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
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by

B. M. NINGEGOWDA

DEPARTMENT OF MECHANICAL ENGINEERING

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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

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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.

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NOMENCLATURE

A	area, m^2
$\boldsymbol{A}$	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
$\boldsymbol{I}$	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

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

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, $u_o = \left(\lambda_o / t_o\right)$, *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)

$\overrightarrow{X}$ 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, $\lambda_o = \sqrt{\left[\sigma / \left\{g\left(\rho_l - \rho_v\right)\right\}\right]}$, 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	QUAuadratic 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