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Research paper

Modeling of annular-mist flow during mixtures boiling

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HIGHLIGHTS

- Mixture boiling process is studied numerically by the annular-mist flow model.
- The coupled thermodynamic and hydrodynamic non-equilibrium effects are considered.
- The effect of initial entrainment fraction and nucleation-induced entrainment is studied.
- The sensitivity analysis for eleven parameters is carried out.
- The effect of non-uniform heat flux distribution is investigated.

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ABSTRACT

This work presents a one-dimensional, steady-state, three-field model to simulate the annular-mist flow regime during mixtures boiling process. The governing equations with the additional constitutive models are solved to predict the occurrence of the film dryout. The effect of various setups for the initial entrainment fraction and the nucleation-induced entrainment on the predicted dryout quality is investigated. It is found that the result of the model considering both a large initial entrainment and a non-negligible nucleation-induced entrainment shows the best agreement with the experimental data from the literature. The sensitivity analysis of the total eleven semi-empirical/empirical parameters is carried out. The dryout for the mixtures boiling under non-uniform heat flux distributions is studied, and it is observed that the local critical heat flux and the dryout location are almost linearly dependent on the mixture compositions under non-uniform heat flux distributions.

1. Introduction

Heat exchangers are the main components in refrigeration, liquefaction and power generation systems. The study of flow and heat transfer characteristics of convective boiling is of importance for the design of heat exchangers, in terms of capital cost and technical challenges. Particularly, the critical heat flux and the onset of boiling crisis are the major issues in evaluating the performance of the heat exchangers.

The critical heat flux (CHF) is characterized by a sharp reduction of the local heat transfer coefficient which results from the replacement of liquid by vapor adjacent to the heat transfer surface [1]. There are mainly two mechanisms causing CHF conditions: departure from nucleate boiling (DNB) and the liquid film dryout which often occurs at a low and high quality, respectively. The CHF for single component boiling has been extensively studied with both experimental work and numerical modeling. Nevertheless, the research on CHF for mixtures is still limited. Celata et al. [2] experimentally investigated the CHF for binary mixtures of different compositions in forced convective upflow, and they found a linear dependence on inlet mole fraction of the CHF in the case of DNB type crisis while a negligible dependence in the dryout conditions. Sindhuja et al. [3] carried out experiments on the CHF for a ternary refrigerant mixture, and they deduced the experimental data may be attributed to dryout mechanism based on the negligible dependence on mixture effects of the CHF. Barbosa et al. [4] did both experimental and numerical research on CHF for mixtures in upward flow. They observed an over-prediction of dryout quality due to the inaccuracy of the correlations for the prediction of entrainment and deposition. They proposed a correction for the droplet interchange rates correlations and found that it improved the prediction of dryout quality for single component but less affected mixtures.

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Nomenclature

A	interfacial area density [m^2/m^3]
C_D	droplet concentration in the core [kg/m^3]
c_p	specific heat capacity [J/kg K]
D	diameter of tube [m]
d	mean diameter of droplets [m]
E_0	initial entrainment fraction
F	slope of heat flux profile
f	friction factor
G	longitudinal mass flux [kg/m^2 s]
H	enthalpy [J/kg]
h	heat transfer coefficient [W/m^2 K]
ΔH_{FG}	specific enthalpy of vaporization [J/kg]
k_{dep}	deposition rate coefficient [m/s]
L	axial length [m]
p	pressure [Pa]
Q	heat flux [W/m^2]
Re	Reynolds number, $Re_F = G_F\delta/\mu_F$, $Re_D = \rho_G d\|u_G - u_D\|/\mu_G$
T	temperature [K]
u	velocity [m/s]
W	mass transfer rate per unit area [kg/m^2 s]
X	mass fraction
x	vapor quality
z	axial coordinate along the pipe [m]

Greek symbols

α	void fraction
β	mass transfer coefficient [m/s]
δ	liquid film thickness [m]
μ	viscosity [Pa s]
ρ	density [kg/m^3]
σ	surface tension [N/m]
τ	shear stress [N/m^2]

Subscripts

1	component 1
2	component 2
avg	average
CHF	critical heat flux
D	droplets
dep	deposition
DG	droplets-gas
do	dryout
eb	entrainment due to burst of boiling bubbles
evap	evaporation
ew	entrainment due to breakup of disturbance waves
F	liquid film
FC	critical liquid film
FG	film-gas
G	gas core
i	interface
in	inlet
oaf	onset of annular flow
w	pipe wall

The aim of this work is to present a three-field model for the prediction of dryout of binary mixtures boiling. The mathematical model including both conservation and constitutive equations is presented in Section 2. Section 3 shows the validation of the model by comparing the results with experimental data from Celata et al. [2]. The sensitivity analysis for the semi-empirical models and parameters affecting the dryout quality are also carried out. Section 4 investigates the effect of non-uniform heat flux distributions on the dryout of mixtures. Final comments and conclusions are made in Section 5.

2. Problem description and model formulation

The problem describes a binary mixture flowing and boiling in a vertical round tube. The physical model is based on the annular-mist flow regime characterized by a liquid film, droplets and a vapor phase, as sketched in Fig. 1. The liquid droplets caused by the breakup of disturbance waves and the burst of boiling bubbles are entrained from the liquid film to the vapor core. Meanwhile, some droplets are also deposited from the vapor core to the liquid film. The vapor bubbles are generated from the liquid evaporation and move to the vapor core. The model is used to predict the occurrence of the dryout condition where the liquid film is depleted and the vapor is in contact with the wall.

A one-dimensional, steady-state, three-field model is presented to simulate the annular-mist flow regime during the mixtures boiling. The mathematical formulation considers the axial evolution of ten variables: volume fraction α_k, velocity u_k and composition by mass X_k for each field k (F = film, D = droplets, G = gas) and pressure p.

The mass conservation equations for each field are:

$$\frac{d}{dz}(\alpha\rho u)_F = A_{FG}\left(W_{dep} - W_{ew} - W_{eb}\right) - \frac{4}{D}W_{evap} \quad (1)$$

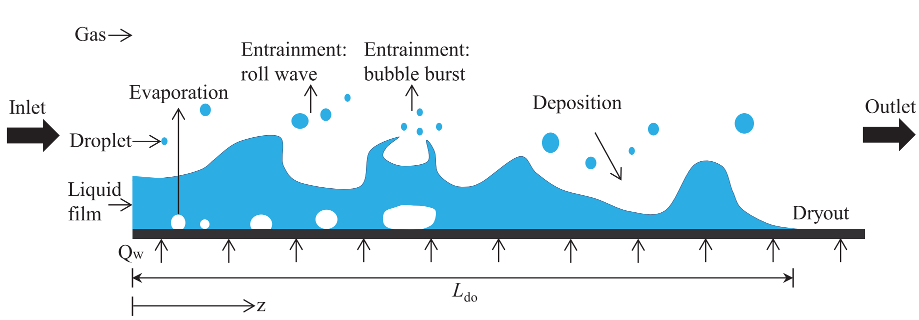

Fig. 1. Physical model.