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Review of correlations for subcooled flow boiling heat transfer and assessment of their applicability to water

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ABSTRACT

The subcooled flow boiling heat transfer of water has many applications, such as cooling devices of nuclear power systems and electronics, and the applicability of correlations of subcooled flow boiling heat transfer to water needs to be assessed. A number of correlations for subcooled flow boiling heat transfer were proposed. However, their prediction accuracy for water was not systematically investigated. This paper presents a comprehensive review of correlations of subcooled flow boiling heat transfer. A large database of subcooled flow boiling heat transfer of water containing 1184 data points is compiled from 14 published articles, based on which 21 correlations of subcooled flow boiling heat transfer are assessed, and their prediction accuracy is analyzed for different channel sizes, channel shapes, and flow directions. The results are helpful for understanding the prediction methods of subcooled flow boiling heat transfer and choosing a proper correlation for a given application.

1. Introduction

Subcooled flow boiling heat transfer of water in channels is widely used in plasma facing components of fusion nuclear systems, thermal power plants, as well as electronic cooling systems [1–5]. The calculation of subcooled flow boiling heat transfer of water is important for designing such facilities. A number of correlations for subcooled flow boiling heat transfer were proposed, of which some are also employed for more sophisticated geometries, such as hypervapotron [6] and swirl tubes [7].

There are a variety of factors that affect subcooled flow boiling heat transfer, such as fluid, mass flux, heat flux, subcooling, pressure, and channel geometry, 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, among which most were based on experimental data with water.

Such intensive investigations have led to a better understanding of subcooled flow boiling heat transfer characteristics and mechanisms. Meanwhile, over 20 correlations of subcooled flow boiling heat transfer have been proposed [2,3,5,8–26]. A large number of correlations provide the engineers and designers more choices in engineering practice. On the other hand, they are confronted with considerable confusion in choosing a suitable correlation for a given application since it is hard for them to know which correlation may yield a better calculation result.

Neither the systematic review on the correlations of subcooled flow boiling heat transfer nor the assessment of their applicability to water with a multiple-source database has been found. The goal of the present work is to review the correlations of subcooled flow boiling heat transfer and to evaluate their applicability to water based on a large experimental database compiled from 14 published articles, which contains 1184 data points of subcooled flow boiling heat transfer of water in various channel sizes and both vertical and horizontal flow directions over a wide range of parameters. Twenty-two existing correlations of subcooled flow boiling heat transfer are reviewed, among which 21 are assessed and analyzed using the database. The results provide a strong support for understanding prediction methods of subcooled flow boiling heat transfer and choosing a proper correlation for a given application.

2. Overview of correlations for subcooled flow boiling heat transfer

This section presents a systematic review of correlations for subcooled flow boiling heat transfer. These correlations can be classified into five categories: enhancement-factor, superposition, asymptotic, $q \sim \Delta T_{sat}^{n}$, and flow pattern based types. The wall superheat ΔT_{sat} is

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Nomenclature

Bo	Boiling number
c_p	Specific heat at constant pressure (J/kg K)
D	Diameter, hydraulic diameter (m)
F	Reynolds number factor
Fr	Froude number
f	Moody friction factor
G	Mass flux (kg/m^2 s)
H	Channel height (m)
h	Heat transfer coefficient (W/m^2 K)
h_{lg}	Latent heat of vaporization (J/kg)
Ja	Jacob number
Ja^*	Modified Jacob number
L	Channel length (m)
M	Molecular mass (kg/kmol)
Nu	Nusselt number
p	Pressure (Pa)
P_R	Reduced pressure, $P_R = p/p_{crit}$
Pr	Prandtl number
q	Heat flux from channel wall to fluid (W/m^2)
Re	Reynolds number
S	Suppression factor
T	Temperature (K)
ΔT_{sat}	Wall superheat (K)
$\Delta T_{sat,ONB}$	Wall superheat at onset of nucleate boiling (K)
ΔT_{sub}	Subcooling (K)
u	Velocity (m/s)
W	Channel width (m)
We^*	Modified Weber number
X_{tt}	Martinelli parameter for turbulent liquid/turbulent gas

Greek symbols

β	Volumetric thermal expansion coefficient (1/K)
λ	Thermal conductivity (W/m K)
μ	Dynamic viscosity (kg/s m)
ρ	Density (kg/m^3)
σ	Surface tension (N/m)
ψ	Enhancement factor

Subscripts

b	Bulk temperature
cp	Constant property
$crit$	Critical point
cv	Convection
exp	Experimental
f	Film
fc	Forced convection
g	Gas phase
in	Inlet
l	Liquid phase
lo	Liquid only, assuming all fluid as liquid
loc	Local
nb	Nucleate boiling
nc	Natural convection
$pred$	Predicted
sat	Saturated
sp	Single-phase
tp	Two-phase
w	Channel inner wall surface

defined as the difference between the inner wall temperature T_w and the saturated temperature T_{sat},

$$\Delta T_{sat} = T_w - T_{sat} \tag{1}$$

2.1. Enhancement-factor models

For enhancement-factor models, the subcooled flow boiling heat transfer coefficient h_{tp} may be reduced to

$$h_{tp} = \psi h_{sp,l} \tag{2}$$

where ψ is the enhancement factor, which accounts for the enhancement of the boiling to the subcooled flow boiling heat transfer, and $h_{sp,l}$ is the forced convection heat transfer coefficient of the single-phase liquid and can be generalized as

$$h_{sp,l} = CRe_l^m Pr_l^n \frac{\lambda_l}{D} \tag{3}$$

where constants C, m and n need to be determined by curve fitting of experimental data. Substituting Eq. (3) into Eq. (2) yields

$$h_{tp} = YRe_l^m Pr_l^n \frac{\lambda_l}{D} \tag{4}$$

or

$$Nu_{tp} = h_{tp}\frac{D}{\lambda_l} = YRe_l^m Pr_l^n \tag{5}$$

where Y is a fluid and flow condition dependent function, which can be determined through curve fitting of experimental data. The liquid Prandtl number Pr_l and the liquid Reynolds number Re_l are defined as

$$Pr_l = \frac{c_{pl}\mu_l}{\lambda_l} \tag{6}$$

$$Re_l = \frac{G_l D}{\mu_l} \tag{7}$$

where G_l is the liquid mass flux.

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, where G is the total mass flux of the two-phase flow. Thus,

Table 1
Values of the constant C_{sf} in the Rohsenow correlation (from Ghiaasiaan [28]).

Fluid-surface combination	C_{sf}	Fluid-surface combination	C_{sf}
Water–nickel	0.006	Benzene–chromium	0.01
Water–platinum	0.013	*n*-Pentane–chromium	0.015
Water–emery polished copper	0.0128	*n*-Pentane–emery polished copper	0.0154
Water–brass	0.006	*n*-Pentane–emery polished nickel	0.0127
Water–ground and polished stainless steel	0.008	Ethyl alcohol–chromium	0.0027
Water–Teflon pitted stainless steel	0.0058	Isopropyl alcohol–copper	0.0025
Water–chemically etched stainless steel	0.0133	35% $K2CO_3$–copper	0.0054
Water–mechanically polished stainless steel	0.0132	50% $K2CO_3$–copper	0.0027
Water–emery polished, paraffin treated copper	0.0147	*n*-Butyl alcohol–copper	0.0030
CCl_4–emery polished copper	0.007		