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Application of thermodynamic models to estimating the convective flow boiling heat transfer coefficient of mixtures

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ABSTRACT

A large number of experiments has been performed to measure the forced convective and nucleate flow boiling heat transfer coefficient of three different none-volatile mixtures at different heat fluxes (up to 175 kW m^{-2}) and five different volumetric concentrations (10–50% of heavier component). The test mixtures include water/glycerol, water/monoethylene glycol (MEG), and water/diethylene glycol (DEG). The experimental apparatus provides conditions to investigate the influence of the main operating parameters such as: heat flux, concentration, and flow rate of fluid on the forced convective and flow boiling heat transfer coefficient. It is shown that physical properties of the mixtures have a considerable effect on the prediction of flow boiling heat transfer coefficients by the predictive correlations. In almost all of the predictive correlations, physical properties are strongly involved which can be estimated by different thermodynamic models. This work demonstrates that thermodynamic models for the calculation of specific heat, liquid density and heat of vaporization do not obtain identical results and consequently, the heat transfer coefficient obtained from a specified predictive correlation (Chen type model) can be tolerated according to the used thermodynamic model for the calculation of the physical properties. This point has been ignored by the investigators and they compare their experimental data with the correlations without specifying that, which one of the thermodynamic models has to be used for the obtaining of the thermo-physical properties. After reading the present study, a new vision can be opened to the readers interested in prediction of the flow boiling heat transfer coefficient and may help the researchers to reliably predict the thermo-physical properties of fluids particularly for forced convective and boiling phenomena.

1. Introduction

After publishing our article about influence of thermodynamic models on the pool boiling heat transfer coefficient of dilute mixtures [1], we were encouraged to repeat the work in case of flow boiling heat transfer; since, flow boiling (as opposed to pool boiling) is widely used in industries and power cycles and refrigerant systems. On the other hand, flow boiling has long played a major role in many technological applications due to its superior heat transfer performance. The complexity encountered in the boiling process has stimulated numerous investigators to conduct extensive research in this field. Because of unknown properties which are hidden inside of boiling phenomenon, researchers have conducted large number of experiments on different substances. This complexity is due to the heterogeneous nature of heat transfer medium. Flow boiling of liquid mixtures is furthermore integrated with simultaneous heat and mass transfer between vapor inside the bubble and the vapor/liquid interfaces, which makes the phenomenon more complicated and therefore, engages the investigators with prediction of thermo-physical properties. So far, the boiling phenomenon has not been modeled through any simple and reliable theoretical model. Flow boiling heat transfer is also one of the major interests to designers of water liquid cooled nuclear reactors. One source of concern is reactor behavior following a hypothetical loss-of-flow accident or its behavior when cooling flow was unable to provide the sufficient heat transfer. In this particular case, exceeding the heat flux up to critical heat flux can lead to irrecoverable damages to the reactor and industrial installations. Sub-cooled boiling is characterized by the generation of vapor bubbles at the heater surface while the bulk temperature of the liquid is still below the saturation temperature. Bubbles detaching from the heat transfer surface collapse and condense in the sub-cooled liquid bulk while this situation basically occurs in almost every reactor or high temperature surfaces, it is particularly significant in nuclear reactors and around the rod fuel pools. Many investigations have been conducted on the effects of operating parameters on the sub-cooled flow boiling heat transfer. Based on

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Nomenclature

A	area, m^2
A_{ij}	none-temperature energy parameter, cal gmol^{-1}
b	distance, m
B_{ij}	temperature dependent energy parameter, cal gmol^{-1} K^{-1}
Bo	boiling number
C_p	heat capacity, J kg^{-1} K^{-1}
C_p°	ideal heat capacity, J kg^{-1} K^{-1}
D_{AB}	diffusion coefficient, m^2 s^{-1}
d_b	bubble departing diameter, m
d_h	hydraulic diameter, m
f	fanning friction number
F	enhancement factor
G_{ij}	experimental parameter, see Table 11
h	enthalpy, J kg^{-1}
ΔH_v	heat of vaporization, J kg^{-1}
h_{fg}	mass heat of vaporization, J kg^{-1}, see Chen type model
k	thermal conductivity, W m^{-1} °C^{-1}
l_{th}	heated length, m
L	heater length, m
ΔL	characteristic length in Eq. (15), m
$\dot{m}$	mass flow rate, kg h^{-1}
Nu	Nusselt number
P	Parachor number, see Section 5.4
Δp_i	contribution group value
Pe	Peclet number
Ph	phase change number
Pr	reduced pressure
Pr	Prandtl number
P	pressure, Pa
q	heat, W
q^*	Uniquac parameter, see Table 8
$\dot{q}$	heat flux, W m^{-2}
r^*	Uniquac parameter, see Table 8
Re	Reynolds number
R_a	roughness, m
s	distance between thermometer location and heat transfer surface, m
S	suppression factor
T	temperature, K
V	volume, m^3
ΔV^{vap}	volumetric difference between liquid and gas states, m^3 mol^{-1}, see Eq. (8)
x	liquid mass or mole fraction
$\dot{x}$	vapor mass fraction
X_{tt}	Martinelli parameter
y	vapor mass or mole fraction
z	distance from heating section, m
Z	compressibility factor

Subscripts–superscripts

b	bulk
c	critical
fb	flow boiling
h	hydraulic
i	interface
in	inlet
out	outlet
l	liquid
m	mixture
n	number of components
N	number of total contribution groups
nb	nucleate boiling
r	reduced
sat	saturated
th	thermometers
v	vapor
w	wall

Greek symbols

α	heat transfer coefficient, W m^{-2} K^{-1}
α_{id}	ideal heat transfer coefficient, W m^{-2} K^{-1}
$\hat{\alpha}$	thermal diffusion, m^2 s^{-1}
α_{ij}	NRTL interaction parameter
λ_w	thermal conductivity of heating section, W m^{-1} K^{-1}
ρ	density, kg m^{-3}
v	molar volume, m^3 kgmol^{-1} or m^3 gmol^{-1}
μ	viscosity, kg m^{-1} s^{-1}
σ	surface tension, dyn cm^{-1}
δ	differential
Δ	difference
k_{ij}	binary interaction parameters
ω	acentric factor

Dimensionless number

Bo	boiling number $= \frac{\dot{q}}{\dot{m}.h_{fg}}$
Nu	Nusslet number $= \frac{hd}{k}$
Pe	Peclet number $= \frac{\dot{m}.C_p d_h}{k}$
Ph	phase change number $= \frac{-N_{Bo}}{\sqrt{\left(\frac{455}{N_{pe_l}}\right)^2 + 0.0065^2}}$
Pr	Prantdl number $= \frac{c_p \mu}{k}$
Re	Reynolds number $= \frac{\rho v d}{\mu}$

Abbreviations

AAD%	Absolute Average deviation
DEG	diethylene glycol
Gly.	glycerol
MEG	monoethylene glycol
ONB	onset of nucleate boiling
Vol.%	volumetric concentration in percent

the type of coolant fluid, conducted researches may be categorized in terms of investigations on the saturated or sub-cooled flow boiling heat transfer to either pure liquids or mixtures, although the main object of this experimental study is to investigate the latter groups of mentioned test fluids. Almost, in all of the studies explained in the following literature review ignored the influence of thermodynamic model on the prediction of thermo-properties of test fluids and prediction of heat transfer coefficient.

Therefore, the main objectives of this work are to initially, investigate the influence of operating parameters on the flow boiling heat transfer coefficient of binary mixtures and subsequently, flow boiling heat transfer coefficient of test mixtures is predicted by Chen type model. Some of the important thermo-physical properties used in Chen type model can also be estimated by different thermodynamic models. It is shown that results of estimation of thermo-physical properties can be tolerated and therefore, for any investigation on the prediction of heat transfer coefficient, appropriate thermodynamic model should be specified and calculations of estimating of thermo-physical properties should be coupled with the predicting calculations for heat transfer coef-