Fusion Engineering and Design 129 (2018) 286–290

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

A method for developing correlations for subcooled flow boiling heat transfer and its application to water

Xiande Fang*, Chuang Chen, Qi Wu, Lu Tian

Institute of Air Conditioning and Refrigeration, Nanjing University of Aeronautics and Astronautics, 29 Yudao Street, Nanjing 210016, China

ARTICLE INFO

Keywords:
Subcooled flow boiling
Heat transfer
Coefficient
Correlation
Water

ABSTRACT

A systematic method for developing correlations for subcooled flow boiling heat transfer was proposed. On the base of the method, a new correlation for subcooled flow boiling heat transfer of water is developed using a database containing 1184 data points from 14 published articles. The predictions of the new correlation agree with the database very well, with a mean absolute deviation (MAD) of 9.1% and 93.0% of the data within ± 20% error band, which proves the effectiveness of the method.

1. Introduction

There are a variety of factors that affect subcooled flow boiling heat transfer, such as fluid, mass flux, heat flux, subcooling, pressure, and channel shape and size, which makes it a challenge to predict subcooled flow boiling heat transfer. In the past 70 years, many investigations were conducted to determine subcooled flow boiling heat transfer. Due to the complexity of this issue, the experimental study has been the main research approach, and models for calculating subcooled flow boiling heat transfer are mostly experiment-based correlations.

Many correlations for subcooled flow boiling heat transfer were proposed, of which most were based on the experimental data with water, because water is the most widely-used medium in the application of subcooled flow boiling heat transfer, such as in plasma facing components, nuclear power generation plants, thermal power plants, and electronic cooling systems [1–4]. The calculation of subcooled flow boiling heat transfer of water is important for designing such facilities.

The evaluation results from the available literature [1–4] indicated that the previous correlations generally showed significant deviation in the prediction of the given subcooled boiling heat transfer data of water, and the evaluation results among the available literature were not consistent, suggesting that none of existing correlations could predict subcooled flow boiling heat transfer of water with a satisfied accuracy in a broad parameter range. Fang et al. [1] recently conducted a comprehensive review of correlations for subcooled flow boiling heat transfer and assessed 21 correlations [2–22] with a large database of subcooled flow boiling heat transfer of water, which contains 1184 data points from 14 published articles. The results showed that only five correlations [4–8] had the mean absolute deviation (MAD) less than 50%, and that the Liu–Winterton correlation predicted best with an MAD of 32.5%.

Most researchers proposed correlations based on their own experimental data with limited data points and operation ranges, making their correlations applicable only to some narrow ranges. Therefore, it remains an unsolved issue to develop an accurate correlation for subcooled flow boiling heat transfer of water that is applicable to a wide range, including various channel sizes, various flow directions, and broad operation conditions.

The goal of the present work is to propose a systematic method for developing a correlation for subcooled flow boiling heat transfer and substantiate it by developing a correlation of subcooled flow boiling heat transfer coefficients of water. The database from Fang et al. [1] is used for developing such correlation. The new correlation has a high accuracy in a wide range, including various channel sizes, various flow directions, and broad operation conditions.

2. Method for developing new correlation of subcooled flow boiling heat transfer

A systematic method for developing a new correlation for subcooled flow boiling heat transfer was proposed through modifying the methods described in Fang et al. [23–26], as described below:

(1) Finding suitable basic types for a new correlation, which might be done through investigating the existing correlations.

In Fang et al. [1], a comprehensive review of correlations for subcooled flow boiling heat transfer was conducted, and the correlations were classified into five categories: enhancement-factor, superposition, asymptotic, $q \sim \Delta T_{sat}^{n}$, and flow pattern based types. Among the

* Corresponding author.
E-mail address: xd_fang@nuaa.edu.cn (X. Fang).

https://doi.org/10.1016/j.fusengdes.2018.02.084
Received 12 March 2017; Received in revised form 7 January 2018; Accepted 21 February 2018

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Nomenclature

Bd	Bond number
Bo	Boiling number
c_p	Specific heat at constant pressure (J/kg K)
D	Diameter, hydraulic diameter (m)
Fa	Fang number
Fr	Froude number
G	Mass flux (kg/m^2 s)
g	Earth gravity, $g = 9.8$ m/s^2
H	Channel height (m)
h	Heat transfer coefficient (W/m^2 K)
h_{lg}	Latent heat of vaporization (J/kg)
L	Channel length (m)
Nu	Nusselt number
p	Pressure (Pa)
Pr	Prandtl number
q	Heat flux from channel wall to fluid (W/m^2)
Re	Reynolds number
T	Temperature (K)
ΔT_{sat}	Wall superheat (K)
ΔT_{sub}	Subcooling (K)
u	Velocity (m/s)
W	Channel width (m)
X	Martinelli parameter
x	Vapor quality

Greek symbols

λ	Thermal conductivity (W/m K)
μ	Dynamic viscosity (kg/s m)
ρ	Density (kg/m3)
σ	Surface tension (N/m)

Subscripts

b	Bulk fluid
exp	Experimental
g	Gas, vapor
go	Gas only, assuming all fluid as gas
in	Inlet
l	Liquid
lo	Liquid only, assuming all fluid as liquid
$pred$	Predicted
sat	Saturated
sub	Subcooling
tp	Two-phase
w	Channel inner wall surface

reviewed correlations, 21 were evaluated with a large database of subcooled flow boiling heat transfer of water, and the results showed that the enhancement-factor and asymptotic types had more potential to yield more accurate correlations.

Through further analysis, the enhancement-factor type is taken as the basic type for a new correlation.

(2) Identifying dimensionless parameters that have potential to be incorporated into the new correlation.

This could be achieved through finding the dimensionless parameters used in the top correlations of subcooled flow boiling heat transfer and saturated flow boiling heat transfer. The scope of finding the dimensionless parameters is extended to saturated flow boiling heat transfer because saturated flow boiling heat transfer also involves the forced convection and nucleate boiling mechanisms. Besides, the Liu–Winterton [5] correlation, which performs best for predicting the database in Fang et al. [1], has a form both for subcooled and saturated flow boiling heat transfer.

The dimensionless parameters appearing two or more times in the top five correlations [4–8] of subcooled flow boiling heat transfer, as indicated in Fang et al. [1], are the liquid Prandtl number Pr_l, the liquid Reynolds number Re_l, and the boiling number Bo.

The dimensionless parameters appearing two or more times in the top correlations of saturated flow boiling heat transfer, as indicated in Fang et al. [25] are the Nusselt number Nu, the liquid Reynolds number Re_l, the liquid only Reynolds number Re_{lo}, the liquid Prandtl number Pr_l, the boiling number Bo, the Fang number Fa, the Bond number Bd, the liquid only Froude number Fr_{lo}, the vapor only Reynolds number Re_{go}, the vapor Prandtl number Pr_g, and the Martinelli parameter X. The dimensionless parameters of the thermophysical or operational parameter ratios include viscosity ratio ($\mu_{l,sat}/\mu_{l,w}$), density ratio (ρ_l/ρ_g), and vapor quality x.

Since vapor phase accounts for very small potion in subcooled flow boiling, Re_{lo} can be replaced by Re_l, and Re_{go}, Pr_g, X, and x could not play an important role in correlating subcooled flow boiling heat transfer coefficients. Therefore, the dimensionless parameters that have potential to be incorporated into the new correlation are Nu, Re_l, Pr_l, Bo, Fa, Bd, Fr_{lo}, $\mu_{l,sat}/\mu_{l,w}$, and ρ_l/ρ_g.

$$Nu = h_{tp}\frac{D}{\lambda_l} \tag{1}$$

$$Re_l = \frac{G_l D}{\mu_l} \approx \frac{GD}{\mu_l} = Re_{lo} \tag{2}$$

where G_l and G are the liquid mass flux and the total mass flux, respectively. Since the vapor mass flux is far smaller than the liquid mass flux in subcooled flow boiling, it is reasonable to simplify the calculation by substituting G for G_l.

$$Pr_l = \frac{c_{pl}\mu_l}{\lambda_l} \tag{3}$$

$$Bo = \frac{q}{Gh_{lg}} \tag{4}$$

$$Fa = \frac{(\rho_l - \rho_g)\sigma}{G^2 D} \tag{5}$$

$$Bd = \frac{g(\rho_l - \rho_g)D^2}{\sigma} \tag{6}$$

$$Fr_{lo} = \frac{G^2}{gD\rho_l{}^2} \tag{7}$$

(3) Constructing the tentative forms of new correlation.

As mentioned above, the enhancement-factor type is taken as the basic type for a new correlation. From Fang et al. [1], the enhancement-factor type correlation of subcooled flow boiling heat transfer coefficients may be of the form

$$Nu = FRe_l^m Pr_l^n \tag{8}$$

where m and n are the constants which can be determined through curve fitting of experimental data, and F is a fluid and flow condition dependent function associated with the above identified dimensionless parameters.

There are different forms for function F, corresponding to different baseline forms of subcooled flow boiling heat transfer correlations. For example, assume F is the product of the identified dimensionless parameters, yielding one of the baseline form as the following:

$$Nu = c_0 Re_l^{c_1} Pr_l^{c_2} Bo^{c_3} Fa^{c_4} Bd^{c_5} Fr_{lo}^{c_6} (\mu_{l,sat}/\mu_{l,w})^{c_7} (\rho_l/\rho_g)^{c_8} \tag{9}$$

where c_0, c_1, $c_2 \ldots c_8$ are the constants needed to be determined.

(4) Reducing the baseline forms.