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International Journal of Heat and Mass Transfer 49 (2006) 171–186
International Journal of HEAT and MASS TRANSFER
www.elsevier.com/locate/ijhmt

Choking flow modeling with mechanical and thermal non-equilibrium

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Received 24 May 2005; received in revised form 20 July 2005
Available online 1 December 2005

Abstract

The mechanistic model, which considers the mechanical and thermal non-equilibrium, is described for two-phase choking flow. The choking mass flux is obtained from the momentum equation with the definition of choking. The key parameter for the mechanical non-equilibrium is a slip ratio. The dependent parameters for the slip ratio are identified. In this research, the slip ratio which is defined in the drift flux model is used to identify the impact parameters on the slip ratio. Because the slip ratio in the drift flux model is related to the distribution parameter and drift velocity, the adequate correlations depending on the flow regime are introduced in this study. For the thermal non-equilibrium, the model is developed with bubble conduction time and Bernoulli choking model. In case of highly subcooled water compared to the inlet pressure, the Bernoulli choking model using the pressure undershoot is used because there is no bubble generation in the test section. When the phase change happens inside the test section, two-phase choking model with relaxation time calculates the choking mass flux. According to the comparison of model prediction with experimental data shows good agreement. The developed model shows good prediction in both low and high pressure ranges.

Keywords: Choking mass flux; Mechanical non-equilibrium; Thermal non-equilibrium; Slip ratio; Relaxation

1. Introduction

The choking flow is the phenomenon which occurs in very wide range of engineering industry. This phenomenon is the most important in the nuclear power plant which is cooled by the water. In the loss of coolant accident (LOCA) situation, the choking flow determined the water inventory of the reactor vessel, and the integrity of core eventually depends upon the choking flow [1]. Therefore, the analytical description and prediction of choking flow rate plays an important role in the design of the engineered safeguards in the nuclear power plant. The serious study for two-phase flow started from 1892 by Sauvage [2]. Rateau [3] showed the existence of choking flow in the boiling water through the nozzle. Historically mechanical and thermal equilibrium between gas and liquid phases were commonly assumed in the early choking flow models. This model is called the homogeneous equilibrium model. However, this assumption is valid only for some ideal conditions such as for a long pipe where there is sufficient time for equilibrium to be achieved and when the flow pattern gives sufficient interphase forces to suppress significant relative motion.

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0017-9310/$ - see front matter © 2005 Published by Elsevier Ltd.
doi:10.1016/j.ijheatmasstransfer.2005.07.044

Nomenclature

A	area
C_o	distribution parameter
c_p	specific heat
D	diameter
D_d	bubble departure diameter
f_d	bubble departure frequency
F	function
g	gravitational acceleration
G	mass flux (kg/m^2 s)
h	enthalpy
J	multiplier
k	Boltzmann constant
L	length
$\dot{m}$	mass flow rate
P	pressure
s	entropy
S	slip ratio
t	time
T	temperature
T_c	critical temperature
T_r	reduced temperature
V	velocity
$\langle\langle V_{gj}\rangle\rangle$	weighted drift velocity
$\overline{V}_{gj}$	mean drift velocity
x	quality
z	axial distance

Greek symbols

α	void fraction
β	volumetric thermal expansion coefficient
Γ	mass change rate
θ	contact angle
ρ	density
Σ	depressurization rate
τ	shear stress, relaxation time

Subscripts

c	choking
char	characteristic
cond	conduction
down	downstream
e	equilibrium
f	liquid
fl	flashing
g	vapor or gas phase
growth	bubble growth
i	interface
in	inlet or initial
m	mixture
nucl	nucleation
o	stagnation
s	saturation
sat	saturation
sub	subcooling
tot	total
up	upstream
w	wall
x–s	cross-section

2. Review of choking flow models

It is also important to understand the existing choking flow models. In this section, the choking flow models are classified as homogeneous equilibrium, homogeneous non-equilibrium, non-homogeneous equilibrium, and non-homogeneous non-equilibrium model.

2.1. Homogeneous equilibrium model

According to Starkmann's homogeneous equilibrium model [4], it is based on the assumptions of no slip, thermal equilibrium between phases, isentropic expansion and equation of state in the steam table. According to this model the choking mass flux in the homogeneous equilibrium model depends not on the break geometry or pipe length but on the upstream thermodynamic condition.

A feature of the homogeneous equilibrium model is adherence of the fluid properties along the saturation condition. In reality, the liquid can be superheated in order to nucleate near the wall during the depressurization process. If the single-phase liquid velocity is high enough, the choking flow may occur at the outlet of the pipe with the nucleation of the first bubble. If the coolant temperature is low and nucleation is suppressed by non-equilibrium phenomena, it might be required to consider the transition from single-phase to two-phase choking flow during the early stage of a blowdown in a LOCA analysis [5]. According to the review of Abdollahian et al. [6], the homogeneous equilibrium model showed good agreement with the Marviken critical flow data for subcooled stagnation condition and long pipe condition ($L/D > 1.5$). However, in general, the homogeneous equilibrium model is the simplest approach and not highly accurate for the subcooled liquid stagnation state [1]. Recently, Fthenakis et al. [7] showed that the homogeneous equilibrium model can overestimate the choking flow rate in case that the break is large, and that makes the rapid depressurization. However,