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Review

Fundamental issues, mechanisms and models of flow boiling heat transfer in microscale channels

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ABSTRACT

This paper presents state-of-the-art review on the fundamental and frontier research of flow boiling heat transfer, mechanisms and prediction methods including models and correlations for heat transfer in microscale channels. First, fundamental issues of current research on flow boiling in microscale channels are addressed. These mainly include the criteria for macroscale and microscale channels. Then, studies on flow boiling heat transfer behaviours and mechanisms in microscale channels are presented. Next, the available correlations and models of flow boiling heat transfer in microscale channels are reviewed and analysed. Comparisons of 12 correlations with a database covering a wide range of test parameters and 8 fluids are presented. It shows that all correlations poorly agree to the database. No generalized model or correlation is able to predict all flow boiling heat transfer data. Furthermore, comparisons of the mechanistic flow boiling heat transfer models based on flow patterns including the Thome et al. three-zone heat transfer model for evaporation in microchannel and the flow pattern based model combining the Thome et al. three zone heat transfer models with the Cioncolini-Thome annular flow model for both macro- and microchannel to the database are presented. It shows that the flow pattern based model combining the three zone model with the annular flow model gives better prediction than the three zone heat transfer model alone. The flow pattern based heat transfer model favourably agrees with the experimental database collected from the literature. According to the comparison and analysis, suggestions have been given for improving the prediction methods in the future. Next, flow patterned based phenomenological models and their applications to microscale channels are presented. Finally, as an important topic, unstable and transient flow boiling phenomena in microscale channels are briefed and recommendations for future research are given. According to this comprehensive review and analysis of the current research on the fundamental issues of flow boiling, mechanisms and prediction methods in microscale channels, the future research needs have been identified and recommended. In general, systematic and accurate experimental data of flow boiling heat transfer in microscale channels are still needed although a large amount of work has been done over the past decades. The channel size effect on the flow boiling behaviours should be systematically investigated. Heat transfer mechanisms in microscale channels should be further understood and related to the corresponding flow patterns. Furthermore, effort should be made to develop and improve generalized mechanistic prediction methods and theoretical models for flow boiling heat transfer in microscale channels according to the physical phenomena/mechanisms and the corresponding flow structures. The effects of the channel size and a wide range of test conditions and fluid types should be considered in develop new methods. Furthermore, systematic experimental, analytical and modeling studies on unstable and transient flow boiling heat transfer in microscale channels should be conducted to understand the physical mechanisms and theoretical models.

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Nomenclature

Acs	cross sectional area, m^2
Bd	Bond number, defined by Eqs. (4a), (18d) and (24e)
Bo	boiling number, $q/(Gi_{fg})$
C	constant
Co	confinement number
c_p	specific heat at constant pressure, J/kg K
D	characteristic number, defined by Eq. (4b)
D_{eq}	equivalent diameter, m
D_h	internal tube hydraulic diameter, m
d	diameter, m
d_b	bubble diameter, m
E	convective boiling heat transfer enhancement factor
E'	convective boiling heat transfer enhancement factor
e	entrained liquid droplet mass fraction
Fr	Froude number, $G^2/(\rho_L{}^2 g D_h)$
G	total gas and liquid two-phase mass velocity, kg/m^2 s
g	gravitational acceleration, 9.81 m/s^2
h	heat transfer coefficient, W/m^2 K
i_{fg}	latent heat of evaporation, J/kg
J	superficial velocity, m/s
k	thermal conductivity, W/m K
L	laplace number, defined by Eq. (1)
M	molecular weight
m	parameter defined by Eq. (27a)
Nu	Nusselt number defined by Eq. (23)
n	parameter defined by Eq. (27b)
p	pressure, N/m^2
p_r	reduced pressure, p/p_{crit}
Pr_l	Prandtl number, $\mu_l c_{pl}/k_l$
q	heat flux, W/m^2
Re	Reynolds number
Re_{lo}	Reynolds number considering the total gas-liquid two phase flow as liquid flow, $GD_h/(\mu_l)$
Re_l	Reynolds number considering only liquid phase flow, $G(1-x)D_h/(\mu_l)$
S	nucleate suppression factor
T	temperature, K
T_{sat}	saturation temperature, K
t	time, s
V	velocity, m/s
$V*$	dimensionless velocity
We_l	liquid Weber number considering the total vapor-liquid flow as liquid flow, $G^2D_h/(\rho_l\sigma)$
We_g	gas phase Weber number, $G^2x^2D_h/(\rho_g\ \sigma)$
We_c	gas phase Weber number, $\rho_v J_v{}^2 d/\sigma$
X_{tt}	Martinelli number, $\{[(1-x)/x)]^{0.9}[\rho_g/\rho_l]^{0.5}[\mu_l/\mu_g]^{0.1}\}$
x	vapor quality
y^*	dimensionless length
z	location

Greek symbols

δ	film thickness, m
ε	void fraction
$\delta*$	dimensionless film thickness
ϕ^2	two phase friction multiplier
μ	dynamic viscosity, Ns/m^2
ρ	density, kg/m^3
θ_{dry}	dry angle, rad
σ	surface tension, N/m
τ	time, s, shear stress, Pa
ξ_i	relative error defined by Eq. (16)

Subscripts

b	bubble
CB-AF	confined bubble to annular flow regime
c	core flow
crit	critical
cs	cross section
dry	dry perimeter
end	end
F	fluid
f	frequency, Hz
fg, lv	latent
film	liquid film
g	gas phase
IA	intermittent flow to annular flow transition
l	liquid phase
lf	liquid film
lo	considering the total gas-liquid two phase flow as liquid flow
min	minimum
nb	nucleate boiling
p	constant pressure, pair
pool	pool boiling
ref	reference
sat	saturation
tp	two phase
v	vapor phase
w	tube wall
wet	wetted perimeter
δ_0	initial film thickness
0	initial