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A general correlation for saturated flow boiling heat transfer in channels of various sizes and flow directions

Xiande Fang *, Qi Wu, Yuliang Yuan

Institute of Air Conditioning and Refrigeration, College of Aerospace Engineering, Nanjing University of Aeronautics and Astronautics, 29 Yudao St., Nanjing 210016, China

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A B S T R A C T

A general correlation for heat transfer coefficients of saturated flow boiling is developed based on the first experimental database consisting of 17,778 data points from 101 sources and 13 different fluids. The new correlation makes a significant breakthrough in the prediction accuracy for saturated flow boiling heat transfer, achieving a mean absolute deviation (MAD) of 4.5% against the database, with 68.1% and 89.7% of the data falling within ±5% and ±10% error bands, respectively. The new correlation is validated and compared with 45 existing correlations on the base of the second database of saturated flow boiling heat transfer. The second database contains 6664 data points from 60 sources and 18 different fluids and has no duplicate data from the first. The validation results show that the new correlation has an MAD of 4.4% against the second database, with 69.0% and 93.5% of the data within ±5% and ±10% error bands respectively, further confirming its superior prediction accuracy and reliability. The best existing correlation for the second database, meanwhile, has an MAD of 26.0%, with only 13.0% and 26.0% of the data falling within ±5% and ±10% error bands, respectively. The new correlation is applicable to various channel sizes, flow directions, and flow regimes.

1. Introduction

It is important to accurately predict saturated flow boiling heat transfer coefficients since a high accurate prediction of these coefficients can reduce the cost and avoid under-design or over-design of related equipment and systems, such as evaporators, electronic cooling devices, and refrigeration systems.

Two important events taking place in the 1980s spurred the rapid development of flow boiling heat transfer: High heat dissipation demands from advanced electronic devices and the Montreal protocol on substances that deplete the ozone layer. The former leads to the wide usage of flow boiling heat transfer in mini/micro-channels, and the latter yields a transfer from CFC and HCFC refrigerants to alterative refrigerants, such as R134a, CO_2, R410A, R407C, and R1234yf. As a result, intensive analytical and experimental investigations of prediction methods of flow boiling heat transfer have been conducted since 1980s [1–3], leading to a large number of correlations for flow boiling heat transfer coefficients.

The existing correlations may be classified into two types according to the fluids in the database for developing them. The correlations in the first type were developed based on the experimental data of a single fluid. Most of the correlations in this type were developed with the authors' own experimental data, which have a narrow range of parameters and may be useful for application within the similar range of parameters. Some of these correlations [3–6] were developed using a large database compiled from multiple data sources. These correlations are generally preferable for the given fluid and may also be applicable to some other fluids. The correlations in the second type were developed on the base of a large number of data points involving a number of fluids over a wide range of parameters [7–13] and sometimes called general correlations. Among [7–13], Chen [7], Shah [8], Gungor and Winterton [9], Kandlikar [10], and Liu and Winterton [11] are well known, and Bertsch et al. [12] and Kim and Mudawar [13] are relatively new.

General correlations are more preferable since they represent a larger database and cover a much broader range of parameters, leading to less restriction for their applications. However, their prediction accuracies remain unsatisfactory. The Gungor and Winterton [9] and Liu and Winterton [11] correlations were developed based on around 4200 data points of saturated flow boiling heat transfer from nine fluids, and they predicted these data with the mean absolute deviation (MAD) of 20.9% and 20.5%, respectively. The Kandlikar [10] correlations was developed based on the database containing 5246 data points from 24 experimental investigations with 10 fluids, and it predicted the database with an MAD of 18.8%. The Bertsch et al. [12] correlation was developed based on the database containing 3899 data points from 14 sources

* Corresponding author.
E-mail address: xd_fang@yahoo.com (X. Fang).

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Nomenclature

A_c	flow area or cross-sectional area (m^2)
A_{eff}	effective heat transfer area (m^2)
Bd	Bond number
Bo	boiling number
c_p	specific heat at constant pressure (J/kg·K)
Fa	Fang number
D	diameter, hydraulic diameter (m)
Fr	Froude number
G	mass flux (kg/m^2·s)
g	Earth gravity, $g = 9.8$ m/s^2
H	height of rectangular channel (m)
h	heat transfer coefficient (W/m^2·K)
h_{lg}	latent heat of vaporization (J/kg)
L	channel length (m)
M	molecular mass (kg/kmol)
Nu	Nusselt number
P	wetted perimeter (m)
Pr	Prandtl number
p	pressure (Pa)
p_r	reduced pressure
Q	heat transfer rate (W)
q	heat flux from channel wall to fluid (W/m^2)
Re	Reynolds number
T	temperature (K)
W	width of rectangular channel (m)
X	Martinelli parameter
x	vapor quality

Greek symbols

δ	fin thickness (m)
η	fin efficiency
λ	thermal conductivity (W/m·K)
μ	dynamic viscosity (kg/s·m)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscriptscrit

	critical point
exp	experimental
f	fluid
g	saturated vapor
go	gas only, assuming all fluid as gas
l	saturated liquid
lo	liquid only, assuming all fluid as liquid
$pred$	predicted
sat	saturated
tp	two-phase
tt	turbulent liquid/turbulent gas
w	channel inner wall surface

covering 12 fluids, predicting the database with an MAD of 28%. The Kim and Mudawar [13] correlation was developed based on the database containing 10,805 pre-dryout data, and it predicted the database with an MAD of 20.3%. It is seen that the smallest MAD is 18.8% even for the database on which the correlation was proposed. The MAD would be much larger for a correlation to predict other databases. For example, the Liu and Winterton [11] correlation predicts the Kim and Mudawar [13] database with an MAD of 28.1% and the Bertsch et al. [12] database with an MAD of 46%. Therefore, there is still a need to develop a more accurate and reliable correlation.

The primary goal of the present work is to propose a correlation of flow boiling heat transfer coefficients for the design of cooling devices, such as a heat exchanger for electronic cooling. In such design, the known parameters usually include the heat flux and wall temperature, which are determined by the power and the preset surface temperature of the electronics to be cooled, respectively. Two completely different databases without any overlap were compiled, with the first for developing the new correlation and the second for verifying its accuracy and reliability. The first database consists of 17,778 data points from 101 sources and covers 13 different fluids, and the second contains 6664 data points from 60 sources and covers 18 different fluids. The two databases cover a wide range of parameters of both pre-dryout and post-dryout flow regimes, various channel sizes from micro- to macro-channels, various flow directions including horizontal, vertical, and incline flows, and various fluids including halogenated refrigerants, inorganic compounds, and hydrocarbons. The validation with the second database confirms the superior prediction accuracy and reliability of the new correlation.

2. Correlation development

2.1. Introduction to the first database

The first database of saturated flow boiling heat transfer contains 17,778 data points from 101 sources and covers 13 different fluids, including R134a, R22, R410A, R407C, R1234yf, R236fa, R245fa, R32, CO_2, ammonia, water, nitrogen, and R290, with CO_2 having the most data (3355 points), followed by R134a (2575 points), and R32 having the fewest data of 237 points, as shown in Fig. 1.

The data sources are not listed due to the limitation to the number of the references. The data sources for some fluids were reported in part or whole in [2,5] for CO_2 (R744), [4,14] for R134a, [6] for water (R718), [15] for R22, [16] for ammonia (R717), and [17] for nitrogen (R728). The ranges of the important parameters of the first database are as follows:

Diameter or hydraulic diameter $D = 0.207–32$ mm, with 8374 data having $D < 3$ mm and 9404 having $D \geqslant 3$ mm, as illustrated in Fig. 2(a).

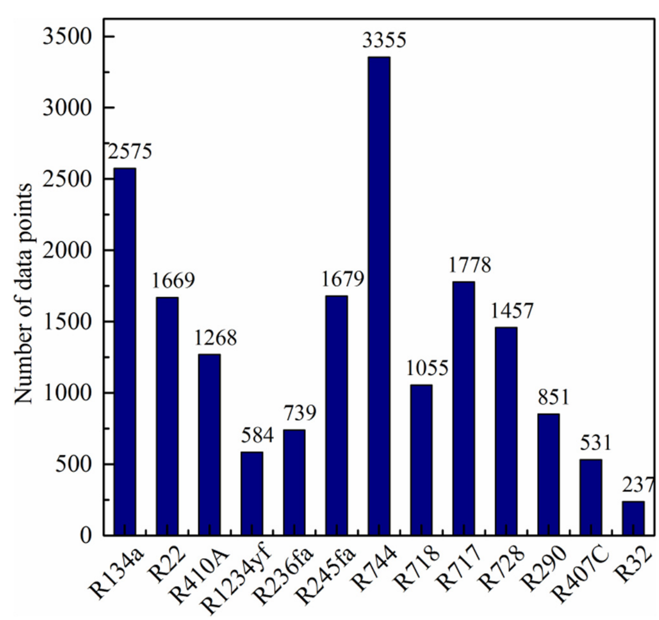

Fig. 1. Data distribution of the first database related to fluid.