

**A COUPLED LEVEL SET AND VOLUME OF FLUID
METHOD FOR NUMERICAL SIMULATION OF
BOILING FLOWS**

B. M. NINGEGOWDA



**DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
OCTOBER-2016**

Copyright © at Indian Institute of Technology (IIT) Delhi, New Delhi, India, 2016.

**A COUPLED LEVEL SET AND VOLUME OF FLUID
METHOD FOR NUMERICAL SIMULATION OF BOILING
FLOWS**

by

B. M. NINGEGOWDA

DEPARTMENT OF MECHANICAL ENGINEERING

Submitted

In fulfilment of the requirements for the degree of

Doctor of Philosophy to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

OCTOBER-2016

CERTIFICATE

This is to certify that the thesis entitled “**A Coupled Level Set and Volume of Fluid Method for Numerical Simulation of Boiling Flows**” being submitted by **Mr. B. M. Ningegowda** to the Indian Institute of Technology Delhi (India) for the award of the **Doctor of Philosophy** in Department of Mechanical Engineering is a bonafide record of research work carried out by him under my guidance and supervision. To the best of our knowledge, the thesis has reached the requisite standard. We hereby declare that the content of the thesis, in full or in part, have not been submitted to any other Institute or University for the award of any degree or diploma.

Dr. B. Premachandran

Associate Professor,

Department of Mechanical Engineering,

Indian Institute of Technology Delhi,

Hauz Khas, New Delhi-110016, India.

Date:

Place: IIT Delhi, New Delhi-110016, India

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisor Dr. B. Premachandran, Associate Professor, Department of Mechanical Engineering, Indian Institute of Technology (IIT) Delhi, for introducing me into this interesting area of research field. I really appreciate his guidance, support, help and endless friendliness during my research life at IIT Delhi. He was always available whenever I needed help. I am really thankful for sparing his valuable time with me for regular meetings. Every discussion was so fruitful that I could always get hints and new ideas which motivated me for better understanding of the research problems. I am very fortunate to be his full time Ph.D. student.

I would also like to thank my senior research committee (SRC) members, Prof. M. R. Ravi and Dr. Prabal Talukdar from Department of Mechanical Engineering and Dr. Vivek. V. Buwa from Department of Chemical Engineering, for their valuable suggestions and advice during the entire period of research work. I am thankful to other faculty members, students and staff at Department of Mechanical Engineering at IIT Delhi for their continuous support.

I am really grateful to Department of Science and Technology (DST) and Ministry of Human Resource Development (MHRD), Govt. of India for providing me the financial support to complete my research work at IIT Delhi. I am very thankful to Dr. Manish Agarwal and other staff members of High Performance Computing (HPC) facility in computer service centre (CSC) at IIT Delhi.

This page is not enough to mention all the names of my close friends who made my educational life journey more memorable. But some people are very special to me in my education life and I am very thankful them are P.V. Pradeep Kumar (CRRI), C. Kiran (GE), Abhishek Ravindra (Toshiba), K S Rajashekara Reddy, M. Anbalagan, Guarav Singh, Santosh Fatale, Pooja

Gopal, Nikhil Ayyagari, Dr. Gajanan Panchal, Jaya Krishna. Jaya Prakhas, Dr. Skylab, Dr. Piyush Shankya, Dr. Pushparaj Shetty, Shravan, Dr. Sunil Gulia, Vishwanath M., Dr. S. Bharanidharan, Praveen, Chandrahas, Vishwanath D., Kiran S., Prasad Borrannavar, Dr. G. Premkumar, Dr. Raghunath Reddy, Anvesh Redyy, Dr. Naganada, Dr. Kiran Bhat, Badminton Ramesh Babu, Varun, Vinay, Dr. Rajesh, Ragavendra K.N. and Veerabadrappa.

I am thankful to many students who worked under the guidance of Dr. B. Premachandran during my research time at IIT Delhi from Jan-2011 to till date who made my research period more memorable are Verendra Kumar, Sharad Pachpute, Surendra Ghandi, Vijaya Lakshmi, Pawan Kumar, Amith, Subhas Challa, Abhishek Gupta, Lokendra Sharma, Akshat, Akash, Santosh M., Shital Garg, Rithambara Dubey, Sourabh Kumar, Digpal Kumar, Dr. Dushyanth Singh and Kuldeep Singh.

Finally and most importantly, I wish to thank all my family members, especially my parents Smt. Gowramma and Sri. Manjegowda, brother B M Sandeepu and his daughter Dhanalakshmi, PU teacher Putta Range Gowda, primary school teacher Venkatesh and my lovely uncle B N Thimmegowda who always supported me with warmth, affection, everlasting love and unquestionable support.

I take this opportunity to express my gratitude to all those who are associated to me directly or indirectly, throughout my Ph.D. work. I would never have been able to finish my thesis without the guidance of my supervisor, help from my friends, and support from my family.

Last but not least, I would like to thank the reviewers of our published papers, authors of the literature related to this work.

B. M. Ningegowda

ABSTRACT

Experimental studies of boiling flows are expensive and difficult to obtain complex flow and heat transfer characteristics accurately. Direct numerical simulations of boiling flow may provide details which are difficult to observe experimentally. However, for the direct numerical simulation of boiling flows, moving interfaces, the interfacial surface tension force, interfacial heat and mass transfer, moving contact lines must be accurately modelled. Due to the limitations of various models in terms of complexity, accuracy and computational cost, only limited numerical investigations have been carried out till now. In the present work, an attempt has been made to improve the existing boiling flow models to investigate film boiling flow over flat surfaces.

Use of the volume of fluid (VOF) method results in spurious currents and the level set (LS) method has the problem of mass loss, the coupled level set and volume of fluid (CLSVOF) method is preferred for direct numerical simulation of boiling flows. Most of the methods of coupled level set and volume of fluid methods use operator-split method for advection which requires reconstruction of interface and redistancing of level set function twice or thrice per time step depends on whether the model is two-dimensional or three-dimensional. Hence, to reduce computational cost, a volume of fluid method with a multidirectional advection algorithm is preferred for the coupled level set and volume of fluid method which requires interface reconstruction only once per time step for both 2-D and 3D computational models. In the present study, a two-dimensional multi-direction advection algorithm based coupled level set and volume of fluid model has been developed for boiling flow problems for non-uniform grids. The model developed in the present study is extensively validated for benchmark test cases of advection, surface tension and phase change problems and the present results found to compare well with those obtained using operator-split advection algorithms.

For accurate modelling of nucleate boiling, boiling at critical heat flux and transition boiling, moving contact line model has to be incorporated. Moving contact line should also be considered for film boiling over a finite heater size. In the present study, a moving dynamic contact line model has been implemented with a partial slip boundary condition at the wall. A detailed validation study has been carried out and compared with the existing experimental, analytical and computational results.

Three-dimensional numerical simulations of film boiling flows are computationally expensive. Hence, earlier numerical investigations are mainly carried out using two-dimensional models as they could capture flow and heat transfer characteristics reasonably well. Following a similar approach, in the present study, only two-dimensional simulations have been carried out. In the present work, water and R134a at near critical conditions are considered. With the proposed CLSVOF method, numerical investigations are carried out to understand flow and heat transfer characteristics of pool boiling of water and R134a over infinite and finite heaters. For the case of infinite size heaters, both single mode and multi-mode boiling models are used. The numerical results show that multimode models should be used to obtain better results for film boiling flows.

Earlier numerical investigations of film boiling are mostly focused on infinite size heaters. Even though some experimental investigations were carried out using finite size heaters, only heat transfer results were presented and no investigation of flow dynamics was carried out. In the case of film boiling over a finite size heater, solid, liquid and vapour contact line is established and the interface adjacent to the contact line is dynamic. In the case of film boiling over a finite size heater, the contact line may or may not move depending on the flow adjacent to the contact line. Hence, to model film boiling over a finite heater size, a dynamic contact line model has to be included. In the present study, a moving contact line/point model has been developed and used for numerical

simulations of film boiling over a finite size heater for water and R134a at near critical conditions. The present numerical simulations show that the number of vapour releasing locations over a finite size heater is higher compared to that of an infinite size heater. The average heat transfer rate is also high in the case of film boiling over a finite size heater. The results obtained from the present study compare well with those of experimental investigations.

TABLE OF CONTENT

ACKNOWLEDGEMENTS	i
ABSTRACT	iii
TABLE OF CONTENT	vi
LIST OF FIGURES	x
LIST OF TABLES	xxiv
NOMENCLATURE	xxv
CHAPTER 1 INTRODUCTION	1
1.1. Background	1
1.2. Direct Numerical Simulation of Two-Phase Flows	5
1.2.1. Lagrangian Mesh (or) Moving Mesh Methods	6
1.2.2. Interface Capturing Methods	6
1.2.3. Front Tracking Methods	7
1.3. Interface Capturing Methods	8
1.3.1. The Volume of Fluid (VOF) Method	8
1.3.2. The Level Set (LS) Method	9
1.3.3. The Coupled Level Set and Volume of Fluid (CLSVOF) Method	10
1.4. Organization of the Thesis	11
CHAPTER 2 LITERATURE REVIEW	13
2.1. Introduction	13
2.2. Direct Numerical Simulation of Two-Phase Flows	13
2.2.1. Volume of Fluid Methods	14
2.2.2. Level Set Methods	18
2.2.3. Coupled Level Set and Volume of Fluid Methods	26
2.3. Numerical Modelling of Surface Tension Force	29
2.3.1. The Continuous Surface tension Force (CSF) model	30
2.3.2. The Continuous Surface Tension Stress (CSS) Model	32
2.3.3. The Parabolic Reconstruction of Surface Tension (PROST) Model	33
2.3.4. The CLSVOF Based CSF Model	34
2.4. Numerical Modelling of Moving Contact Lines	35
2.5. Semi-empirical and Numerical Modelling of Boiling Flows	40
2.6. Forced Convection Film Boiling Flows over a Flat Horizontal Surface	50

2.7.	Free Convection Film Boiling over Flat Heaters with Different Orientations	51
2.8.	Summary of Literature Review	53
2.9.	Objectives	55
CHAPTER 3	DEVELOPMENT OF A CLSVOF METHOD FOR BOILING FLOWS	56
3.1.	Introduction	56
3.2.	Mathematical Formulation for Two Phase Boiling Flows	56
3.2.1.	Governing Equations used for Two Phase Flow without Phase Change	57
3.2.2.	Governing Equations used for Simulating Boiling Flows	57
3.3.	A Multi-Directional Advection Algorithm of the CLSVOF method	59
3.3.1.	The Volume of Fluid (VOF) Based Multi-Dimensional Advection Algorithms	60
3.3.2.	The Level Set (LS) based Advection Algorithm	63
3.4.	Evaluation of Multi-Dimensional Advection Algorithms of the CLSVOF Method	64
3.4.1.	Translation of Simple Circular Bubble Test	65
3.4.2.	Rotation of Zalesak Slotted Circular Disk Test	68
3.4.3.	Shear or Single Vortex Flow Test	70
3.4.4.	Deformation of the Circular Bubble Test	75
3.5.	Development and Evaluation of Single Phase Flow Solver	78
3.5.1.	Lid Driven Cavity	78
3.5.2.	Natural Convection in a Square Cavity	80
3.6.	A CLSVOF-CSF based Interfacial Surface Tension Force Model	82
3.7.	Numerical Validation of the Two Phase Flow Benchmark Problems	83
3.7.1.	Static Bubble Test	83
3.7.2.	Dam Break Problem	90
3.7.3.	Non-Linear Growth of Larger Amplitude Rayleigh-Taylor Instability	92
3.7.4.	Rising of a Circular Gas Bubble inside a Stationary Liquid Column	95
3.8.	Numerical Modelling of Moving Contact Lines phenomenon	97
3.9.	Validation of Two Phase Flow with MCL Problems	100
3.9.1.	Moving Contact Line Model with a Static Contact Angle	100
3.9.2.	Gas Bubble Sticking and Spreading Test	105
3.9.3.	Evaluation of Dynamic Contact Angle Model	107
3.10.	Numerical Modelling of Interfacial Phase Change Model	109
3.11.	Numerical Validation for the Phase Change Problems	112
3.11.1.	One-Dimensional Stefan Problem	112

3.11.2.	Saturated Film Boiling Flows over a Horizontal Flat Surface	116
3.12.	Conclusions	125
CHAPTER 4	POOL FILM BOILING OF WATER AND R134a OVER FLAT HORIZONTAL SURFACES	127
4.1.	Introduction	127
4.2.	Physical Problem Statement	127
4.3.	Numerical Modelling	128
4.3.1.	Computational Domains used for Single-Mode and Multimode Film Boiling Models	128
4.3.2.	Boundary and Initial Conditions	130
4.3.3.	Selection of Grid Size and Time Step	130
4.4.	Results and Discussions	132
4.4.1.	Single-Mode Saturated Film Boiling Flow of Water	133
4.4.2.	Multimode film boiling for near critical conditions of water	137
4.4.3.	Single-Mode Saturated Film Boiling Model for R134a	146
4.4.4.	Multimode Saturated Film Boiling Model for R134a	150
4.5.	Conclusions	156
CHAPTER 5	SATURATED FILM BOILING OF WATER AND R134a OVER FINITE SIZE HEATERS	158
5.1.	Introduction	158
5.2.	Numerical Model	159
5.2.1.	Computational Domain	159
5.2.2.	Boundary and Initial conditions	160
5.3.	Results and Discussion	161
5.3.1.	Film Boiling of Water	162
5.3.2.	Film Boiling of R134a	182
5.4.	Conclusions	193
CHAPTER 6	FORCED AND FREE CONVECTION FILM BOILING: EFFECT OF HEATER SIZE AND ORIENTATION	195
6.1.	Introduction	195
6.2.	Physical Problems	195
6.2.1.	Forced Convection Film Boiling over an Infinite Flat Surface	196
6.2.2.	Forced Convection Film Boiling over a Finite size Heater	196
6.2.3.	Free Convection Film Boiling over a Finite Size Heater with Surface Orientation	197
6.3.	Results and Discussions	198
6.3.1.	Forced Convection Film Boiling over a Flat Horizontal Surface	198
6.3.2.	Forced Convection Film Boiling over a Discrete Heater	204
6.3.3.	Free Convection Film Boiling over Finite Size Heaters - Effect of Wall Superheat	209

6.3.4.	Effect of Orientation on Film Boiling over a Discrete Heater Flush Mounted on a Flat Plate	211
6.4.	Conclusions	217
CHAPTER 7	CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK	219
7.1.	Introduction	219
7.2.	Broad Conclusions of the Present Study	220
7.3.	Suggestion for Future Work	222
	REFERENCES	223
	LIST OF PUBLICATIONS	238
	BRIEF BIO-DATA OF THE AUTHOR	239

LIST OF FIGURES

Fig 1.1	Typical pool boiling curve of water at 1atm	3
Fig 1.2	Regions considered in modelling of nucleate boiling (Fischer et al., 2015) (a) Microscale microlayer model, (b) Macroscale model and (c) Microscale microlayer contact line model	4
Fig 1.3	Dry patch region during nucleate boiling of methanol obtained using an optical technique (Jawurek, 1969)	4
Fig. 1.4	Methods used for direct numerical simulation of two-phase flow: (a) moving mesh method, (b) interface capturing method and (c) front tracking method (Zhao et al., 2002)	5
Fig 1.5	The surface of the rising gas bubble is tracked by marker points connected with unstructured triangle grid and fluid flow governing equations are solved on a fixed structured grid (Tryggvason et al., 2011)	7
Fig 1.6	Representation of the interface in the VOF method (a) true interface, (b) Simple Line Interface Calculation (SLIC) of Noh and Woodward (1976) and (c) Piecewise Linear Interface construction (PLIC) of Youngs (1982)	8
Fig 1.7	Initialisation of the level set function in a two-phase region	10
Fig. 2.1	F-contour plots for the advection in an oblique flow field of the hollow square problem over a structured grid obtained by Darwish and Moukalled (2006) for (a) low Co , (b) medium Co and (c) high Co	15
Fig. 2.2	Various advection algorithms with geometric reconstruction used in the volume of fluid methods (a) multi-dimensional advection (Rider and Kothe, 1998), (b) x-directional fluxing, (c) y-directional fluxing, (d) Rider and Kothe (1998) modified multi-directional advection, (e) Lopez et al. (2004) EMFPA multi-directional advection.	17

Fig. 2.3	Contours of the level set function of a large water drop, $Re = 10.0$ (a) With reinitialisation and (b) without reinitialisation (Sussman et al., 1994)	19
Fig. 2.4	Typical local refinement in a narrow band region for level set function used by Gómez et al. (2005) (a) the region of refinement and (b) a close up view of the region of refinement around the interface	23
Fig. 2.5	Dual grid used for two phase flows Level Set equations are solved only in a band of Cartesian cells (Herrmann, 2008).	24
Fig. 2.6	Initialisation of the level set (LS) function in the conservative level set method	25
Fig. 2.7	The procedure used to implementation of the CLSVOF method	27
Fig. 2.8	The static bubble test using the VOF-CSF model (a) Formation of spurious currents, (Rudman, 1998) (b) the deformation of interface (Meier et al., 2002)	32
Fig. 2.9	Magnitude of parasitic currents for grid size of 160×160 (Renardy and Renardy, 2002)	34
Fig. 2.10	Impact and spreading of a water droplet (Klitz et al., 2014)	35
Fig. 2.11	Surface tension forces and contact angles (Sikalo et al., 2005c) (a) Surface tension forces (b) Wetting, $\theta < 90^\circ$ (c) De-wetting, $\theta > 90^\circ$	36
Fig. 2.12	Schematics of a pre-cursor thin layer model	38
Fig. 2.13	Sketch of a diffuse interface model with finite thickness (Sibley et al., 2013)	38
Fig. 2.14	Schematic of the different slip conditions at the MCL (Klitz et al., 2014) (a) no-slip, $\lambda_S = 0$ (b) perfect-slip, $\lambda_S = \infty$ and (c) partial-slip, $0 < \lambda_S < \infty$	39
Fig. 2.15	Bubble releasing pattern in film boiling (a) Boiling of water - Wall superheat $\Delta T_{Sup} = 141.67^\circ\text{C}$, $q_w'' = 41,956\text{W/m}^2$, Hosler and Westwater (1962), (b) film boiling in 5mm deep pool of water, $\Delta T_{Sup} = 319\text{K}$, $q_w'' \sim 63\text{kW/m}^2$, Duignan et al. (1989).	42

Fig. 2.16 A typical computational domain used for a single mode model	44
Fig. 2.17 Snap shots of multimode film boiling flow at $Ja_v = 0.064$ presented by Esmaeeli and Tryggvason (2004b) (a) three-dimensional model and (b) two-dimensional model	46
Fig. 2.18 Film boiling over a wire (a) Film boiling of acetone at 1atm over a wire of radius, $R=0.323\text{mm}$, $q_w''=1.3 \times 10^5 \text{ W/m}^2$ (Lienhard and Dhir, 1980) (b) film boiling of CO_2 over at near critical condition (Abadzic and Goldstein, 1970)	48
Fig. 2.19 Convection effect on boiling over a finite heater size at critical heat flux by Lienhard and Witte (1985)	49
Fig. 3.1 The Volume of Fluid element advected out of the interface cell face	62
Fig. 3.2 Nine point stencil of an array of 3×3 cells	63
Fig. 3.3 Translation of a circular bubble at uniform velocity (1.0, 1.0) (a) Translated geometry at time, $t=0.0\text{s}$ and 0.5s . (b) Comparative study of the numerical L1 error norms at different CFL numbers.	67
Fig. 3.4 Rotation of Zalesak's slotted disk (a) The Initial geometry of the circular slotted disk, $r=0.15\text{m}$, $c(0.5\text{m}, 0.75\text{m})$, $a=0.05\text{m}$ and $b=0.25\text{m}$, (b) shape of the slotted disk after one complete rotation using the proposed CLSVOF method and (c) shape of the slotted disk after one complete rotation-the CLSVOF method of Wang et al. (2009b)	69
Fig.3.5 Grid resolution study of shear flow test at $t=4.0\text{s}$ and 8.0s (a) for grid size: 128×128 , (b) grid size: 256×256 , (c) grid size: 384×384 and (d) grid dependent comparison of time reversed shear flow test at time, $t=8.0\text{s}$	72
Fig. 3.6 Qualitative comparison of the shear flow test for the grid size of 128×128 and $\text{CFL}=1.0$ at time, $t=3.0\text{s}$ (a) CLSVOF method of Wang et al. (2009b) and (b) the Proposed un-split CLSVOF method	73

- Fig.3.7 Comparison of the interface of the fluid element in the shear flow test after 1000 time step forward and another 1000 time step reverse (a) operational split CLSVOF method of Gerlach et al. (2006) and (b) the proposed un-split CLSVOF method 75
- Fig. 3.8 Comparison of the interfaces obtained in the time reversed deformation test case for the number of vertices, $n=4$ at $CFL=0.25$ for the grid size of 128×128 (a) Initial non-uniform computational domain, (b) at $t=0.5s$ - uniform grid and (c) at $t=0.5s$ - non-uniform grid (d) at $t=1.0s$ - uniform grid and (e) at $t=1.0s$ - non-uniform grid 77
- Fig.3.9 Lid driven cavity at $Re = 1000$ (a) geometry and boundary conditions, (b) flow pattern and (c) variation of velocity component u along the vertical direction at $x=L/2$ and velocity component v along the horizontal direct at $H/2$ inside a lid driven cavity. 79
- Fig. 3.10 Geometry and boundary conditions of the buoyancy flow in a square cavity 80
- Fig.3.11 Natural convection in a square cavity at $Ra = 105$ (a) Flow pattern and (b) Temperature distribution 81
- Fig. 3.12 Comparative study of transient mean velocity field for density ratio=1, viscosity ratio=10 and three different grids: 20×20 , 40×40 and 80×80 (a) CLSVOF-PBM of Wang and Tong (2010) and the proposed CLSVOF-CSF (b) the effect of density ratio on the generation of spurious current using the CLSVOF-CSF surface tension model 87
- Fig. 3.13 Static bubble test (a) spurious currents formation, (b) comparison of different surface tension models and (c) comparison of present CLSVOF-CSF with VOF-PROST of Renardy and Renardy (2002). 89

Fig. 3.14 Comparison of the numerical and experimental results of the dam break problem based on the non-dimensional parameters (a) location of the leading liquid interface along the horizontal bottom wall v/s time and (b) vertical column height at the left side wall v/s time	91
Fig. 3.15 The interface evolution in the Rayleigh-Taylor instability at time $t = 0.0s, 0.25s, 0.5s, 0.6s, 0.7s, 0.8s, 0.9s, 0.95s, 1.0s, 1.1s$ and $1.3s$ using proposed CLSVOF-CSF method for non-uniform grids	93
Fig. 3.16 Comparison of the interface evolution in the Rayleigh-Taylor instability at time $t = 0.15, 0.3, 0.45, 0.6$ and $0.75s$ (a) the proposed CLSVOF-CSF method and (b) Zuzio and Estivalezes (2011).	94
Fig. 3.17 Initial and boundary conditions of rising gas bubble test case	95
Fig. 3.18 The qualitative comparison of the transient evolution of the interfaces of the rising gas bubble at density ratio of $DR=100$ for the grid size of 128×256 obtained at non-dimensional time, (i) $\tau=1$, (ii) $\tau=3$, (iii) $\tau=4$, (iv) $\tau=5$ and (v) $\tau=6$ from (a) Proposed CLSVOF-CSF method and (b) Zhao et al. (2002)	96
Fig.3.19 Schematic of the Navier partial slip boundaries with varying slip length, λ_s model	97
Fig. 3.20 Initial semi-circular droplet spreading over a solid surface, (a) initial radius, R_0 with $\theta_s=90^\circ$, (b) maximum droplet radius, R , spread length, L and droplet height, e and (c) numerical spread length, L and droplet height, e .	100
Fig. 3.24 Comparative study of shape of the bubble interfaces with different boundary conditions at the MCL such as no-slip, full-slip and Navier partial slip at various times (a) $0.0s$, (b) $0.05s$, (c) 0.015 and (d) $0.25s$	106
Fig. 3.25 Transient variation of MCL position for grid size of 128×128	107

Fig. 3.26 The variations of spreading ratio and the apex height in the case of impact of water droplet on a flat surface (a) Non-dimensional time vs droplet spreading ratio and (b) non-dimensional time vs droplet apex height.	109
Fig. 3.27 Interfacial heat and mass transfer	110
Fig. 3.28 Numerical and analytical study of one-dimensional Stefan problem (a) Computational domain, initial and boundary conditions at time, $t=0s$, (b) interface location with respect to time and (c) the variation of liquid velocity adjacent to the interface v/s time	115
Fig. 3.29 Typical non-uniform grid used for saturated film boiling over a horizontal surface	118
Fig. 3.30 Numerical study of film boiling (a) effect of grid size on the interface evolution (b) effect of grid size on the local Nusselt number distribution over the plane heater surface and (c) effect of CFL number	122
Fig. 3.31 Periodic bubble release cycle - interface morphology for the near critical water with the wall superheat $\Delta T_{Sup}=5K$ at (a) $t=0.0s$, (b) $0.09s$, (c) $0.13s$, (d) $0.15s$, (e) $0.35s$ and (f) $0.4s$	123
Fig. 3.32 Comparison of the space averaged Nusselt number variations obtained from the present study with the correlations of Berenson (1961) and Klimenko (1981) at wall superheat of $\Delta T_{Sup}=5K$	123
Fig. 3.33 The formation of the columns of vapour jet in the film boiling of water at wall superheat, $\Delta T_{Sup}=10K$ at time (a) $0.085s$, (b) $0.09s$, (c) $0.1s$, (d) $0.11s$, (e) $0.125s$, (f) $0.15s$, (g) $0.25s$, (h) $0.275s$, (i) $0.3s$, (j) $0.325s$, (k) $0.35s$ and (l) $0.375s$	124
Fig. 3.34 Comparison of the numerical time averaged Nusselt numbers with the correlation of Berenson (1961) for different wall superheats	124

- Fig.4.1 The computational domain and the boundary conditions used for the simulation of film boiling flows (a) single-mode model and (b) multimode model 129
- Fig. 4.2 Grid independence and time step convergence study of single-mode film boiling of water at near critical conditions for Jacob number, $Ja_v = 12.735$ ($\Delta T_{Sup}=10K$) (a) the effect of grid size (b) the effect of CFL number, C . 131
- Fig. 4.3 Interface morphologies of the periodic bubble release cycle obtained using single-mode boiling model for water at different Jacob numbers (a) $Ja_v=2.547$ ($\Delta T_{Sup}=2K$), (b) $Ja_v=6.367$ ($\Delta T_{Sup}=5K$), (c) $Ja_v=10.188$ ($\Delta T_{Sup}=8K$), (d) $Ja_v=12.735$ ($\Delta T_{Sup}=10K$), (e) $Ja_v=19.103$ ($\Delta T_{Sup}=15K$) and (f) $Ja_v=25.47$ ($\Delta T_{Sup}=20K$). 134
- Fig. 4.4 The velocity vector plots for single-mode boiling model for water at near critical conditions (a) The formation of discrete bubble at Jacob number, $Ja_v=10.19$ and (b) The formation of jets of stable vapour column at Jacob number, $Ja_v=25.47$. 135
- Fig. 4.5 Transient variations of the space and the time averaged Nusselt numbers obtained with single-mode film boiling model for water at different Jacob numbers (a) $Ja_v = 2.547$ and (b) $Ja_v = 6.367$. 136
- Fig. 4.6 Transient evolution of the discrete periodic bubble release cycle obtained with the multimode film boiling model for water at Jacob number (a) $Ja_v = 2.547$ and (b) $Ja_v = 6.367$. 138
- Fig.4.7 Interface evolution obtained from the multimode film boiling model and the corresponding variation of local Nusselt number for water at Jacob number, $Ja_v=6.367$ (a) interface morphology obtained at $\tau=64.63$ and $\tau=107.71$, (b) the variation of local Nusselt number obtained at $\tau=64.63$ and $\tau=107.71$, (c) interface

morphology obtained at $\tau=172.34$ and $\tau=258.52$, and (d) the variation of local Nusselt number obtained at $\tau=172.34$ and $\tau=258.52$. 140

Fig. 4.8 Evolution of the interface morphology obtained with the multimode film boiling model for water at Jacob number (a) $Ja_v = 19.103$ and (b) $Ja_v = 25.47$. 142

Fig.4.9 Spacing between nodes and anti-nodes for the near critical conditions of water at non-dimensional time, $\tau = 177.73$ for various Jacob numbers (a) $Ja_v = 2.547$, (b) $Ja_v = 6.367$, (c) $Ja_v = 19.103$ and (d) $Ja_v = 25.47$. 144

Fig. 4.10 Variation of the space and the time averaged Nusselt number obtained using the multimode film boiling model for near critical conditions of water at different Jacob numbers (a) $Ja_v = 2.547$, (b) $Ja_v = 6.367$, (c) $Ja_v = 19.103$ and (d) $Ja_v = 25.47$. 145

Fig.4.11 Comparison of the time averaged Nusselt number obtained using both the single-mode and the multimode film boiling models for the near critical conditions of water at different wall superheat, ΔT_{Sup} . 146

Fig. 4.12 Interface morphologies of the periodic bubble release cycle obtained using the single-mode film boiling model for refrigerant R134a at different Jacob numbers (a) $Ja_v = 0.163$, (b) $Ja_v = 0.407$, (c) $Ja_v = 0.651$, (d) $Ja_v = 0.814$, (e) $Ja_v = 1.221$ and (f) $Ja_v = 1.628$. 147

Fig. 4.13 Transient variation of the space and the time averaged Nusselt numbers for refrigerant R134a obtained with the single-mode film boiling model at different Jacob numbers (a) $Ja_v=0.163$, (b) $Ja_v = 0.407$, (c) $Ja_v = 0.651$, (d) $Ja_v = 0.814$, (e) $Ja_v = 1.222$ and (f) $Ja_v = 1.629$. 149

Fig.4.14 Evolution of the interface morphology obtained with the multimode film boiling model for refrigerant R134a at Jacob numbers (a) $Ja_v=0.163$ ($\Delta T_{Sup}=2K$), (b) $Ja_v=0.814$ ($\Delta T_{Sup}=10K$), (c) $Ja_v=1.628$ ($\Delta T_{Sup}=20K$). 151

- Fig. 4.15 Interface evolution obtained from the multimode film boiling model and the corresponding variation of a local Nusselt number for R134a at Jacob number, $Ja_v = 1.63$ (a) $\tau = 86.9$ (b) $\tau = 184.6$ (c) $\tau = 217.2$ (d) $\tau = 260.62$ 152
- Fig. 4.16 Spacing between nodes and anti-nodes for the near critical conditions of refrigerant R134a at non-dimensional time, $\tau = 168.32$ for various Jacob numbers (a) $Ja_v = 0.163$, (b) $Ja_v = 0.407$, (c) $Ja_v = 0.814$, (d) $Ja_v = 1.222$ and (e) $Ja_v = 1.629$. 154
- Fig. 4.17 The variation of the space and the time averaged Nusselt numbers obtained using the multimode film boiling model for the near critical conditions of R134a at different Jacob numbers (a) $Ja_v = 0.163$, (b) $Ja_v = 0.407$, (c) $Ja_v = 0.814$, (d) $Ja_v = 1.222$ 155
- Fig. 4.18 Comparison of the time averaged Nusselt number obtained using both the single-mode and the multimode film boiling models for the near critical conditions of refrigerant R134a at different wall superheats, ΔT_{Sup} . 156
- Fig. 5.1 The computational domain used for film boiling of water over a finite heater surface along with the initial vapour layer 160
- Fig. 5.2 The phase interfaces obtained for film boiling of water at $Ja_v = 1.274$ ($\Delta T_{Sup} = 1K$) 163
- Fig. 5.3 The phase interface obtained for film boiling of water at $Ja_v = 2.55$ ($\Delta T_{Sup} = 2K$) 164
- Fig. 5.4 The phase interface obtained for water at $Ja_v = 6.37$ ($\Delta T_{Sup} = 5K$) 165
- Fig. 5.5 Flow pattern obtained for water with $\Delta T_{Sup} = 5K$ at $\tau = 280.06$ (a) full domain and (b) enlarged view 166
- Fig. 5.6 The phase interface obtained for water at $Ja_v = 12.74$ ($\Delta T_{Sup} = 10K$) 167
- Fig. 5.7 The phase interface obtained for water at $Ja_v = 19.10$ ($\Delta T_{Sup} = 15K$) 168

Fig. 5.8 The phase interface obtained for water at $Ja_v=25.47$ ($\Delta T_{Sup}=20K$)	169
Fig. 5.9 Flow characteristics at the wall superheat of $20K$ (a) phase interface obtained from present study and (b) a photograph of Reimann and Grigull (1975) presented in Son and Dhir (1998)	170
Fig. 5.10 The phase interface obtained for water at $Ja_v = 38$ ($\Delta T_{Sup} = 30K$)	171
Fig. 5.11 The phase interface obtained in the case of film boiling of water at the wall superheat of $30K$ (a) Present numerical results and (b) Experimental study of film boiling over a wire presented by Reimann and Grigull (1975)	172
Fig. 5.12 Interface evolution at the wall superheat of $30K$, (a) $\tau=215.43$, (b) $\tau=220.81$, (c) $\tau = 231.59$, (d) $\tau = 242.36$	173
Fig. 5.13 The bubble growth and movement in the region near the left side contact point	175
Fig. 5.14 Frequency of bubble departure from the vapour layer at the wall superheat of $30K$	175
Fig. 5.15 Effect of wall superheat on distance between bubble releasing locations	177
Fig. 5.16 The variation of the interface thickness and its corresponding local Nusselt number, Nu_x for different wall superheats of (a) $2K$, (b) $5K$, (c) $15K$ and (d) $30K$	179
Fig. 5.17 The transient variation of space and time averaged Nusselt number obtained for film boiling over finite and infinite size horizontal flat heater for the wall superheats of (a) $\Delta T_{Sup}=1K$, (b) $\Delta T_{Sup}=2K$, (c) $\Delta T_{Sup}=5K$, (d) $\Delta T_{Sup}=10K$, (e) $\Delta T_{Sup}=15K$, (f) $\Delta T_{Sup}=20K$.	181
Fig. 5.18 The variation of time averaged Nusselt number with the wall superheat	182

- Fig. 5.19 The transient evolution of the interface morphology for film boiling of R134a over the finite horizontal surface with Jacob number, $Ja_v = 0.0815$ (or wall superheat of $\Delta T_{Sup}=1K$) 184
- Fig. 5.20 The transient evolution of the interface morphology for film boiling of R134a over the finite horizontal surface with Jacob number, $Ja_v = 0.163$ (or wall superheat of $\Delta T_{Sup}=2K$) 184
- Fig. 5.21 The transient evolution of the interface morphology for film boiling of R134a over the finite horizontal surface with Jacob number, $Ja_v = 0.407$ (or wall superheat of $\Delta T_{Sup}=5K$) 185
- Fig. 5.22 The transient evolution of the interface morphology for film boiling of R134a over the finite horizontal surface with Jacob number, $Ja_v = 0.651$ (or wall superheat of $\Delta T_{Sup}=8K$) 185
- Fig. 5.23 The transient evolution of the interface morphology for film boiling of R134a over the finite horizontal surface with Jacob number, $Ja_v = 0.814$ (or wall superheat of $\Delta T_{Sup}=10K$) 186
- Fig. 5.24 The transient evolution of the interface morphology for film boiling of R134a over the finite horizontal surface with Jacob number, $Ja_v = 1.221$ (or wall superheat of $\Delta T_{Sup}=15K$) 186
- Fig. 5.25 The transient evolution of the interface morphology for film boiling of R134a over the finite horizontal surface with Jacob number, $Ja_v = 1.628$ (or wall superheat of $\Delta T_{Sup}=20K$) 187
- Fig. 5.26 The transient evolution of the interface morphology for film boiling of R134a over the finite horizontal surface with Jacob number, $Ja_v = 2.442$ (or wall superheat of $\Delta T_{Sup}=30K$) 187
- Fig. 5.27 Bubble departure frequency in film boiling of R134a over a finite size heater 188

Fig. 5.28 Spacing between bubble release locations for the wall superheats, $\Delta T_{Sup} = 1K$ to $30K$	189
Fig. 5.29 The local Nusselt number distribution for film boiling of refrigerant R134a, (a) $\Delta T_{Sup} = 1K$, (b) $\Delta T_{Sup} = 30K$	190
Fig. 5.30 Transient distribution of space and time averaged Nusselt numbers for film boiling of R134a at various wall superheats, (a) $\Delta T_{Sup} = 1K$ (b) $\Delta T_{Sup} = 2K$, (c) $\Delta T_{Sup} = 5K$ (d) $\Delta T_{Sup} = 10K$, (e) $\Delta T_{Sup} = 15K$ and (f) $\Delta T_{Sup} = 20K$	191
Fig. 5.31 Comparative study time averaged Nusselt numbers for R134a	192
Fig. 6.1 Physical model of forced convection film boiling	196
Fig. 6.2 Pool film boiling initial and boundary conditions with surface orientation, α	197
Fig. 6.3 Variations of thickness of vapour layer for effects of (a) at wall superheat and (b) free stream velocities	200
Fig. 6.4 Effects of wall superheats based for the local wall heat transfer coefficients compared with Cess and Sparrow (1961a) correlations (a) at $\Delta T_{Sup} = 100K$ and (b) at $\Delta T_{Sup} = 400K$.	201
Fig. 6.5 Effects of wall superheats based on the local wall shear stress compared with Cess and Sparrow (1961a) correlations for (a) $\Delta T_{Sup} = 100K$ and (b) $\Delta T_{Sup} = 400K$	203
Fig. 6.6 Effects of liquid free stream velocities based on the local heat transfer coefficients.	204
Fig. 6.7 Effects of surface orientations for forced convection film boiling of water over a discrete heat source for the wall superheat of $100K$	205
Fig. 6.8 The variation of the non-dimensional thickness of vapour layer, δ_v^* with respect to various Reynolds number, Re_L at the wall superheat of $100K$	206
Fig. 6.9 Variation of temperature within the vapour layer for $\Delta T_{Sup} = 100K$ and $l_h/L = 0.556$	207

- Fig. 6.10 Effect of Reynolds numbers on film boiling of water at the wall superheat of 100K
obtained for different discrete heater size. 207
- Fig. 6.11 Effect of Reynolds numbers on film boiling of water at the wall superheat of 300K
obtained for different discrete heater size 208
- Fig. 6.12 Transient evolution of the liquid-vapour interfaces for free convection film
boiling of water over the horizontal flat discrete heater surface at 10K with effect
of different sizes of discrete heater (a) $l_h/L = 0.2$ (b) $l_h/L = 0.385$ (c) $l_h/L = 0.556$
210
- Fig. 6.13 Effect of discrete heater size and wall superheat on film boiling of water 211
- Fig. 6.14 The transient evolution of interface at 100K and orientation angle, $\alpha = 0^\circ$ for l_h/L
 $= 0.556$ at (a) $\tau = 43.09$, (b) $\tau = 53.86$, (c) $\tau = 86.63$ and (d) $\tau = 107.71$ 212
- Fig. 6.15 Interface evolution of water at 100K with orientation angle, $\alpha = 15^\circ$ and $l_h/L = 0.556$
for non-dimensional time (a) $\tau = 21.54$ (b) $\tau = 43.09$, (c) $\tau = 53.86$ and (d) $\tau =$
 86.63 212
- Fig. 6.16 The variation of the vapour layer thickness, δ_v obtained at the centre of the discrete
heater surface in the case of free convection film boiling of water with the wall
superheat of 100K 213
- Fig. 6.17 The distribution of the non-dimensional temperature, $\theta = (T - T_{Sat}) / (T_w - T_{Sat})$ with
respect to non-dimensional height, (y/H) for free convection film boiling of water
at 100K with different heater surface orientations (a) $l_h/L = 0.2$ (b) $l_h/L = 0.385$
(c) $l_h/L = 0.556$ 214
- Fig. 6.18 The distribution of the non-dimensional velocity, u/u_{ref} with respect to non-
dimensional height, (y/H) for free convection film boiling of water at 100K for
the heater size of $l_h/L = 0.385$ 215

Fig. 6.19 Effect of the orientation of plate with the discrete heater in the case of free convection film boiling of water at 100K with various discrete heater sizes 216

Fig. 6.20 Variation of $Nu_{T,\alpha} / Nu_{T,\alpha=0}$ with the heater orientation (α) 217

LIST OF TABLES

Table 3.1	Comparison of the L_2 (relative) error norms of Zalesak's slotted circular disk after one complete rotation using various interface reconstruction/advection algorithms.	70
Table 3.2	Comparison study of L_1 (absolute) error norms of reversed shear flow at time, $t=8$ s and $CFL=1.0$ in a unit square computational domain	74
Table 3.3	Comparison of relative errors obtained for shear flow test using the proposed CLSVOF method with different methods of Gerlach et al. (2006) at $CFL=0.25$ at different number of iterations, N .	75
Table 3.4	Comparison of wall average Nusselt number, Nu_{Avg} with the available numerical results for the case of natural convection in a square cavity.	81
Table 3.5	Comparison of the present CLSVOF-CSF results with the different surface tension models of Gerlach et al. (2006) for density ratios of $DR = 2$ and 1000 at time step, $\Delta t = 10^{-5}s$.	85
Table 3.6	Thermo-physical properties of fluid used in study of 1-D Stefan problem	114

NOMENCLATURE

A	area, m^2
$\mathbf{A}$	symmetric matrix
A_{F_T}	net advection flux of the cell, m^2
C	constant of interfacial line segment
C	CFL number
C_P	the specific heat at constant pressure, $J/kg\ K$
d	diameter, m
F	VOF void fraction indicator function
F_{mt}	rate of the volume fraction generated due to phase change, $1/s$
F_{sa}	interfacial surface tension stress, N/m^2
F_{st}	interfacial volumetric surface tension force, N/m^3
Gr	Grashof number
g	acceleration due to gravity, m/s^2
h_{lg}	latent heat of vaporization, $J/kg\ K$
h_x	heat transfer coefficient, $W/m^2 \cdot K$
H	domain height, m
$H(\phi)$	smoothed Heaviside function
$\mathbf{I}$	Identity matrix
Ja	Jacob number
k	thermal conductivity, $W/m \cdot K$
la	length of the adiabatic wall, m
l_h	length of the finite size heater, m
L	width of the domain, m

$\dot{m}_I$	interfacial mass flux, kg/m^2s
$\vec{n}$	unit normal vector of the interface
Nu_B	Nusselt number correlation of Berenson
Nu_K	Nusselt number correlation of Klimenko
Nu_{SD}	Nusselt number correlation of Son and Dhir
Nu_x	local Nusselt number
$Nu_{L, Avg}$	space averaged Nusselt number
$Nu_{T, Avg}$	time averaged Nusselt number
$\vec{n}$	unit normal vector of the phase interface
P	pressure, Pa
Pr	Prandtl number
$\dot{q}_I$	interface heat flux, W/m^2
r	radius, m
Ra	Rayleigh number, $g\beta(T_H-T_C)/\nu\alpha$
Re	Reynolds number, $\rho VL/\mu$
S_I	surface area of the interface line segment, m^2
S_C	surface of line segment bounded by the control volume cell, m^3
$S(\phi_o)$	signed function
t_o	time scale, $t_o = \sqrt{(\lambda_o / g)}$, s
t	time, s
T	temperature, K
$\mathbf{T}$	tensor
T_{Sat}	saturated temperature, K
T_I	liquid-vapour interface temperature, K

u_o	velocity scale, $u_o = (\lambda_o / t_o)$, m/s
u	velocity components in x direction, m/s
v	velocity components in y direction, m/s
V	velocity vector (u, v) , m/s
V_I	interfacial velocity due to phase change, m/s
$\vec{V}_s$	slip velocity, m/s
X	position vertex of the interface generic point, (x, y)
$\vec{X}$	position vector of the interface

Subscripts

adv	advancing contact angle
CL	contact line
$cell$	control volume cell
d	dynamic
e	equilibrium
f	fluid
g	gas phase
I	liquid-vapour phase interface
l	liquid phase
max	maximum
mt	mass transfer
rec	receding contact angle
s	static or solid surface
S	slip
st	surface tension

v vapour phase

Superscripts

n previous time level

$n+1$ current time level

Greek symbols

α thermal diffusivity, m^2/s

Δx grid size, m

Δt time step size, s

ΔT_{Sup} wall superheat, $(T_W - T_{Sat})$

δ vapour layer thickness, m

δ_s Dirac surface delta function

ε width of smoothed transition region, m

κ interfacial local mean curvature, $1/m$

λ_c critical wavelength, $\lambda_c = 2\pi\lambda_o$, m

λ_{d2} two-dimensional most dangerous wavelength, $\lambda_{d2} = \sqrt{3}\lambda_c$, m

λ_o characteristic capillary length scale, $\lambda_o = \sqrt{[\sigma / \{g(\rho_l - \rho_v)\}]}$, m

λ_s slip length, m

μ dynamic viscosity, $N \cdot s/m^2$

ρ density, kg/m^3

σ surface tension coefficient, N/m

τ non-dimensional time, (t/t_o)

ϕ continuous level set distance function, m

φ_n vertex signed distance function, m

Ω control volume, m^3

Acronyms

BGM	Bounded Gradient Maximization
CDS	Central Differencing Scheme
CFL	Courant-Friedrichs-Lewy convergence condition for PDE
CICSAM	Compressive Interface Capturing Scheme for Arbitrary Meshes
CLSVOF	Coupled Level Set and Volume of Fluid
CSF	Continuous Surface tension Force
CSS	Continuous Surface tension Stress
DCA	Dynamic Contact Angle
DR	Density Ratio
ELVIRA	Efficient Least squares Volume-of-fluid Interface Reconstruction Algorithm
EMFPA	Edge Matched Flux Polygon Advection
ENO	Essentially Non-Oscillatory scheme
FBICS	Flux Blend Interface Capturing Scheme
FMFPA	Face Matched Flux Polyhedron Advection
HRIC	High- Resolution Interface Capturing
LS	Level Set
LWENO	Linear Weighted Essentially Non-Oscillatory scheme
MAC	Marker And Cell method
MCL	Moving Contact Line
MCP	Moving Contact Point
PBM	Pressure Boundary Method
PDE	Partial Differential Equation
PLIC	Piecewise Linear Interface Calculation

PROST	Parabolic Reconstruction Of Surface Tension
PVC	Polyvinyl Chloride
QUASI	QUAadratic Spline based Interface
QUICK	Quadratic Upstream/Upwind Interpolation for Convective Kinematics
SCA	Static Contact Angle
SIMPLE	Semi-Implicit Method for Pressure Linked Equation
SIR	Spline-based Interface Reconstruction
SLIC	Simple Line Interface Calculation
SMART	Sharp and Monotonic Algorithm for Realistic Transport
STACS	Switching Technique for Advection and Capturing of Surfaces
TVD	Total Variation Diminishing
VOF	Volume of Fluid
VOSET	coupled Volume Of fluid and level SET
WENO	Weighted Essentially Non-Oscillatory scheme