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Comparison of phase interaction models for high pressure subcooled boiling flow in long vertical tubes

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A R T I C L E I N F O

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A B S T R A C T

In this article, Eulerian two fluid model is used for prediction of high pressure subcooled nucleate flow boiling in vertical tubes. Predictions of different turbulence models, phase interaction models have been compared with previous experimental data. Axial and radial profiles of vapor fraction and liquid temperature have been used for comparison of these models. Bubble departure diameter models and bubble induced turbulence models show the significant effect on the vapor fraction prediction. It was found that use of Kocamustafaogullari and Ishii models for bubble departure diameter and nucleation site density are suitable for predicting vapor distribution and liquid temperature for high pressure boiling. Models of interfacial heat transfer and bubble departure frequency developed for low pressure or atmospheric conditions showed a good applicability for high pressure conditions also. Inclusion of wall lubrication force showed the void fraction peak near the wall. Simulated pressure drop predictions for high pressure flow boiling in a 13 m long vertical tube shows the error of 2–10% with experimental data. This indicates that computational fluid dynamics (CFD) is the promising technique for pressure drop prediction.

1. Introduction

The word subcooled itself means that temperature of the fluid is below its saturation temperature. Subcooled boiling has important characteristics of high heat transfer coefficient. The phenomenon of subcooled boiling play an important role in flow boiling. It appears in steam generator tubes in thermal power plants as well as nuclear power plants, electronics cooling systems, boilers. Fig. 1 shows the phenomenon of subcooled boiling. When wall temperature reaches above local saturation temperature, vapor bubbles are generated on wall nucleation sites as fluid is exposed to a heated wall. This point is called onset of nucleate boiling (ONB). The temperature of liquid in the vicinity of the wall reaches its saturation temperature, while a temperature of the bulk of the liquid is still below saturation. Vapor bubbles detached from the wall carry latent heat with them. Bubbles are condensed when come in contact with bulk liquid in the core region. Effect of subcooling is high in this region. At a point when subcooling effect decreases, significant vapor generation takes place. This point is called Onset of void (OSV) (Collier and Thome, 1994).

Subcooled boiling phenomenon significantly affects thermal hydraulics of the system because of non-uniform vapor distribution. Many aspects of high pressure subcooled boiling flow such as uneven distribution of vapor, temperature, mass velocity etc. need to be understood well as system pressure has the significant effect on heat transfer characteristics through subcooled flow behavior (Yun et al., 2012). Pressure drop prediction for flow boiling in a long vertical tube is one of the important tasks. Pressure drop is mainly dependant on vapor fraction. A computational modeling approach for flow boiling problems has received increased attention in recent years (Končar and Krepper, 2008; Murallidharan et al., 2016). In order to predict subcooled nucleate boiling flow behavior at local scale, comparative study of different phase interaction forces, turbulence models, and boiling models need to be done. Many variables such as temperature, void fraction, velocity are related to each other in these models. In addition, parameters like bubble departure diameter, bubble departure frequency, nucleation site density plays an important role in flow boiling phenomenon. Therefore, several correlations were developed by different researchers to model these variables and to visualize flow behavior. The selection criterion for these models needs to be decided with proper analysis of results.

Present work involves comparison of different phase interaction force models, turbulence model, and boiling models. Eulerian two fluid model coupled with wall boiling model is used for comparison of these models. CFD simulations for comparison of different models were

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Nomenclature

T_w	wall temperature, (K)
T_l	liquid temperature, (K)
T_i	inlet temperature, (K)
C_p	specific heat, (J/kg K)
h_{lv}	latent heat of vaporization, (J/kg)
k	thermal conductivity, (W/m K)
d_{bw}	bubble departure diameter, (m)
g	acceleration due to gravity, (m/s)
P	pressure, (N/m^2)
T_{sat}	saturation temperature, (K)
U_b	near wall liquid bulk Velocity, (m/s)
U_o	liquid bulk velocity, (m/s)
$\vec{u}$	velocity, (m/s)
$\dot{m}$	mass flow rate, (kg/s)
H	specific enthalpy, (J/kg)
$\lvert\vec{U_r}\rvert$	relative velocity between vapor and liquid, (m/s)
q	heat flux, (W/m^2)
d_b	bubble diameter, (m)
D	pipe diameter, (m)
Re	Reynolds Number
Pr	Prandtl Number
Sc	Schmidt Number
y_w	distance from near wall cell, (m)
C_D	Drag Coefficient
C_L	lift force coefficient
F	force, (N)
A	area, (m^2)
N_a	nucleation site density, (No. of sites/m^2)
t_w	waiting period, (s)
f	bubble departure frequency (s^{-1})
h	heat transfer coefficient, (W/m^{2}s)
q_{c1}	single phase convective heat flux to liquid
q_{c2}	single phase convective heat flux to vapor
S	source term
C_{vm}	virtual mass coefficient
R_c	critical cavity size base on wall superheat, (m)
D_c	critical cavity diameter, (m)
R_a	arithmetic average roughness
Q	heat, (W)

Greek

σ	surface tension, (N/m)
ρ	density, (kg/m^3)
α	volume fraction, (–)
Γ_c	interfacial rate of condensation, (kg/s)
ΔT_{sup}	($T_w - T_{sat}$), Superheated temperature, (K)
ΔT_{sub}	($T_{sat} - T_l$), Subcooled temperature, (K)
μ	viscosity, (kg/m s)
ϕ	contact angle, (deg.)
β	dimensionless bubble diameter, (–)

Subscripts

v	vapor
l	liquid
s	solid
k	phase k
i	phase i
w	wall
in	inlet
c	convective
q	quenching
e	evaporative
lv	liquid to vapor
vl	vapor to liquid
con	condensation
eq.	equivalent
D	drag
L	lift
WL	wall lubrication
TD	turbulent dispersion

Superscripts

*	dimensionless quantities
T	turbulent

Abbreviations

CFD	Computational Fluid Dynamics
ID	Inner Diameter
SST	Shear Stress Transport
RNG	Renormalization Group
RSM	Reynolds Stress Model

performed for high pressure subcooled boiling experiments of Bartolomei and Chanturiya (1967). Based on comparison study, CFD modeling strategy has been developed and validated.

2. Literature review

Different aspects of modeling studies of subcooled boiling water in a vertical tube have been carried out in the past few years. Table 1 shows a summary of models used by different researchers. Very few experimental studies on high pressure subcooled boiling in a vertical tube are available in the literature. More precise experimental study has been done by Bartolomei and Chanturiya (1967) and Bartolomei et al. (1982) on high pressure subcooled boiling in a vertical tube with water as working fluid. Heated tubes made up of stainless steel material having length of 2 m and different inner diameters of 15.4 mm, 24 mm, and 12 mm were used in the studies. Liu et al. (2010) carried out pressure drop studies for flow boiling in vertical tube of 13.4 m length and inner diameter of 11.6 mm at pressure of 150 bar. Experimental studies on two phase flow boiling for refrigerants and water at high as well as low pressure have been mentioned in Table 2. Detailed discussion about modeling studies done by various researchers is described below.

Končar et al. (2004), Krepper et al. (2007), Končar and Krepper (2008) and Krepper and Rzehak (2011) have taken substantial efforts for prediction of the subcooled boiling flow behavior of water as well as refrigerants using CFD tool. Details about several models on bubble departure diameter, nucleation site density, bubble departure frequency are provided by Murallidharan et al. (2016) as well as Cheung et al. (2014). Zhang et al. (2015) studied the effect of different turbulence models on prediction of subcooled boiling flow in vertical tube boiling.

Končar et al. (2004) proposed a new model for local bubble diameter which is coupled with bubble departure diameter. This model has been validated against experimental data of Lee et al. (2002) for subcooled nucleate boiling of water in vertical annulus at low pressure. Free slip boundary condition has been given to vapor near the wall. According to authors, wall lubrication and turbulent mixing are weak to