An Improved Correlation for Saturated Flow Boiling Heat Transfer in a Helically Coiled Tube

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1. Introduction

The flow and heat transfer in a helical tube differ significantly from those in a straight tube due to the centrifugal force induced by the tube's geometrical structure [1, 2]. Figure 1 shows the schematic of a helically coiled tube, which is characterized by the tube diameter, helical coil diameter, and pitch.

In a single-phase flow within a helical tube, the flow velocity at the center is greater than that near the tube wall. This difference leads to a greater centrifugal force at the center, resulting in a secondary flow perpendicular to the main axial flow as shown in Fig. 2 [3]. This secondary flow typically consists of two vortices that transport the fluid from the inner wall of the tube to the outer wall. In a two-phase flow, a more complex secondary flow pattern is expected. These features provide additional flow mixing in the circumferential direction, enhancing convective heat transfer [3, 4].

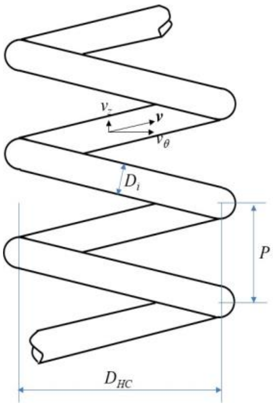

Fig. 1. Schematic of a helical tube.

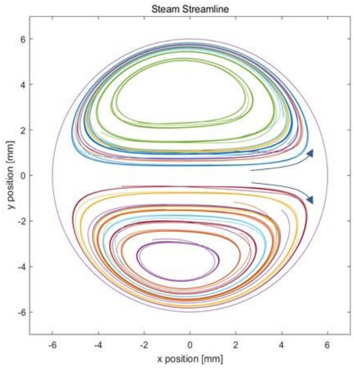

Fig. 2. Streamline of a steam flow in a helical tube [3].

Many researchers have assessed existing convective heat transfer models, which were developed for straight tubes, for application to helical tubes. Some researchers have developed models specifically for helical tubes. However, none of these models explicitly considered the effects of centrifugal force on convective heat transfer in a helical tube. Based on this background, Kim et al. [1] developed a boiling heat transfer correlation for a helically coiled tube, which involves a new dimensionless number defined by the ratio of centrifugal force to gravitational force.

However, when deriving the dimensionless centrifugal force number, their model did not account for the effect of the pitch of the helical tube. By incorporating the pitch into the dimensionless number, the heat transfer correlation needs to be adjusted appropriately. In this study, a modified correlation is proposed and assessed against a wide range of the experimental data.

2. Modification of the dimensionless centrifugal force number and its effect on boiling heat transfer

To investigate the influence of centrifugal force in a helically coiled tube, a dimensionless centrifugal force number N_{CF} is devised, which represents the centrifugal force relative to the gravity force:

$$N_{CF} = \frac{\rho v_\theta^2 / (D_{HC}/2)}{\rho g}, \tag{1}$$

where v_θ is the azimuthal component (i.e., horizontal component in Fig. 1) of the fluid velocity. It can be written as:

$$v_\theta = v\sqrt{\frac{(\pi D_{HC})^2}{(\pi D_{HC})^2 + P^2}}$$

$$= \frac{G}{\rho}\frac{1}{\sqrt{1+(P/\pi D_{HC})^2}} \tag{2}$$

Then, the centrifugal force number is re-written as

$$N_{CF} = \frac{2G^2}{\rho^2 g D_{HC}}\frac{1}{1+(P/\pi D_{HC})^2}. \tag{3}$$

Eq. (3) can be recast as:

$$N_{CF} = 2Fr\frac{D_i}{D_{HC}}\frac{1}{1+(P/\pi D_{HC})^2}. \tag{4}$$

Eq. (4) shows that the dimensionless centrifugal force number is a curvature-weighted, pitch-corrected Froude number. For the liquid phase in a two-phase flow, the dimensionless centrifugal force number is expressed as:

$$N_{CF,l} = \frac{\rho_l v_{l,\theta}^2 / (D_{HC}/2)}{\rho_l g} = \frac{2G^2(1-x)^2}{\alpha_l^2 \rho_l^2 g D_{HC}} \frac{1}{1+(P/\pi D_{HC})^2} . \qquad (5)$$

In the previous study [1], the pitch P was not reflected in the dimensionless number.

To investigate the influence of the centrifugal force on boiling heat transfer, we made an X-Y plot of the heat transfer coefficient ratio, h_{exp}/h_{lo}, versus $N_{CF,l}$. where h_{lo} is the single-phase heat transfer coefficient with only the liquid fraction flowing in the tube. In this work, the Dittus-Boelter equation is used to calculate h_{lo}. Figure 3 clearly shows that, for a given helical tube, the ratio increases by increasing $N_{CF,l}$.

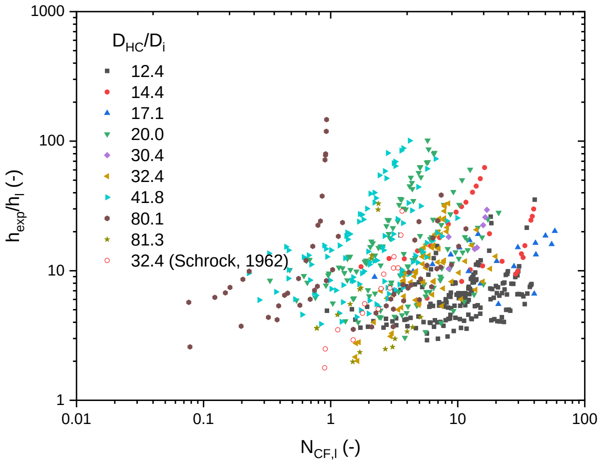

Fig. 3. Heat transfer coefficient ratio vs. the dimensionless centrifugal force number of the liquid phase.

3. Modification of the previous boiling heat transfer correlation and assessment

The basic form of the heat transfer correlation for a helical tube [1] was taken from the Kandlikar's correlation [5], which was selected for its simplicity and accuracy. It was modified to reflect the effect of the dimensionless centrifugal force number as follows.

$$h_{TP} = \left[C_1 Co^{C_2} \left(1 + C_3 N_{CF,l}\right)^{C_4} + C_5 Bo^{C_6} + C_7 \right] h_{lo} , \qquad (6)$$

where C_1=0.983, C_2=-0.874, C_3=0.024, C_4=0.377, C_5=3858.4, C_6=0.920, and C_7=0.517. These constants were determined so that the root mean square error of the predicted heat transfer coefficient can be minimized. For curve fitting, 617 experimental data sets were used, which are listed in Table I.

In the previous work [1], the flow conditions were divided into two regions according to the Froude number ($Fr \leq 1$ and $Fr > 1$) and the constants for each region were determined. However, in this work, all the flow conditions were treated as one region since the effect of the Froude number can be represented by the dimensionless centrifugal force number.

For the assessment of the modified correlation, we compared the heat transfer coefficient ratios of 617 experimental data listed in Table I with those calculated by the modified and the previous correlations. Figure 4 shows the results. The two correlations provide very similar results. Table II presents a quantitative comparison between the modified correlation, the previous one, and those by Kandlikar [5] and Shah [6]. The modified one demonstrates the best performance in terms of the root mean square error, with a 2.45% decrease compared to the previous one, and surpasses the correlations by Kandlikar and Shah.

It is noted that, in the previous work [1], the correlations by Kandlikar and Shah presented best results for the prediction of the boiling heat transfer coefficients for helical tubes (602 data points).

Table I. Experimental database selected for the boiling heat transfer correlation assessment.

Authors	Tube inner dia. (mm)	Helical diameter (mm)	Pitch (mm)	Pressure (MPa)	Heat flux (kW/m^2)	Mass flux (kg/m^{2}s)	No. of Data points
Chang [7]	8.0	650	181	8.0 ~ 14.0	100 ~ 300	500 ~ 1,000	18
Hardik [8]	8.0, 9.7	137, 144	50	0.14 ~ 0.28	290 ~ 620	129 ~ 400	39
Owhadi [9]	12.5	250.4, 522.5	99.1, 116.8	0.10 ~ 0.21	60.8 ~ 253.6	77 ~ 314	235
Santini [10]	12.5	1000	790	2.0 ~ 6.0	46 ~ 200	200 ~ 820	59
Xiao [11]	12.5, 14.5	180, 280, 380	37.8, 58.9, 79.9	2.0 ~ 7.6	300 ~ 400	600 ~ 800	22
Xiao [12]	14.5	180	37.8	2.0 ~ 7.6	200 ~ 500	400 ~ 1,000	156
Zhao [13]	9.0	292	30	3.0	70 ~ 470	400 ~ 700	73
Schrock [14]	9.0	292	30	7.5	70 ~ 200	400	15

Table II. Comparison of the modified and existing flow boiling heat transfer correlations for helically coiled tube data.

Correlation	The modified*	The previous [1]*	Kandlikar	Shah
Root mean square error, RMSE (-)	0.1869	0.1916	0.207	0.205
Mean absolute relative error, MARE (-)	0.1470	0.1415	0.153	0.155
Data within ±30% error band (%)	91.09	91.25	91.04	91.12

*Obtained with 617 data points (including the 15 new data).

$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\frac{\left|h_{\exp,i} - h_{cal,i}\right|}{h_{\exp,i}}\right]^2}$ and $\mathrm{MARE} = \frac{1}{N}\sum_{i=1}^{N}\frac{\left|h_{\exp,i} - h_{cal,i}\right|}{h_{cal,i}}$, where N is the number of experimental data.

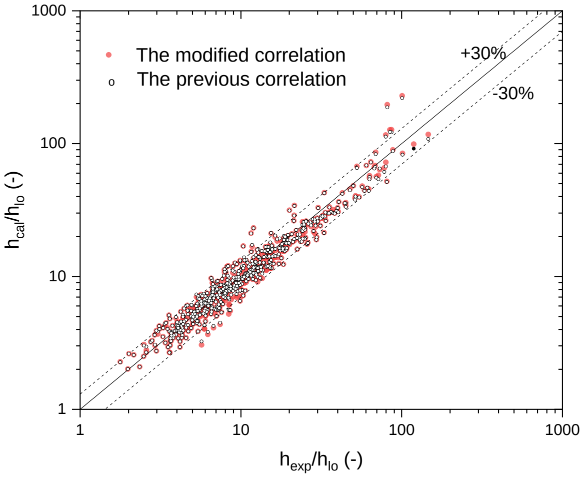

Fig. 4. Heat transfer coefficient ratios for the helical tubes: Calculated vs. measured.

4. Conclusions

The flow in a helically coiled tube exhibits a unique feature due to the centrifugal force acting on the fluid. It generates a secondary flow perpendicular to the main axial flow in the form of a circular trajectory. This feature is known to enhance convective heat transfer in the tube. To account for this effect on boiling heat transfer, Kim et al. [1] developed a new correlation, which involves a dimensionless centrifugal force number defined as the ratio of centrifugal force to gravitational force.

This study aims at the improvement of the Kim et al.'s model. Their work did not include the pitch of a helical tube in the dimensionless centrifugal force number. By incorporating the pitch into the dimensionless number, the heat transfer correlation needed to be revised. The resulting correlation was evaluated using 617 experimental data points for boiling heat transfer in helically coiled tubes. The modified correlation outperforms both the previous one and the existing Kandlikar and Shah correlations.

NOMENCLATURE

Bo	the boiling number, $q/(Gh_{fg})$
Co	the convection number, $[(1-x)/x]^{0.8}(\rho_g/\rho_f)^{0.5}$
D_i	inner diameter of the tube (*mm*)
D_{HC}	diameter of helical coil (*mm*)
Fr	the Froude number, $v^2/(gD_i)$
g	acceleration of gravity (*m/s²*)
G	mass flux, ρv (kg/m^2s)
h	heat transfer coefficient (W/m^2K)
N_{CF}	the dimensionless centrifugal force number
P	pitch of the helical tube (*mm*)
q	heat flux (W/m^2)
v	velocity (*m/s*)
x	vapor quality (-)

Greek symbols

α	void fraction (-)
ρ	density (kg/m^3)

Subscripts

cal	calculated
exp	experimental
l	liquid phase
lo	liquid only
TP	two-phase

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