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Research Paper

Numerical simulation of subcooled flow boiling under conjugate heat transfer and microgravity condition in a vertical mini channel

M. Bahreini, A. Ramiar*, A.A. Ranjbar

Faculty of Mechanical Engineering, Babol Noshirvani University of Technology, Babol, Iran

HIGHLIGHTS

- Void fraction changes along the mini channel from terrestrial to micro gravity.
- Bubble departure diameters are strongly influenced by gravity.
- Terrestrial frictional pressure loss becomes 2.1 times larger than micro gravity.
- Heat transfer coefficient increases with a declination in gravity.

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ABSTRACT

In this study, subcooled flow boiling in a vertical mini channel is simulated using Color Function Volume Of Fluid (CF-VOF) in micro gravity condition. The continuous surface force model and Lee model are used for analyzing surface tension forces and mass transfer via interface, respectively. The Newtonian flow equations are solved using the finite volume method, which is based on the Pressure Implicit with Splitting of Operators (PISO) algorithm. The existing OpenFOAM two phase solver i.e. interFoam was developed by adding energy equation and the source terms corresponding phase change. Moreover, in order to increasing the accuracy of the simulation, the effect of axial conduction is taken into account by applying the conjugate heat transfer model. The validation of developed solver and mathematical model indicates a proper compliance with experimental data of technical literature. Results show variation in flow patterns and heat transfer coefficients in the micro gravity (gravity level of ±0.05g) condition comparing with the normal gravity condition. Moreover, it is found that some imperative parameters such as heat flux and mass flux affect aforementioned patterns and coefficients. In addition, simulation results show that the size of bubbles formed in the micro gravity condition is larger than the bubbles in normal gravity condition and the variation in the size of bubbles increases the heat transfer coefficient in the micro gravity (%22) compared to the normal gravity condition.

1. Introduction

Two-phase thermal systems are significantly practical in a plethora of industries and engineering areas. The applications of heat transfer caused by subcooled flow boiling include power plants (energy production or conversion), cooling liquids transportation and other chemical or petrochemical processes. Thus, the understanding of boiling mechanisms is of importance for accidental off-design situations. Latent heat transfer is one of the benefits of such systems which results in an appropriate performance in heat exchangers. Therefore two phase thermal management system usage is particularly advantageous for space practical programs. In fact, in satellites or space platforms, one of the major problems is removing the heat that is produced by devices, in a way that less harm the environment and working conditions. Furthermore, due to the growing interest in space applications like communication satellites, and increase of required power for onboard devices, complicated management systems are essential to deal with the large heat loads [1]. Subcooled flow boiling process is a complex phenomenon which is a combination of heat and mass transport, hydrodynamic and interfacial phenomena. Due to the great capacity of heat transfer accompanied by phase change and slight change in temperature, this phenomenon would be an appropriate solution to reduce the size and weight of thermal systems. Moreover, effect of gravity in fluid dynamics may cause some unpredictable performance changes in thermal management systems. Therefore, it is required to perform experiments in an

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* Corresponding author.
E-mail address: aramiar@nit.ac.ir (A. Ramiar).

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Nomenclature

A_i	interfacial surface area (m^2)
C_α	compression factor
C_p	specific heat (J/kg K)
D_h	hydraulic diameter (m)
g	gravity acceleration (m/s^2)
h_{LG}	latent heat (J/kg)
k	thermal conductivity (W/m^2 K)
L	length (m)
L_c	Laplace length (m)
M	molecular weight (kg/kmol)
$\dot{m}'''$	condensate or evaporate mass flow rate per unit volume (kg/m^3 s)
p	pressure (Pa)
r	smooth parameter
r_e	evaporation mass transfer time relaxation parameter (1/s)
r_c	condensation mass transfer time relaxation parameter (1/s)
R	universal gas constant (J/Mol K)
Re	Reynolds number ($\rho_L U D_h/\mu_L$) (–)
T	temperature (K)
T_w	wall temperature (K)
ΔT	temperature difference (K)
U	velocity (m/s)
U_c	compressive velocity (m/s)
W	width (m)

Greek symbols

α	volume fraction factor
κ	interface curvature (1/m)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
σ	surface tension (N/m)
χ	evaporation or condensation coefficient
ϕ_N	flux at neighbor cell (ms)
ϕ_p	flux at evaluated cell (ms)

Subscripts

a	acceleration associated with phase change
f	fluid/stands for two phase or single phase
g	gravitational
G	gas
ie	Inlet and exit region
inlet	inlet
L	liquid
s	solid
sat	saturation
sp	single phase
tp	two phase
v	vapor

arrhythmic environment. However, flow boiling heat transfer experiments in micro gravity condition require large heat loads and space. These factors may restrict test equipment and taking a test for more than once may not be possible. This problem can lead to doubtful received data and lack of consistency between measurements. Thus, numerical simulations are for the key solution of understanding flow boiling mechanism in micro gravity condition. One of the most important advantages of numerical simulation is of possibility of considering complicated geometries and various situations [1].

Experimental study of two phase flow in micro gravity condition was widely performed in technical literature especially in adiabatic cases [2–5] and conditions that include both heat transfer and phase change [1,6–9]. The experiments of micro gravity condition were conducted in different cases such as drop tower [10], parabolic flight platforms [8] and acoustic jets [5]. Yang et al. [11] studied numerically the effect of micro gravity on heat transfer and bubble behaviors. They found that bubble growth in micro gravity condition is more complex than in the normal case and it depends on the value of micro gravity. Moreover, they found that there is a variation of bubble diameter in micro gravity condition and the amplitude of vibration in heat transfer coefficient increases with the micro gravity value.

Dhir [12] numerically and experimentally studied nuclear boiling in micro gravity condition in order to understand it's mechanism. Esmaeeli and Tryggvason [13] simulated explosive boiling in micro gravity condition. They used front tracking technique for solving problem and validated their numerical results with the help of analytical correlations. Pu et al. [14] simulated condensation bubble in micro gravity condition by using moving mesh method in the Double-staggered Grid. Their results showed that condensation process was different under two micro gravity and normal conditions. A major advantage of numerical modeling of heat transfer problems is detailed information about flow and temperature fields that can be obtained. However, continuous deformation of the liquid-vapor interface, small spatial-temporal scale, and high nonlinearity of governing equations impose significant complexities on numerical solutions of boiling problems. Interface tracking method i.e. level-set (LS) [15], volume of fluid (VOF) [16,17], front tracking (FT) [18] and other numerical methods such as Lattice Boltzmann (LBM) [19] are methods which have been widely used for numerical simulations of two-phase isothermal flows. It has been near one decade that working on phase change process in two-phase flows using interface tracking method has attracted attentions [20,21]. Also, early attempts to apply the phase change LBM to boiling and condensation heat transfer were not successful owing to the facts that the source term in the energy equation was wrongly derived and the method could only be applied to problems of small vapor/liquid density ratios (i.e., at a high temperature near the critical temperature). Most recently, some authors proposed an improved lattice Boltzmann method for liquid–vapor phase-change heat transfer which has overcome some of these shortcomings [22–24]. Despite complexities of phase change flow such as different spatial and temporal scales, numerical simulation of this process is still one of the most important research fields, because of the extensive applications. Analysis of conjugate heat transfer generally requires solving the Navier-Stokes and energy equations for the fluid side coupled with the energy equation for the solid side. Numerical methods for the solution of the conjugate problem with single-phase fluids have been well established. However, analysis of conjugate heat transfer involving boiling fluids represents a much more challenging problem [25].

Although diverse works have been devoted to the subcooled flow boiling in different conditions, there still are many applications that have not been addressed in the literature. In the present work, numerical investigation of the subcooled flow boiling under microgravity condition is carried out. The influence of gravity on pressure drop, heat transfer and flow pattern in micro gravity (0.05g) and normal gravity (g) is studied and compared with experimental data [26]. Also the effect of axial conduction and conjugate heat transfer is taken into account.