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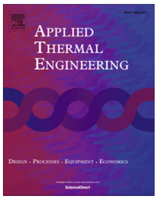

Dryout quality prediction for boiling two-phase flow in vertical helically coiled tubes

Xiaojuan Niu, Huaijie Yuan, Chen Quan, Liang Zhao *

State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an, China

HIGHLIGHTS

- A dryout quality prediction model for vertical helically coiled tubes is proposed.
- Three dimensionless numbers are used to modify the net entrainment rate.
- The dryout quality model for helical tube is assessed by the experimental data.

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ABSTRACT

An analytical model for the prediction of the onset of dryout quality in annular flow regime in helically coiled tubes is present in this paper. According to the liquid film dryout mechanism, film dryout is primarily dependent on the competition between droplet entrainment and deposition with a certain heat flux. To this effect, it is necessary to define the net entrainment rate in the helical tube. The factors significantly affecting the droplet entrainment and deposition characteristics in the helical tube are analyzed theoretically. Three dimensionless numbers are used to modify the net entrainment rate in straight tube. A total of 252 experimental points from 6 different datasets are used to test the performance of the model. Comparisons between the calculated and experimental results in literatures indicate that the present model has good predictive capability in predicting onset of dryout in helically coiled tubes.

1. Introduction

The critical heat flux phenomenon is usually accompanied by a sharp decrease in heat transfer coefficient and sudden increase in wall temperature, which has a significant influence on the safe and efficient operation of heat exchangers. In some industrial applications, heat exchangers must be operated under post-dryout conditions [1] where the accurate prediction of onset of dryout quality is essential.

Many experimental and theoretical research works have been carried out concerning the onset of dryout vapor quality in straight pipes. Various prediction methods including flow charts, look-up tables, empirical correlations, and mechanism models have been proposed. Existing dryout prediction models in straight tubes can be generally divided into two categories. The first category is represented by models proposed by Carey et al. [2] and Marathe et al. [3], in which the dryout quality was defined as the quality that corresponds to the peak of the two-phase heat transfer coefficient. This kind of model implements easily, but the prediction results are heavily dependent on the accuracy and form of the correlation of the two-phase heat transfer coefficient. What's more, the effect of gravity was not taken into consideration in these models and these models are more suitable in predicting dryout quality in vertical straight pipes and horizontal pipes with high velocity.

The second category of prediction model is based on the liquid film dryout mechanism in annular flow regime. Liquid droplets are entrained into the gas phase and then re-deposited onto the surface of the liquid film due to the turbulent pulsation of the gas core. The liquid film mass flux decreases along the flow direction under the combined action of entrainment and evaporation, and dryout occurs once the liquid film flow rate decreases to zero. This model was first proposed by Whalley et al. [4]. In recent years a number of researchers [5–13] have attempted to improve upon or establish new entrainment rate and deposition rate correlations. Levy et al. [5] and Katto et al. [6] defined the entrainment rate in terms of a concentration in equilibrium condition as Wallay et al. [4]. The difference is that Levy et al. [5] and Katto et al. [6] gave new

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* Corresponding author.
E-mail address: lzhao@mail.xjtu.edu.cn (L. Zhao).

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Nomenclature

c	droplet concentration (kg/m^3)
d	inner diameter (mm)
D	curvature diameter (mm)
E	entrainment fraction
f	friction factor
g	gravitational acceleration (m/s^2)
G	mass flux (kg/m^2 s)
h	enthalpy (kJ/kg)
h_{fg}	latent heat (kJ/kg)
j	superficial velocity (m/s)
k_d	deposition mass transfer coefficient (m/s)
k_e	entrainment mass transfer coefficient (m/s)
m_d	deposition rate (kg/m^2 s)
m_e	entrainment rate cause by wave crest shearing-off (kg/m^2 s)
m_{eb}	entrainment rate cause by the bubbles bursting (kg/m^2 s)
med	net entrainment rate ($m_e - m_d$) (kg/m^2 s)
m_{et}	total entrainment rate (kg/m^2 s)
m_v	vaporization rate (kg/m^2 s)
P	pressure (MPa)
q	heat flux (kW/m^2)
S	entrainment parameter
S_R	modified entrainment parameter (Sugawara)
x	vapor quality
x_b	x-coordinater of the “correlation map” (Berthoud)
y_b	y-coordinater of the “correlation map” (Berthoud)
y^+	dimensionless distance from the wall
Y_f	liquid film thickness (m)
Y_f^+	dimensionless liquid film thickness
z	distance along the channel (m)
Δh_{eq}	equivalent wave height (m)

Dimensionless numbers

Bo	Boiling number
Fr	Froude number
π_1	dimensionless number define in Eq. (19)
π_e	entrainment dimensionless number (Okawa, in Eq. (14))
Re	Reynolds number
Sc	Schmidt number
We	Weber number
α	volume fraction
β	entrainment parameter
μ	viscosity (kg/m s)
ρ	density (kg/m^3)
δ	liquid film thickness (m)
σ	surface tension (N/m)
τ	shear stress (N/m^2)
ω	parameter of linear interpolation

Subscripts

c	critical
$coil$	helically coiled tube
do	dryout
eq	equilibrium state
f	liquid film
g	gas or vapor
i	phase interface
l	liquid
o	onset of annular flow
str	straight tube
tal	total
w	wall

correlation for equilibrium concentration concerning different liquid film thickness. Katto et al. [6] extended the Levy’s model to a wide range of pressure and short tubes by modifying the initial film thickness equation. Sugawara et al. [7] proposed a new droplet deposition correlation by taking the effect of the droplet concentration and Schmidt number into consideration. In their work, the writer also developed a new droplet entrainment correlation by taking into account the force balance at the gas-liquid wavy interface, the density ratio between the liquid film and vapor, and the hydrodynamic equivalent wave height. Based on force analysis similarly, Okawa et al. [12] supposed that the entrainment rate is proportional to a dimensionless number which was defined as the ratio of interfacial shear force to the surface tension. What’s more, the quasi-equilibrium entrainment fraction and the mass transfer coefficients of droplet deposition which can be applicable to a wide range of flow condition were recommend in their work. Some researchers such as Mishima et al. [8], Govan et al. [9] and Zhang et al. [13], introduced a critical Reynolds number or mass flux in their entrainment rate correlation, in which the critical Reynolds number is a criterion to judge whether the entrainment occur. Azzopardi [10] verified that the model improved by Govan et al. [9] also has well applicable in prediction of the position of dryout when there is a non-uniform distribution of axially heat flux. Celata et al. [11] developed a new model to predict the CHF in vertical tubes with uniform heating and good agreement between experimental results and perdition results was found.

Helical tube steam generator has been widely used in industrial applications due to the advantages of high heat transfer efficiency and compact structure, such as the helical tube steam generator in pressurized water reactor and helical tube water wall in supercritical once-through boiler. There has been a large number of research works concerning critical heat flux (CHF) characteristics in helically coiled tubes over the last 30 years [14–27].

Jensen and Bergles [14] studied the subcooled and high-quality region CHF characteristics in helical tubes with uniform heating and circumferential non-uniform heating. The writers analyzed the effects of the flux tilt, mass flux, and the ratio of tube diameter to coil diameter on CHF. Styrikovich et al. [15] investigated the critical heat flux and post-dryout temperature characteristics with the water-steam two-phase up-flow and down-flow in a helically coiled tube. The experimental results were compared with that in a vertical straight tube. Berthoud et al. [16] found that film thickness in the annular flow region is determined by four mechanisms: Droplet entrainment, droplet deposition, liquid film vaporization, and secondary re-distribution. The dryout experiment data from five datasets were collected including two kinds of fluids: R-12 and water. The experimental data were classified into three zones, and a two-dimensional map was developed to identify the zones. Hwang et al. [17] studied the dryout characteristics in vertical helical tubes at low mass flux, and modified the boundary between two zones on Berthoud’s map. Chen et al. [18] investigate the CHF characteristics in a horizontal helical coil with the refrigerant R134a as working fluid. The characteristics of wall temperatures distributions and the effect of operating parameters on dry-out were analyzed and a new correlation was proposed for the prediction of the CHF of R134a.

The State Key Laboratory of Multiphase Flow in Power Engineering of Xi’an Jiaotong University has conducted extensive