COMPUTATIONS OF PHASE CHANGE FLOWS ON CURVED SURFACES USING MULTI-DIRECTIONAL INTERFACE CAPTURING METHODS

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Dedicated to my beloved mother and younger brother

Certificate

This is to certify that the thesis entitled **Computations of Phase Change Flows on Curved Surfaces using Multi-directional Interface Capturing Methods**, being submitted by **Mr. Rohit Kumar** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** in the Department of Mechanical Engineering is a bonafide record of the research work carried out by him under my guidance and supervision. To the best of my knowledge, the thesis has reached the requisite standard. We hereby declare that the content of the thesis, in full or in part, has not been submitted to any other Institute or University for the award of any degree or diploma.

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Rohit Kumar

Abstract

The small spatial and temporal scales associated with boiling problems make experimental measurements very challenging. On the other hand, direct numerical simulations of boiling flow problems can resolve the small spatial and temporal scales associated with the problem. Therefore, in the past two decades many numerical models have been developed for simulating boiling flow problems. For modelling boiling flow problems, accurate interface capturing and accurate prediction of the interfacial heat and mass transfer is very important.

For numerical simulations of phase change problems, the front tracking method and the interface capturing methods are widely used. However, the front-tracking method is very challenging to implement for boiling flow problems as interface breakup, and merger is very common in boiling flow problems. Therefore, the interface capturing method is preferred for modelling boiling flow problems. The volume of fluid (VOF), the level set (LS), and the coupled level set and volume of fluid (CLSVOF) methods are the popular interface capturing methods preferred for simulating boiling flow problems. However, the use of the VOF method alone leads to unwanted spurious currents in the vicinity of the interface whereas the LS method suffers from the mass loss problem. Therefore, the CLSVOF method is preferred for the direct numerical simulation of boiling flow problems. However, most of the CLSVOF methods available in the literature use the operator-split advection method which is computationally expensive, as it requires interface reconstruction twice and thrice for 2D and 3D problems, respectively. Additionally, most of the numerical studies reported in the literature were performed using structured mesh. Hence, these studies were mostly limited to simple geometries. However, for real-life applications, geometries are complex, and it will be easy to mesh these geometries with unstructured meshes. Thus, in the present work, a CLSVOF method has been proposed for 3D unstructured polyhedral meshes with multi-directional advection. The proposed CLSVOF was thoroughly validated against a number of standard advection test cases. The interface error norms obtained using the proposed CLSVOF method compare well with the results available in the literature, which were obtained using higher-order interface reconstruction techniques. The accuracy and

performance of the proposed CLSVOF method were also checked for various two-phase flow test cases without phase change. Finally, the proposed CLSVOF method was used to simulate natural convection film boiling over a 3D flat surface and a 3D horizontal cylinder. The present heat transfer results are in good agreement with the results available in the literature.

Many analytical and experimental studies on flow film boiling over a sphere are available in the literature. However, most of these studies are focused on subcooled and saturated flow film boiling over a sphere in the natural and forced convection regime. For the natural convection regime, the effect of the surface tension force and the size of the heated spherical surface under reduced gravity levels is not very clear from the literature. Therefore, in the present work, the proposed multi-directional CLSVOF method was used to numerically study the effect of the size of the heated sphere on the interface evolution and the associated heat transfer characteristics for natural convection film boiling over a sphere under different gravity levels. For flow film boiling over a sphere, there is no proper heat transfer data available in the literature for the mixed convection regime as compared to the forced convection regime. Therefore, the proposed multi-directional CLSVOF method was used to numerically study flow film boiling over a sphere in the mixed convection regime. Simulations were performed for both the vertical and the horizontal flow configurations. The interface evolution, vapour wake dynamics, and heat transfer have been thoroughly investigated by varying the saturated liquid flow velocity, sphere diameter, and wall superheat for both flow configurations.

The experimental studies in the literature have reported that peculiar structures appear in the vapour film as the fluid approaches the critical pressure for film boiling over a wire. However, the exact physics behind this observation is not clearly explained in the literature. Therefore, this problem is studied numerically in the present work.

The mixed convection regime can also be important in some scenarios for film condensation over a bank of cylindrical tubes. However, the literature on condensation over a bank of cylindrical tubes in the mixed convection regime is very limited. Therefore, in the present work, the proposed multi-directional CLSVOF method was used to simulate flow film condensation over an inline arrangement of two cylinders in the mixed convection regime. The interface evolution and the associated

heat transfer characteristics were thoroughly studied by varying various flow and geometrical parameters. The condensate removal from the top cylinder was mostly observed to be in the form of individual droplets. However, a liquid column is formed between the two cylinders as condensate from the top cylinder gets drained to the second cylinder. The number of droplet generation sites was observed to increase as the cylinder diameter is increased. Interfacial waves were evident in the liquid film around the bottom cylinder for the large diameter cylinder. These interfacial waves significantly affect the heat transfer for the bottom cylinder. As the wall subcooling increases, the condensate removal pattern between the top cylinder and the bottom cylinder changes from a combination of liquid droplets and columns to stable liquid columns.

Finally, a new multi-directional advection method based moment of fluid (MOF) method developed for 2D unstructured messh was extended to for 3D unstructured polyhedral mesh. The proposed multi-directional MOF method is computationally efficient and inexpensive than the multi-directional CLSVOF method proposed earlier in this work. The accuracy and performance of the proposed multi-directional MOF method were observed to be much better than the other multi-directional methods available in the literature.

सार

क्वथन समस्याओं से जुड़े छोटे स्थानिक और लौकिक पैमाने प्रयोगात्मक माप को बहुत चुनौतीपूर्ण बनाते हैं। दूसरी ओर, क्वथन प्रवाह समस्याओं के प्रत्यक्ष संख्यात्मक सिमुलेशन समस्या से जुड़े छोटे स्थानिक और लौकिक पैमानों को हल कर सकते हैं। इसलिए, पिछले दो दशकों में क्वथन प्रवाह समस्याओं के अनुकरण के लिए कई संख्यात्मक मॉडल विकसित किए गए हैं। क्वथन प्रवाह समस्याओं के मॉडलिंग के लिए, सटीक इंटरफ़ेस कैप्चरिंग और इंटरफ़ेसीय ऊष्मा और द्रव्यमान स्थानांतरण की सटीक भविष्यवाणी बहुत महत्वपूर्ण है।

चरण परिवर्तन समस्याओं के संख्यात्मक सिमुलेशन के लिए, फ्रंट ट्रैकिंग विधि और इंटरफ़ेस कैप्चरिंग विधियों का व्यापक रूप से उपयोग किया जाता है। हालाँकि, क्वथन प्रवाह समस्याओं के लिए फ्रंट–ट्रैकिंग विधि को लागू करना बहुत चुनौतीपूर्ण है क्योंकि क्वथन प्रवाह समस्याओं में इंटरफ़ेस ब्रेकअप और विलय बहुत आम है। इसलिए, क्वथन प्रवाह समस्याओं के मॉडलिंग के लिए इंटरफ़ेस कैप्चरिंग विधि को प्राथमिकता दी जाती है। द्रव की मात्रा (VOF), स्तर सेट (LS), और युग्मित स्तर सेट और द्रव की मात्रा (CLSVOF) विधियाँ लोकप्रिय इंटरफ़ेस कैप्चरिंग विधियाँ हैं जिन्हें क्वथन प्रवाह समस्याओं के सिमुलेशन के लिए प्राथमिकता दी जाती है। हालाँकि, अकेले VOF विधि के उपयोग से इंटरफ़ेस के आस–पास अवांछित नकली धाराएँ उत्पन्न होती हैं जबकि LS विधि द्रव्यमान हानि की समस्या से ग्रस्त है। इसलिए, क्वथन प्रवाह समस्याओं के प्रत्यक्ष संख्यात्मक सिमुलेशन के लिए CLSVOF विधि को प्राथमिकता दी जाती है। हालाँकि, साहित्य में उपलब्ध अधिकांश CLSVOF विधियाँ ऑपरेटर–विभाजन संवहन विधि का उपयोग करती हैं जो कम्प्यूटेशनल रूप से महंगी है, क्योंकि इसमें क्रमशः 2D और 3D समस्याओं के लिए दो बार और तीन बार इंटरफ़ेस पुनर्निर्माण की आवश्यकता होती है। इसके अतिरिक्त, साहित्य में रिपोर्ट किए गए अधिकांश संख्यात्मक अध्ययन संरचित जाल का उपयोग करके किए गए थे। इसलिए, ये अध्ययन अधिकतर सरल ज्यामिति तक ही सीमित थे। हालाँकि, वास्तविक जीवन के अनुप्रयोगों के लिए, ज्यामिति जटिल होती हैं, और इन ज्यामिति को असंरचित जालों के साथ जोड़ना आसान होगा। इस प्रकार, वर्तमान कार्य में, बहु–दिशात्मक संवहन के साथ 3D असंरचित बहुफलकीय जालों के लिए एक CLSVOF विधि प्रस्तावित की गई है। प्रस्तावित CLSVOF को कई मानक संवहन परीक्षण मामलों के विरुद्ध पूरी तरह से मान्य किया गया था। प्रस्तावित CLSVOF विधि का उपयोग करके प्राप्त किए गए इंटरफ़ेस त्रुटि मानदंड साहित्य में उपलब्ध परिणामों के साथ अच्छी तरह से मेल खाते हैं, जो उच्च–क्रम इंटरफ़ेस पुनर्निर्माण तकनीकों का उपयोग करके प्राप्त किए गए थे। प्रस्तावित CLSVOF विधि की सटीकता और प्रदर्शन को चरण परिवर्तन के बिना विभिन्न दो–चरण प्रवाह परीक्षण मामलों के लिए भी जाँचा गया।

अंत में, प्रस्तावित CLSVOF विधि का उपयोग 3D समतल सतह और 3D क्षैतिज सिलेंडर पर प्राकृतिक संवहन फिल्म उबलने का अनुकरण करने के लिए किया गया था। वर्तमान ऊष्मा स्थानांतरण परिणाम साहित्य में उपलब्ध परिणामों के साथ अच्छी तरह से मेल खाते हैं।

साहित्य में गोले पर फ्लो फिल्म क्वथन पर कई विश्लेषणात्मक और प्रायोगिक अध्ययन उपलब्ध हैं। हालाँकि, इनमें से अधिकांश अध्ययन प्राकृतिक और जबरन संवहन शासन में गोले पर उपशीतित और संतृप्त फ्लो फिल्म क्वथन पर केंद्रित हैं। प्राकृतिक संवहन शासन के लिए, कम गुरुत्वाकर्षण स्तरों के तहत सतह तनाव बल और गर्म गोलाकार सतह के आकार का प्रभाव साहित्य से बहुत स्पष्ट नहीं है। इसलिए, वर्तमान कार्य में, प्रस्तावित बहु–दिशात्मक CLSVOF विधि का उपयोग विभिन्न गुरुत्वाकर्षण स्तरों के तहत गोले पर प्राकृतिक संवहन फिल्म क्वथन के लिए इंटरफ़ेस विकास और संबंधित ऊष्मा हस्तांतरण विशेषताओं पर गर्म गोले के आकार के प्रभाव का संख्यात्मक रूप से अध्ययन करने के लिए किया गया था। गोले पर फ्लो फिल्म क्वथन के लिए, मजबूर संवहन शासन की तुलना में मिश्रित संवहन शासन के लिए साहित्य में कोई उचित ऊष्मा हस्तांतरण डेटा उपलब्ध नहीं है। इसलिए, मिश्रित संवहन शासन में गोले पर फ्लो फिल्म क्वथन का संख्यात्मक रूप से अध्ययन करने के लिए प्रस्तावित बहु–दिशात्मक CLSVOF विधि का उपयोग किया गया था। ऊर्ध्वाधर और क्षैतिज प्रवाह विन्यास दोनों के लिए सिमुलेशन किए गए थे। दोनों प्रवाह विन्यासों के लिए संतृप्त द्रव प्रवाह वेग, गोले के व्यास और दीवार के अतिताप को परिवर्तित करके इंटरफ़ेस विकास, वाष्प वेक गतिकी और ऊष्मा स्थानांतरण की गहन जांच की गई है।

साहित्य में प्रयोगात्मक अध्ययनों ने बताया है कि जब द्रव तार पर उबलने वाली फिल्म के लिए महत्वपूर्ण दबाव के करीब पहुंचता है, तो वाष्प फिल्म में अजीबोगरीब संरचनाएं दिखाई देती हैं। हालाँकि, इस अवलोकन के पीछे सटीक भौतिकी को साहित्य में स्पष्ट रूप से नहीं समझाया गया है। इसलिए, इस समस्या का वर्तमान कार्य में संख्यात्मक रूप से अध्ययन किया गया है।

मिश्रित संवहन व्यवस्था बेलनाकार नलियों के एक समूह पर फिल्म संघनन के लिए कुछ परिदृश्यों में भी महत्वपूर्ण हो सकती है। हालाँकि, मिश्रित संवहन व्यवस्था में बेलनाकार नलियों के एक समूह पर संघनन पर साहित्य बहुत सीमित है। इसलिए, वर्तमान कार्य में, मिश्रित संवहन व्यवस्था में दो सिलेंडरों की इनलाइन व्यवस्था पर प्रवाह फिल्म संघनन का अनुकरण करने के लिए प्रस्तावित बहु–दिशात्मक CLSVOF विधि का उपयोग किया गया था। विभिन्न प्रवाह और ज्यामितीय मापदंडों को बदलकर इंटरफ़ेस विकास और संबंधित ऊष्मा स्थानांतरण विशेषताओं का गहन अध्ययन किया गया। शीर्ष सिलेंडर से संघनन निष्कासन को अधिकतर व्यक्तिगत बूंदों के रूप में देखा गया। हालाँकि, दो सिलेंडरों के बीच एक

तरल स्तंभ बनता है क्योंकि शीर्ष सिलेंडर से संघनन दूसरे सिलेंडर में चला जाता है। सिलेंडर व्यास बढ़ने पर बूंद निर्माण स्थलों की संख्या में वृद्धि देखी गई। बड़े व्यास वाले सिलेंडर के लिए निचले सिलेंडर के चारों ओर तरल फिल्म में इंटरफेसियल तरंगें स्पष्ट थीं। ये इंटरफेसियल तरंगें निचले सिलेंडर के लिए ऊष्मा स्थानांतरण को महत्वपूर्ण रूप से प्रभावित करती हैं। जैसे–जैसे दीवार का उपशीतलन बढ़ता है, शीर्ष सिलेंडर और निचले सिलेंडर के बीच संघनन निष्कासन पैटर्न तरल बूंदों और स्तंभों के संयोजन से स्थिर तरल स्तंभों में बदल जाता है।

अंत में, 2D असंरचित मेस के लिए विकसित एक नई बहु–दिशात्मक संवहन विधि आधारित द्रव का क्षण (MOF) विधि को 3D असंरचित बहुफलकीय जाल के लिए विस्तारित किया गया। प्रस्तावित बहु–दिशात्मक MOF विधि इस कार्य में पहले प्रस्तावित बहु–दिशात्मक CLSVOF विधि की तुलना में कम्प्यूटेशनल रूप से कुशल और सस्ती है। प्रस्तावित बहु–दिशात्मक MOF विधि की सटीकता और प्रदर्शन साहित्य में उपलब्ध अन्य बहु–दिशात्मक विधियों की तुलना में बहुत बेहतर पाया गया।

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Nomenclature

	Alphabetical
$\vec{V}$	Velocity, [m/s]
$\vec{V}_I$	Interface velocity, [m/s]
$\vec{V}_{mt}$	Interface velocity due to mass transfer, [m/s]
v_c, V_c	Volume of the computational cell, [m^3]
V_f	Volumetric flux through a face, [m^3]
v_{fl}	Net fluid volume leaving a mixed cell, [m^3]
V_d	Advected volume, [m^3]
V_p	Flux polyhedron volume, [m^3]
p	Pressure, [Pa]
F_s	Volumetric surface tension force, [N/m^3]
$\vec{g}, g, g_e$	Gravitational constant, [m^2/s]
C_p	Specific heat at constant pressure, [J/kg $\cdot$ K]
T	Temperature, [K]
k	Thermal conductivity, [W/m $\cdot$ K]
$\dot{m}$	Interfacial mass flux, [kg/m^2 $\cdot$ s]
q_I	Interfacial heat flux, [W/m^2]
q_n	Normal heat flux, [W/m^2]
t	time, [s]
Δt	time step size, [s]
h_{lg}	Latent heat, [J/kg]
H	Heaviside function
Nu	Nusselt number
h	Characteristic cell size
u, v, w	x,y and z velocity components, [m/s]
p/p_c	Pressure ratio
p_t	Pitch between the cylinders, [m]

Fr	Froude number
D	Diameter, [m]
D_{vb}	Vapour bubble diameter, [m]
U_∞	Free-stream velocity, [m/s]
$\bar{h}$	Average heat transfer coefficient, $[\mathrm{W/m^2 \cdot K}]$
N	Number of cylindrical tubes
$\hat{n}$	Interface unit normal vector
$\hat{n}_{f_c}$, $\hat{n}_f$	Face unit normal vector
S_f	Face area, $[\mathrm{m^2}]$
Re	Reynolds number
Eo	Eötvös number
M	Morton number
Gr	Grashof number
Pr	Prandtl number
Ja	Jacob number
Bo	Bond number
d_b/D	Dimensionless departure bubble diameter, [m]
$\mathcal{M}_0$	Zeroth moment of fluid
$\mathcal{M}_1$	Second moment of fluid
$\mathbf{x}_\Omega$	Fluid centroid
$area$	Area, $[\mathrm{m^2}]$
	Greek symbols
ρ	Density, $[\mathrm{kg/m^3}]$
τ	Stress tensor
σ	Coefficient of surface tension, [N/m]
κ	Interfacial curvature, $[\mathrm{m^{-1}}]$
δ	Dirac delta function
α	Volume fraction
α_{mt}	Rate of generation of volume fraction
ϕ	Level set function
μ	Viscosity, $[\mathrm{Pa \cdot s}]$
ϵ	Emissivity
σ_{SB}	Stefan-Boltzmann constant, $[\mathrm{W/m^2 \cdot K^4}]$
τ_v	time-averaged vapour film thickness at the front stagnation point

θ_s	flow separation angle
λ_0	Capillary length scale, [m]
λ_c	Critical wavelength, [m]
λ_d	Most dangerous wavelength, [m]
	Superscripts
$n+1$	present time step
n	previous time step
	Subscripts
I	Interface
l	Liquid phase
g	Vapour phase
sat	Saturation
sup	Superheat
sub	Subcooling
avg	Average
$quad$	Quadilateral cells
w, $wall$	wall
	Acronyms
VOF	Volume of fluid
FT	Front tracking method
LS	Level set method
CLSVOF	Coupled level set and volume of fluid method
MOF	Moment of fluid method
Str	Structured mesh
Unstr	Unstructured mesh
PF	Phase field method
CICS	Compressive high-resolution interface capturing scheme
CSF	Continuum surface force
HPC	High performance computing
MPI	Message passing interface
PLIC	Piecewise linear interface calculation
EMFPA	Edge matched flux polygon advection

FMFPA	Face matched flux polygon advection
ELVIRA	Efficient least squares volume of fluid interface reconstruction algorithm
PROST	Parabolic reconstruction of surface tension
SIR	Spline interface reconstruction
QUASI	Quadratic spline interface reconstruction
VOSET	Coupled volume of fluid and level set method
AMR	Adaptive mesh refinement
EI-LE	Eulerian-implicit and Lagrangian-explicit
CLSMOF	Coupled level set and moment of fluid method
IDW	Inverse Distance Weighted
GMRES	Generalized minimal residual method
FFT	Fast-Fourier transform