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Research paper

Heat transfer correlation for saturated flow boiling of water

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HIGHLIGHTS

- Compiles a database of 1055 data points of H_2O flow boiling heat transfer.
- Evaluates 41 correlations of flow boiling heat transfer coefficient.
- Generalize approach for developing experiment-based correlation.
- Propose a correlation of H_2O flow boiling heat transfer in small channels.
- The new correlation has a mean absolute deviation of 10.1% for the database.

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ABSTRACT

The saturated flow boiling heat transfer of water (H_2O, R718) is encountered in many applications such as compact heat exchangers and electronic cooling, for which an accurate correlation of evaporative heat transfer coefficients is necessary. A number of correlations for two-phase flow boiling heat transfer coefficients were proposed. However, their prediction accuracies for H_2O are not satisfactory. This work compiles an H_2O database of 1055 experimental data points from micro/mini-channels from nine independent studies, evaluates 41 existing correlations to provide a clue for developing a better correlation of saturated flow boiling heat transfer coefficients for H_2O, and then proposes a new one. The new correlation incorporates a newly proposed dimensionless number and makes great progress in prediction accuracy. It has a mean absolute deviation of 10.1%, predicting 81.9% of the entire database within ±15% and 91.2% within ±20%, far better than the best existing one. Besides, it also works well for several other working fluids, such as R22, R134a, R410A and NH_3 (ammonia, R717), being the best for R22, R410A and NH_3 so far.

1. Introduction

The saturated flow boiling heat transfer of water (H_2O, R718) has many applications, such as compact heat exchangers and electronic cooling. The calculation of H_2O flow boiling heat transfer coefficients is important for designing such facilities. A number of correlations for two-phase flow boiling heat transfer coefficient have been proposed, and their applicability to H_2O is an interest issue. Many studies assessed the applicability to H_2O of the correlations of two-phase flow boiling heat transfer coefficients.

Sumith et al. [52] investigated experimentally the characteristics of H_2O flow boiling heat transfer in a 1.45 mm inner diameter (ID) vertical tube at atmospheric pressure, with mass flux from 23.4 to 152.7 kg/m^{2}s, heat flux from 36 to 391 kW/m^2, and quality up to 0.6. They examined the effects of mass flux, heat flux and quality on the flow boiling heat transfer coefficient and compared the measurements with flow boiling heat transfer correlations of [4,30] and [38]. It was found that the liquid film evaporation was the predominant heat transfer mechanism, that slug-annular and annular flow patterns were dominated, and that the three correlations largely under-predicted the heat transfer coefficient, especially for a low heat flux condition. The underprediction gradually decreased with increasing heat flux.

Steinke and Kandlikar [47] preformed an experimental investigation of H_2O flow boiling heat transfer at the atmospheric pressure in six parallel horizontal copper micro-channels with a hydraulic diameter of 207 μm in the range of mass flux from 157 to 1782 kg/m^{2}s, heat flux from 55 to 898 kW/m^2, and vapor quality up to 0.958. It was observed that the local flow boiling heat transfer coefficient

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Nomenclature

Bd	bond number
Bo	boiling number
Cov	convection number
D	diameter, hydraulic diameter (m)
Fa	Fang number
Fr	Froude number
G	mass flux (kg/m^2 s)
h	heat transfer coefficient (W/m^2 K)
h_{lg}	latent heat of vaporization (J/kg)
M	molecular mass (kg/k mol)
Nu	Nusselt number
p	pressure (Pa)
Pr	Prandtl number
P_R	reduced pressure
q	heat flux from tube wall to fluid (W/m^2)
Re	Reynolds number
T	temperature (°C)
We	Weber number
X	Martinelli parameter
x	vapor quality

Greek symbols

λ	thermal conductivity (W/m K)
μ	viscosity (kg/s m)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

crit	critical point
exp	experimental
f	fluid
g	saturated vapor
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

exhibited a decreasing trend with increasing quality. The comparison of the measurements with the [22] correlation showed good agreement for $x > 0.2$. For $x < 0.2$, the [22] correlation showed large underprediction, and the underprediction increased with decreasing quality.

Wen et al. [62] conducted an experimental study of H_2O flow boiling heat transfer at the atmospheric pressure in a vertical rectangular tube of 2 mm by 1 mm with heat flux ranging from 27 to 160 kW/m^2, mass flux from 134 to 211 kg/m^{2}s, and quality up to 0.3. They compared the measurements with 11 flow boiling heat transfer correlations [4,8,22,25,26,32,33,38,56,60,64]. It was shown that the [38] correlation had the smallest mean absolute deviation (MAD) of 28%, followed by the [25] correlation of 45%, the [4] of 46%, and the [64] of 47%. They thought that the conventional methods were unreliable and that it was in need to develop better correlations.

Qu and Mudawar [42,43] tested H_2O flow boiling heat transfer in rectangular channel heat sink containing 21 parallel 231 × 712 μm channels with mass flux from 135 to 402 kg/m^{2}s, heat flux from 53.6 to 519.2 kW/m^2, quality up to 0.17, and outlet pressure of 1.17 bar. With the experimental data, they evaluated 11 flow boiling heat transfer correlations [4,17,22,32,33,38,45,48,56,60,64]. The results showed that the [64] correlation provided best predictions with an MAD of 19.3% but did not capture the correct trend of heat transfer coefficient with vapor quality, while the [60] correlation provided a closer prediction of the trend but had a greater MAD of 25.4%. They pointed a need for new predictive tools that could both capture the correct micro-channel heat transfer trends and yield more accurate predictions.

Diaz and Schmidt [9] conducted an experimental investigation of H_2O flow boiling heat transfer at the atmospheric pressure in a 0.3 × 12.7 mm rectangular channel with mass flux from 200 to 500 kg/m^{2}s, heat flux from 90.4 to 359.8 kW/m^2, and quality up to 0.32. They compared the experimental data with the predictions of six correlations [4,23,32,38,48,65]. The results showed that the measurements were largely overpredicted at higher quality and remarkably underpredicted when quality less than 0.05 by all the correlations, and that no correlation could capture the trend of heat transfer coefficient with vapor quality, indicating a strong need for new predictive methods.

Kuznetsov and Shamirzaev [31] conducted the experiment of boiling heat transfer of H_2O flow in rectangular parallel stainless steel microchannels with a size of 0.64 × 2.05 mm in cross-section and a typical wall roughness of 10–15 μm at atmospheric pressure. The local flow boiling heat transfer coefficients were measured at low mass flux of 17 and 51 kg/m^{2}s, heat flux from 30 to 150 kW/m^2, and vapor quality up to 0.8. They compared the measurements with the correlations of [22] and [65] and observed that the two correlations demonstrated incorrect trend of heat transfer coefficient with vapor quality at smaller mass flux.

Kim and Mudawar [27,28] evaluated 13 previous correlations of saturated flow boiling heat transfer [1,3,8,11,17,32,37,38,40,45,56,60,64] with a database for flow boiling in mini/micro-channels, among which there are 485 data points from experiments with H_2O. The [3] correlation performed best for the H_2O data, with an MAD of 23.9%. They proposed a new generalized correlation for pre-dryout flow boiling in mini/micro-channels, which had an MAD of 21.2% for the H_2O data. The accuracies of the [27] and [3] correlations were quite good, but the data points for H_2O were limited. Therefore, their accuracies to H_2O need to be confirmed using a large database.

The above brief review clearly shows that the applicability of existing correlations of flow boiling heat transfer coefficients to H_2O remains unclear. Results from different authors are not consistent. One reason for this is that only very limited data were used. Most authors conducted the evaluations only with their own measurements. Kim and Mudawar [27] used H_2O data from multiple sources, but only 485 data points were compiled. Another reason for this is that the correlations evaluated were limited. The maximum number of the correlations involved was only 13, while the existing correlations of flow boiling heat transfer coefficients are more than 40. It is also clearly demonstrated that there is a need to develop a more accurate correlation for H_2O flow boiling heat transfer. Flow boiling heat transfer depends on working fluids. People have been studying flow boiling heat transfer intensively for more than 50 years, and a correlation that works satisfactorily for a majority of working fluids has not been found yet. Therefore, it is necessary to develop a correlation specific for H_2O.