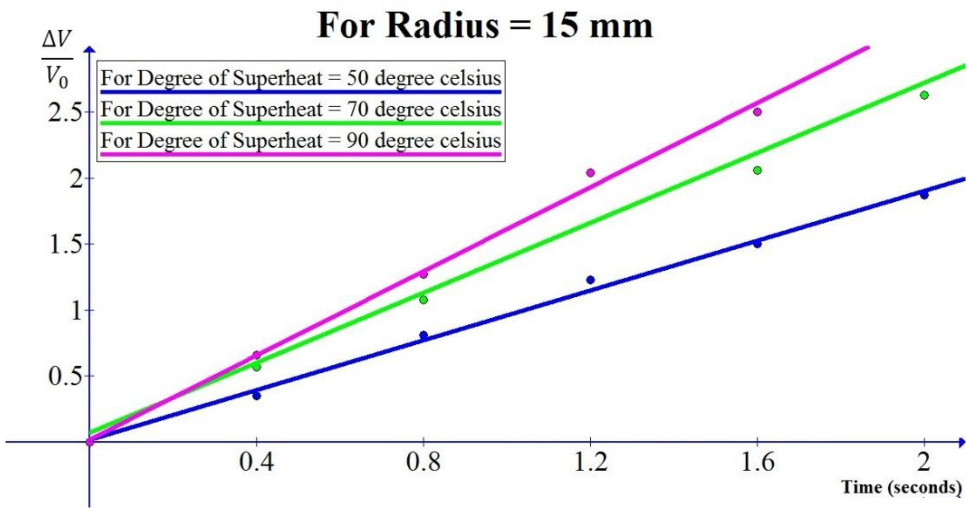
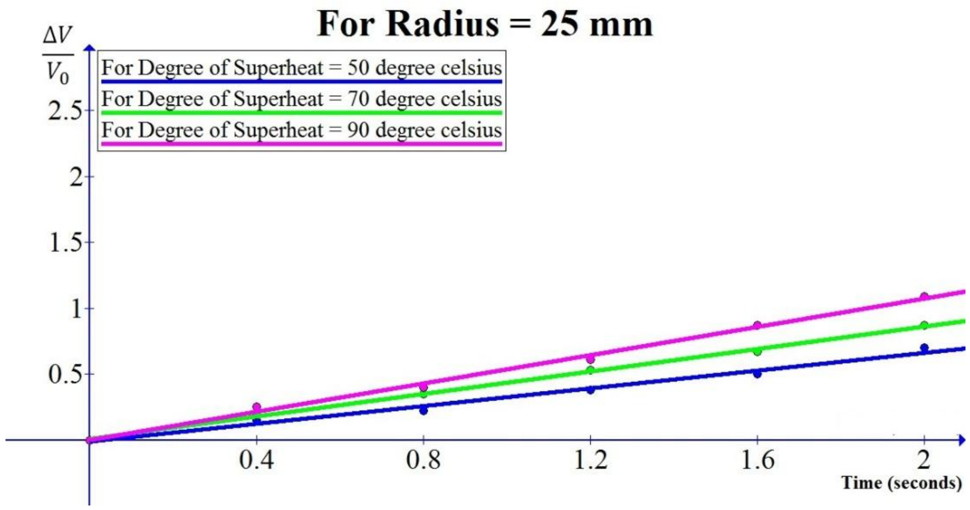


Figure 4.10: Dynamics of superheated bubble with degree of superheat 90^0C

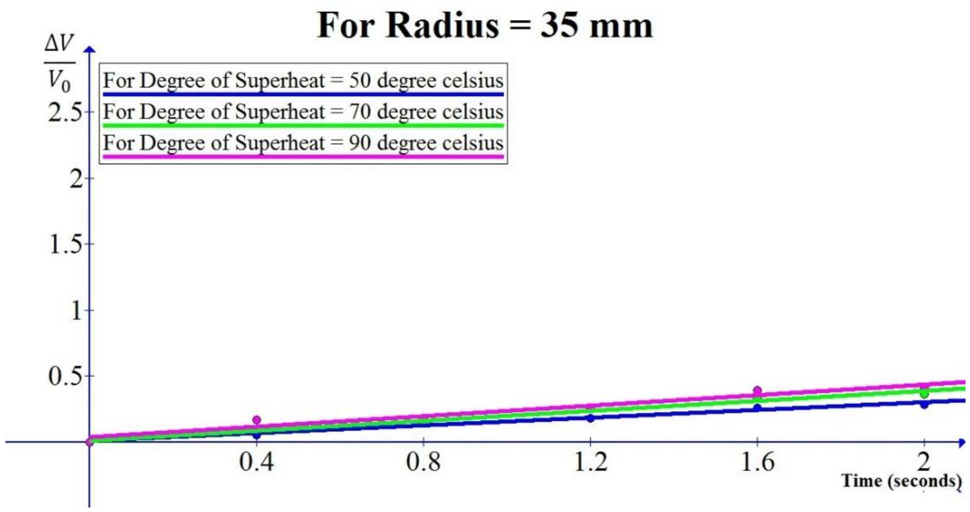
Next graph is plotted between $\Delta V/V_0$ and time where ΔV is the gain in volume of the bubble and V_0 is the initial volume of the bubble. Two types of graph is plotted, first the radius of the bubble is kept constant and degree of superheat is varied *i.e.* the temperature of the bubble is varied. Then degree of superheat is kept constant and radius of the bubble is varied.



(a)

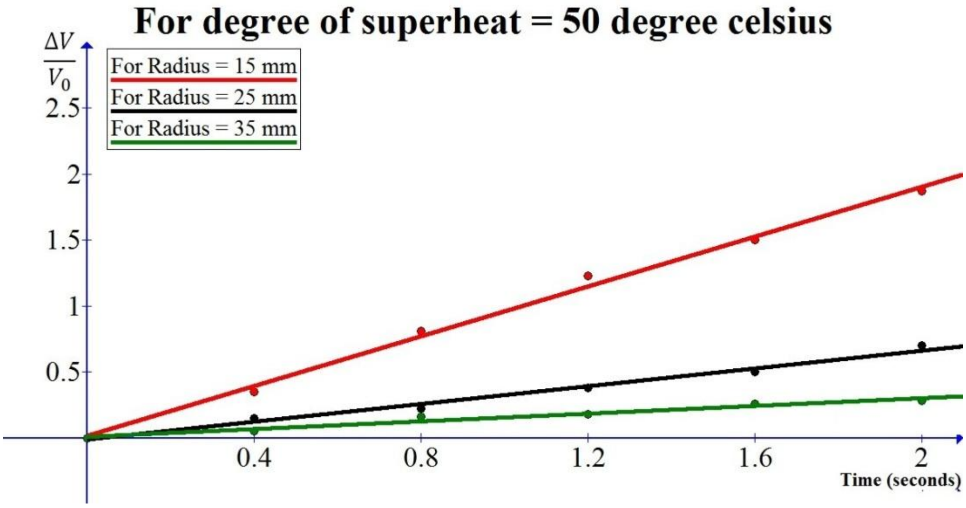


(b)

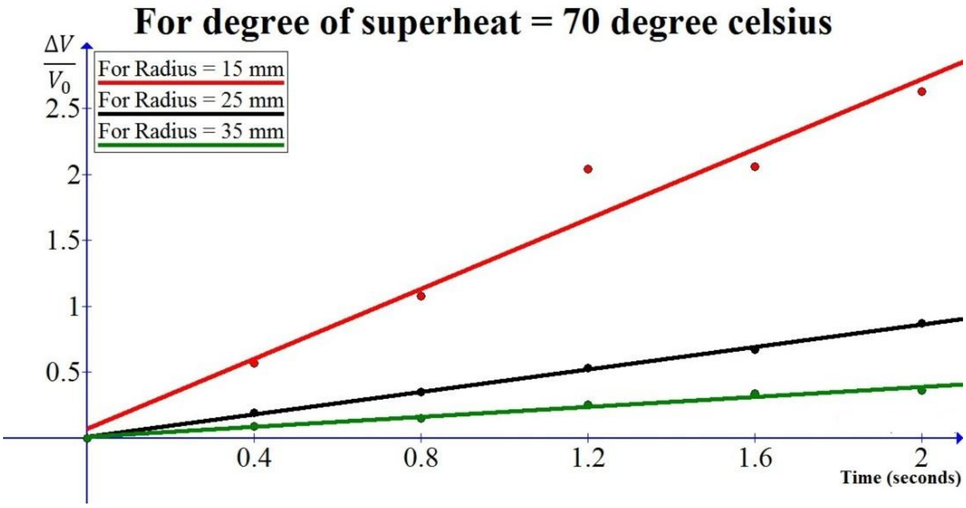


(c)

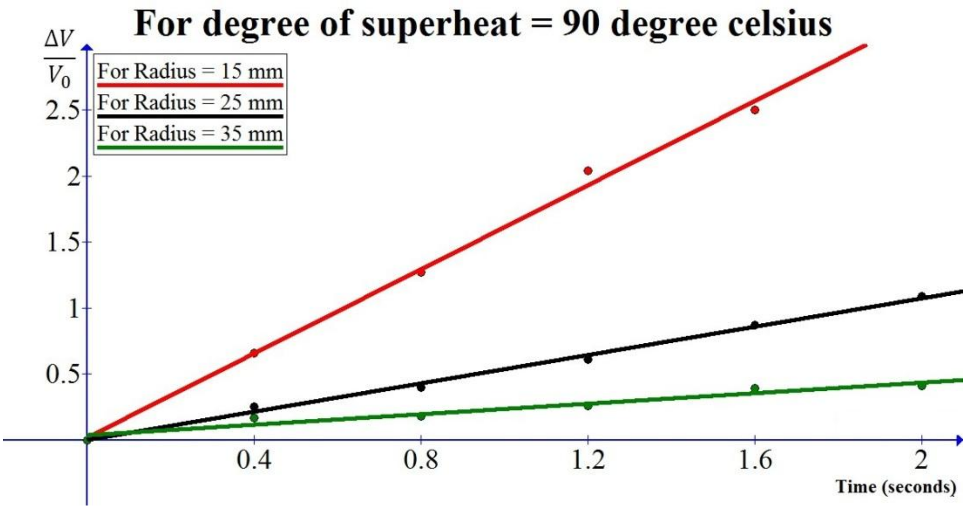
Figure 4.11: $\Delta V/V_0$ vs time with (a) radius = 15, (b) radius = 25 mm and (c) 35 mm



(a)



(b)



(c)

Figure 4.12: $\Delta V/V_0$ vs time at degree of superheat (a) 50^0C (b) 70^0C and (c) 90^0C

4.4 Deformation of drop on a solid surface due to incoming stream

This problem has been simulated for three different radius of the water drop (15 mm, 25 mm and 35 mm). Again, for each of these cases, simulation have been done for three different values of the maximum velocity of the surrounding medium (0.15 m/s, 0.3 m/s and 0.5 m/s). Numerical snapshots is taken at an uniform time interval of 0.2 seconds and is tabulated as shown in Table 4.10, 4.11 and 4.12 for radius 15 mm, 25 mm and 35 mm, respectively.

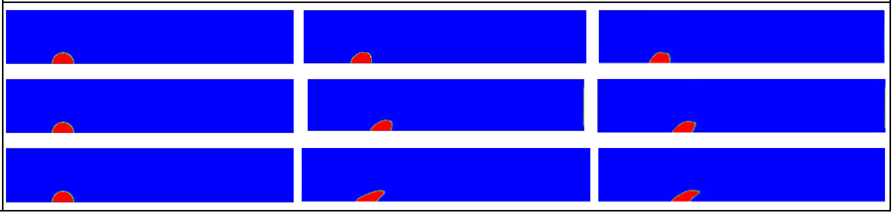
Maximum Velocity (m/s)	**Time (seconds)**		
	t = 0	t = 0.2	t = 0.4
0.15			
0.3			
0.5			

Figure 4.13: Deformation of drop at different velocity profile for radius = 15 mm

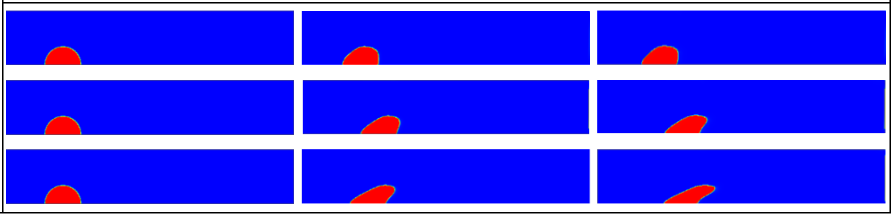
Maximum Velocity (m/s)	**Time (seconds)**		
	t = 0	t = 0.2	t = 0.4
0.15			
0.3			
0.5			

Figure 4.14: Deformation of drop at different velocity profile for radius = 25 mm

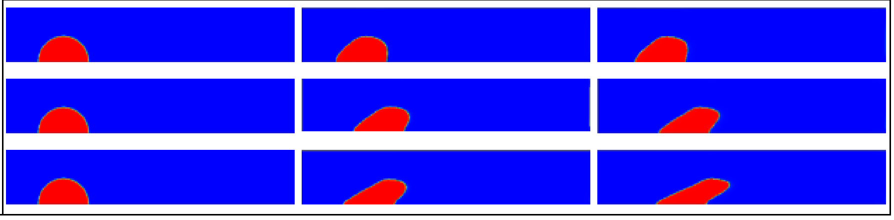
Maximum Velocity (m/s)	Time (seconds)		
	t = 0	t = 0.2	t = 0.4
0.15			
0.3			
0.5			

Figure 4.15: Deformation of drop at different velocity profile for radius = 35 mm

To take into account both deformation as well as displacement of the drop, a new parameter is defined *r* which is given by:

$$r = \frac{a + b}{|a - b|}$$

Where *a* and *b* is the *x* co-ordinate and *y* co-ordinate of the top most point of the drop respectively as shown in Figure 4.16. In this section graph is drawn between *r* and time. Two types of graph are plotted. First the radius of the drop is kept constant and maximum velocity of the surrounding medium is varied as shown in Figure 4.17. Then velocity is kept constant and radius of the drop is varied as shown in Figure 4.18.

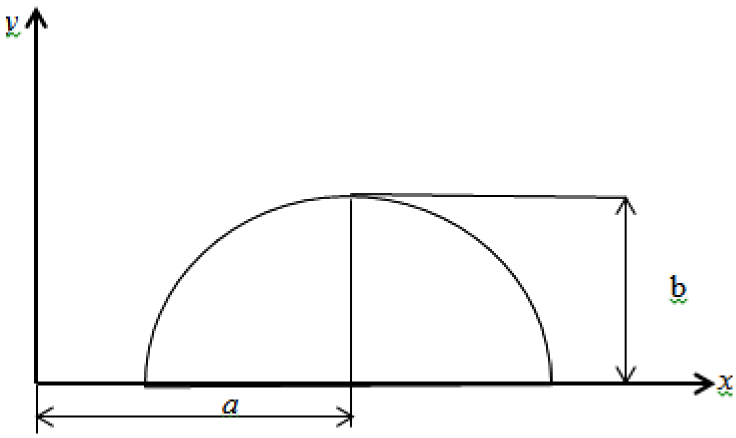
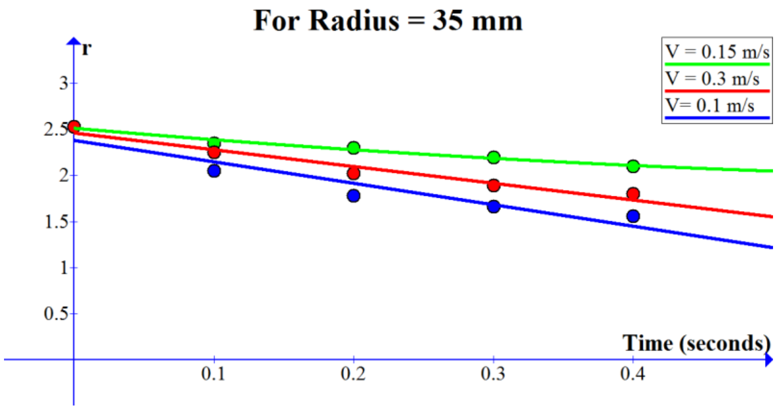
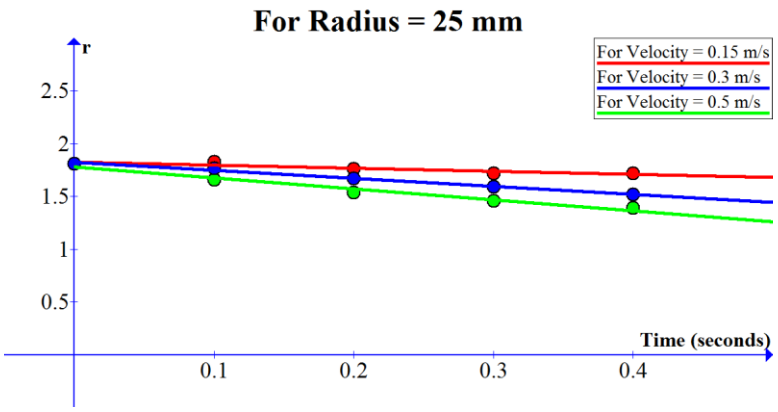


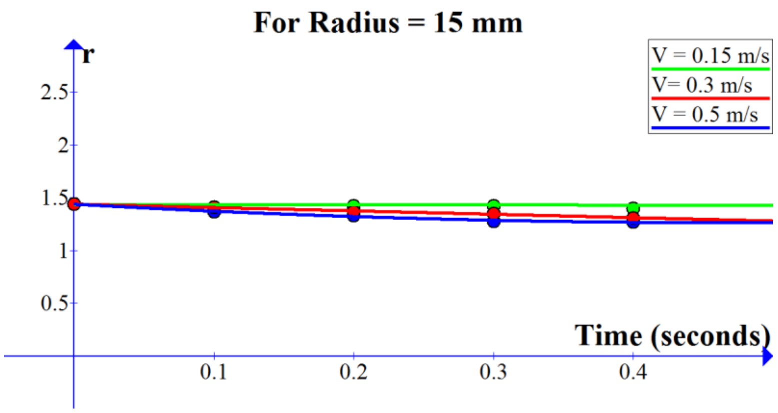
Figure 4.16: Description of calculation of the non-dimensional parameter *r*



(a)

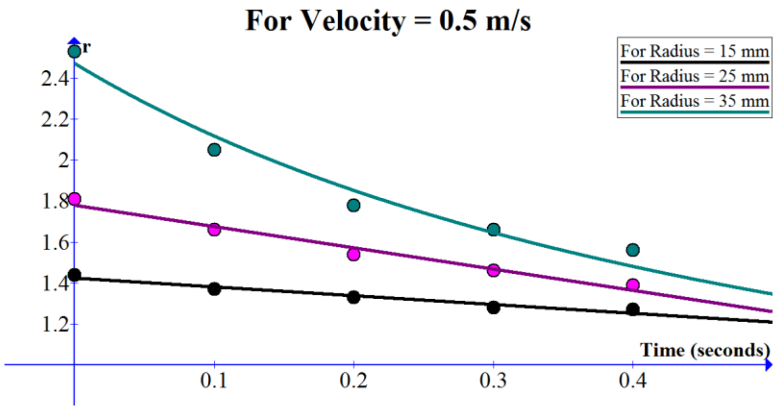


(b)

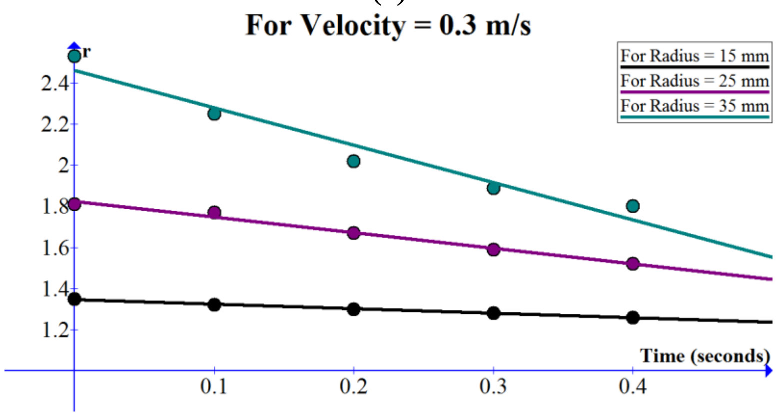


(c)

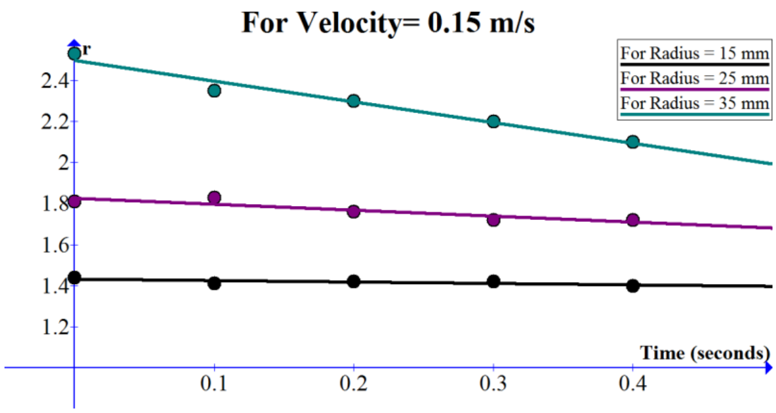
Figure 4.17: r vs time with (a) radius 35 mm, (b) radius 25 mm, (c) radius 15 mm



(a)



(b)



(c)

Figure 4.18: r vs time at (a) velocity = 0.5 m/s, (b) velocity = 0.3 m/s, (c) velocity = 0.15 m/s

Chapter 5 Conclusion and Future Scope

The present chapter deals with the important findings observed from the overall study of the selected problems. Important conclusion has been discussed here. The future scope related to the selected problems has also been pointed out here.

5.1 Important finding and Conclusion

In this paper a 2D lattice Boltzmann model has been developed to study the bubble and drop dynamics in detail. A thermal model is also formulated for problems related to phase change. Deformation and motion of the drop and bubble are tracked accurately using the prescribed methodology at different parabolic and shear velocity profile situations and for different initial radius. It has also been observed that the lattice Boltzmann model accurately predicts the shape and dynamics of the bubble at different degree of superheat and initial radius of the bubble. The important conclusion has been pointed out case-wise separately below.

5.1.1 Study of bubble deformation with parabolic velocity profile

When a bubble (between two plates) is subjected to a parabolic velocity profile at the inlet it is observed that the displacement as well as rate of deformation of the bubble increases with increase in the velocity of the medium. The velocity of the bubble increases steadily and then becomes constant after sometime, attaining a state of equilibrium.

5.1.2 Investigation of bubble deformation under shear flow

Here also, the rate of deformation of the bubble increases with increase in the velocity of the medium. That is, the bubble will undergo more deformation when velocity of the surrounding medium is more.

5.1.3 Study of bubble dynamics under phase change process

In the third case where the bubble is superheated and the surrounding water is kept saturated, the volume of bubble increases with time. This is because due to high temperature of the vapour bubble, the surrounding water turns into vapour contributing to the volume of the vapour bubble. It is also observed that the rate of relative expansion of the vapour bubble having radius 15 mm is greater than that of the vapour bubble having radius 35 mm for the same degree of superheat. Thus, the rate of expansion is inversely proportional to the initial size of the bubble and directly proportional to the degree of superheat.

5.1.4 Deformation of drop on a solid surface due to incoming stream:

When a drop is subjected to an incoming stream having a parabolic velocity profile the rate of deformation of a drop is directly proportional to its initial radius i.e. a drop with initial radius 35 mm will undergo more deformation as compared to a drop with initial radius 15 mm under constant velocity.

5.2 Advantages of LBM

Following are the advantages of the lattice Boltzmann model:

- It delivers results with high accuracy from low computational resources.
- It is suitable for parallel computing as the phenomena of both collision and propagation takes place simultaneously.
- It captures the physics of both deformation and phase change efficiently.

- It can be successfully applied in 3D applications.

5.3 Future Scope

Based on the work done in this dissertation following topics can be identified as future scope of the work:

- 3D simulation for all the problems studied here can be can be simulated.
- Splitting of the bubble can be modeled using finer mesh.
- To capture the interface for other complex non-linear multiphase flow problem can be solved using LBM.

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