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New correlation for heat transfer during subcooled boiling in plain channels and annuli

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A new correlation for predicting heat transfer in plain channels and annuli is presented. It has been verified with data for 13 diverse fluids (water, refrigerants, chemicals) in single and multi channels as well as annuli over a very wide range of test data. These include hydraulic diameters from 0.176 to 22.8 mm, annular gaps 0.5–11.4 mm, reduced pressures from 0.0046 to 0.922, mass flux from 59 to 31500 kg m^{-2} s^{-1} and subcooling from 0 to 165 °C. It was verified with 1340 data points from 68 data sets from 37 sources. The mean absolute deviation was 12.2%. The same database was also compared to other available correlations but their deviations were significantly greater.

1. Introduction

Calculation of heat transfer during subcooled boiling is required for many applications. These include refrigeration system evaporators with recirculation, safety analysis of nuclear reactors, reboilers used in chemical industry, etc. To ensure safe and economical design, accurate prediction of heat transfer is needed. The present author had earlier presented a correlation [64] which was shown to be in good agreement with a wide range of data for tubes and annuli [65]. Well-verified correlations were also published by Gungor & Winterton [27] and Liu and Winterton [47]. Since then, many new fluids have come into use. These include new refrigerants such as R-134a to replace refrigerants such as R-12 which are harmful to environment, and fluids such as FC-72 for electronic cooling. Another important development has been the increasing use of miniature channels. There have been reports, for example Calizzo et al. [11], that correlations based on data for conventional channels fail when applied to minichannels. In view of these developments, it was felt that a re-evaluation of available correlations is needed. The present study was undertaken to fulfil this need. A wide range of data was collected which included, besides older fluids and conventional channels, newer fluids and minichannels, and was compared to leading correlations. While the Shah correlation and a couple of other correlations gave reasonably good agreement with data, effort was made to develop a more accurate correlation. This effort resulted in a new correlation which is significantly more accurate than earlier correlations.

The new correlation takes into consideration the physical phenomena involved and has been verified with data for 13 diverse fluids (water, refrigerants, chemicals) in single and multi channels as well as annuli over a very wide range of test data. These include hydraulic diameters from 0.176 to 22.8 mm, annular gaps 0.5–11.4 mm, reduced pressures from 0.0046 to 0.922, mass flux from 59 to 31500 kg m^{-2} s^{-1} and subcooling from 0 to 165 °C. The database included 1340 data points from 68 data sets from 37 sources. The mean absolute deviation (MAD) was 12.2%.

In the following, previous work is reviewed, the development of the new correlation is described, and its comparison with test data is presented. Comparison of some leading correlation with the same database is also presented.

2. Previous research

Many studies on boiling in tubes have been conducted and many correlations for calculating heat transfer have been proposed. These efforts have been reviewed among others by Collier and Thome [18], Ghiaasiaan [23], and Yan et al. [75]. The results of these

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Nomenclature

AR	Aspect ratio of channel, width divided by height (–)
Bd	Bond number = $g(\rho_L - \rho_G)D^2\,\sigma^{-1}$, (–)
Bo	Boiling number = q (G $h_{LG})^{-1}$, (–)
C_{pl}	Specific heat of liquid at constant pressure, (J kg^{-1} °C^{-1})
D	Diameter or equivalent diameter, (m)
D_i	Outside diameter of inner tube of annulus, (m)
D_{HP}	equivalent diameter based on perimeter with boiling, defined by Eq. (8), m
D_{HYD}	hydraulic equivalent diameter, defined by Eq. (7), m
G	Total mass flux (liquid + vapor), (kg m^{-2} s^{-1})
g	Acceleration due to gravity, (m s^{-2})
h	Heat transfer coefficient, ($Wm^{-2}K^{-1}$)
h_{LG}	Latent heat of vaporization, (J kg^{-1})
h_L	Heat transfer coefficient with all mass flowing as liquid, ($Wm^{-2}K^{-1}$)
h_{pool}	Heat transfer coefficient during pool boiling, (W $m^{-2}K^{-1}$)
h_{TP}	Two-phase heat transfer coefficient defined by Eq. (9), ($Wm^{-2}K^{-1}$)
k	Thermal conductivity, (Wm^{-1} K^{-1})
N	Number of data points, (–)
Pe	Peclet number = (*Re*. *Pr*), (–)
p_r	Reduced pressure, (–)
Pr	Prandtl number, (–)
q	Heat flux, (Wm^{-2})
Re_L	Reynolds number, = $GD\mu_L^{-1}$, (–)
S	Suppression factor in Gungor & Winterton [27] correlation, (–)
T_B	Bulk liquid temperature, (°C)
T_{SAT}	Saturation temperature, (°C)
T_w	Wall temperature, (°C)
ΔT_{SAT}	= (T_w - T_{SAT}), (°C)
ΔT_{SC}	= ($T_{SAT} - T_B$), (°C)
Greek	
μ	Dynamic viscosity, (kg m s^{-1})
ρ	Density, (kg m^{-3})
σ	Surface tension, (N m^{-1})
Ψ_0	Ratio of two-phase to single-phase heat transfer coefficient at zero quality, (–)
Subscripts	
L	Of liquid
G	Of vapor

researches are briefly discussed in the following.

2.1. Classifications of channels

Quite a few classifications of channels have been proposed. Many of them have been discussed by Cheng and Mewes [12] and Ong [53]. A widely used one is by Kandlikar [37] according to which:

Conventional Channels: $D_{HYD} > 3$ mm
Minichannels: 3 mm $\geq D_{HYD} > 0.2$ mm
Microchannels: 0.2 mm $\geq D_{HYD} > 0.01$ mm

This classification was based mainly on flow of gases but he also recommended it for boiling and condensing flows.

Cheng and Wu [13] have given the following criteria based on an analysis considering the magnitudes of gravity and surface tension effects:
Microchannel, if Bd < 0.5 (negligible effect of gravity)
Minichannel, if 0.5 < Bd < 3.0 (both gravity and surface tension have significant effect)
Macrochannel, if Bd > 3.0 (surface tension has negligible effect)
In this paper, the classification by Kandlikar as given above is used, unless specifically stated otherwise.

2.2. Experimental studies & physical phenomena

Controlled experimental studies on boiling heat transfer have been reported since the 1920s. Early studies on subcooled boiling were reviewed by McAdams [49]. Later studies on conventional tubes were reviewed among others by Collier and Thome [18], Ghiaasiaan [23], and Yan et al. [75]. Numerous experimental studies on conventional tubes and annuli providing analyzable heat transfer data have been listed among others by Shah [64,65], Gungor & Winterton [27,28], and Liu and Winterton [47]. There have been numerous experimental studies on mini/micro channels in recent years. Examples are Lee and Mudawar [41], [42], Qu and Mudawar [58], Saraceno et al. [62], etc.

It has been established by visual studies as well as by the study of measured wall and fluid temperatures that there are two regimes of subcooled boiling. These are the high subcooling regime and the low subcooling regime; these are also called partial boiling and fully developed boiling regimes, respectively. In the high subcooling regime, bubbles remain attached to wall and void fraction is very low. In the low subcooling regime, bubbles detach from the wall and enter into the liquid stream. Void fraction is comparatively high in the low subcooling regime. Wall temperature continues to rise in the flow direction in high subcooling regime while it is essentially constant in the low subcooling regime. Thus the behavior and mechanism of heat transfer is different in the two regimes.

2.3. Predictive techniques

Numerous correlations have been proposed for heat transfer in subcooled boiling. Most of them were verified with very limited amount of data. Examples of those for conventional channels are Thom et al. [73], Papell [54], Badiuzzaman [3], Kandlikar [35], Prodanovic et al. [56], and Baburajan et al. [2]. Examples of correlations based on minichannel data are those of Lee & Mudwar [42] and Haynes & Fletcher [30] but these were based on very limited data. Correlations which were based on wide ranging data for conventional channels are Shah [64], Gungor & Winterton [27], Liu & Winterton [47], and Moles & Shaw [51]. Among these, that of Shah is the most verified. None of the correlations has had much verification for minichannels.

Some of the above mentioned correlations have been compared by some researchers with their own data. Baburajan et al. [2] found wide deviations from their data with correlations of Badiuzzaman, Papell, Moles and Shaw, and Prodanovic et al. Calizzo et al. [11]