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Research Paper

Evaluation of prediction methods for heat transfer coefficient of annular flow and a novel correlation

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HIGHLIGHTS

- Evaluates existing HTC prediction methods for flow boiling of annular flow.
- Sets up a flow boiling HTC experimental database of 2783 annular flow data points.
- Proposes a novel HTC correlation for annular flow with MAE of 13.7%.

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ABSTRACT

Flow boiling heat transfer of annular flow is very important to the thermal design of evaporating heat exchanger. In this study, an experimental heat transfer coefficient database containing 2783 data points is built from 26 open literatures for annular flow. The database includes both macro-channels and mini/micro-channels data and covers wide range of working conditions. The annular flow database consists of 7 working fluids, covering hydraulic diameters of 0.5–14.0 mm, mass velocities of 50–1290 kg/m^2 s, liquid-only Reynolds numbers of 240–55,119, vapor qualities of 0.10–0.98, and reduced pressures from 0.01 to 0.77. In addition, 19 existing prediction methods for flow boiling heat transfer coefficient are summarized and evaluated by the built database. At last, a novel correlation of heat transfer coefficient for annular flow is developed. Comparing with the conventional correlations, the proposed correlation gets high prediction accuracy for different tube diameters and fluids. The overall MAE against the database is 13.7%, with 66.5% and 89.0% of the data falling within ±15% and ±30% error bands, respectively. The MAEs against macro-channels and mini/micro-channels data are 12.2% and 15.3%. And the MAEs against R134a, R22, ammonia, CO_2, R236fa, R245fa, and R1234ze data are 12.6%, 18.5%, 12.9%, 23.9%, 6.5%, 12.6% and 9.4%, respectively.

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1. Introduction

Flow boiling of two-phase channel flow is of great importance in many industrial applications, which has been extensively studied, such as in refrigeration, air conditioning systems and nuclear reactors. Flow boiling heat transfer is the key consideration in two-phase flow for designing evaporating heat exchange systems. It is found from the development process of modeling heat transfer coefficient for two-phase flow that numerous prediction methods have been proposed to calculate the flow boiling heat transfer coefficient since last century [1–8], however, the prediction accuracies were found to be not enough for high precision simulation. For example, some methods were developed for Freon refrigerants and proved to be lack of accuracy when dealing with ammonia and CO_2 [9,10]. The methods developed for macro-channels may be not applicative in mini/micro-channels due to the differences in bubble behaviors and flow patterns [11]. Therefore, to improve the prediction accuracy for two-phase flow, many prediction methods have been proposed especially for certain fluid [12] or for mini-channel [13–17]. For instance, Fang's correlations developed for R134a in small channels achieved good precision against its database [12]. However, the methods for a certain fluid were found to be absent of universal applicability [9].

Among all the flow patterns in gas-liquid flow, annular flow is the most frequently observed in practical applications, both in

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Nomenclature

A	cross-sectional area (m^2)
Bd	bond number
Bo	boiling number
C	empirical coefficient
Ca	capillary number
c	empirical coefficient
c_l	liquid specific heat capacity ($J\ kg^{-1}\ °C^{-1}$)
D	tube diameter (m)
D_h	hydraulic diameter (m)
E	empirical coefficient
e	entrainment fraction
F	empirical coefficient
Fa	Fang number
Fr	Froude number
f	friction coefficient
$f(x)$	function of x
G	mass velocity ($kg\ m^{-2}\ s^{-1}$)
g	gravitational acceleration
h	heat transfer coefficient ($W/m^2\ °C^{-1}$)
h_{lg}	latent heat of vaporization ($J\ kg^{-1}$)
h_{tp}	two-phase heat transfer coefficient ($W/m^2\ °C^{-1}$)
J	superficial velocity ($m\ s^{-1}$)
k	thermal conductivity ($W/m\ °C^{-1}$)
L	channel length (m)
M	molecular weight
MAE	mean absolute error
MRE	mean relative error
N	number of data points empirical coefficient
n	empirical coefficient
Nu	Nusselt number
P	pressure (Pa)
P_{crit}	critical pressure (Pa)
P_R	reduced pressure, $P_R = P/P_{crit}$
Pr	Prandtl number
q	heat flux (W/m^2)
Re	Reynolds number
Re_l	superficial liquid Reynolds number $Re_l = G(1-x)D_h/\mu_l$
Re_{lf}	liquid film Reynolds number $Re_{lf} = G(1-x)(1-e)t/\mu_l$
Re_{fo}	liquid-only Reynolds number $Re_{lo} = GD_h/\mu_l$
Re_{go}	vapor-only Reynolds number $Re_{go} = GD_h/\mu_g$
r_0	radius of nucleation site (m)
S	empirical coefficient
t	average liquid film thickness (m)
t^+	dimensionless average liquid film thickness
T	temperature (°C)
We	Weber number
V^*	velocity wall scale ($m\ s^{-1}$)
x	thermodynamic equilibrium quality
x_{di}	dryout incipience quality
X_{tt}	Lockhart–Martinelli parameter
y^*	length wall scale (m)
z	longitudinal abscissa (m)

Greek symbols

α	void fraction
δ	liquid film thickness (m)
ε	surface roughness (μm)
θ_{dry}	dry angle of tube perimeter
θ_{strat}	stratified flow angle of tube perimeter
μ	dynamic viscosity ($N\ s\ m^{-2}$)
ρ	density ($kg\ m^{-3}$)
σ	surface tension ($N\ m^{-1}$)
τ	pair period (s)
τ_w	wall shear stress (N)

Subscripts

0	initial
a	average
c	droplet-laden gas core
cb	convective boiling heat transfer
crit	thermodynamic critical point
de	dryout end
di	dryout inception
dry	dryout zone
dryfilm	dryout of the liquid film
end	end of the liquid film
film	liquid film between the bubble and the wall
exp	experimental
l	saturated liquid
lam	laminar flow
lf	liquid film
lo	liquid only
g	saturated vapor
go	vapor only
max	maximum
min	minimum
mist	mist flow
nb	nucleate boiling heat transfer
pred	predicted
ref	reference
sat	saturation
sp	single-phase
tp	two-phase
trans	laminar-turbulent transition
v	vapor phase

conventional channels and in mini/micro-channels. Annular flow is characterized by the presence of a continuous liquid film flowing on the channel wall, surrounding a central gas core laden with entrained liquid droplets [18]. A big amount of models and correlations for annular flows are available in the literatures, including the prediction of void fractions [19], liquid droplet entrainment [20] and deposition [21], liquid film thickness [22], friction factor [18], heat transfer coefficient [23] and so on. One of the most recent complete works on annular flow has been developed by Cioncolini and Thome [24–27]; the models were built for prediction of liquid droplet entrainment fraction, gas core void fractions, annular liquid film thickness, pressure drop and the local convective heat transfer coefficient in evaporating two-phase annular flow.

There are two kind of heat-transfer mechanisms in flow boiling heat transfer, convective heat transfer (refers to heat transfer across the liquid film driving evaporation at the interface) and nucleate boiling heat transfer (refers to heat transfer at nucleate boiling sites on the channel wall) [24]. However, the nucleate boiling was usually assumed to be completely suppressed in the existing heat transfer models for annular flow [24]. The assumption may be effective under very thin liquid films and low heat-flux density conditions. When the heat-flux density is high, the calculating precision of these methods will drop obviously to moderate vapor quality region where the liquid film is not thin enough. Consequently, the heat transfer coefficient prediction method for annular flow simulation considering both convective and nucleate boiling contribution is imperative to be presented.

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