A boiling heat transfer correlation for a helically coiled tube

Min Gi Kim, Byongjo Yun, Jae Jun Jeong*
School of Mechanical Engineering, Pusan National University, Busan 46241, South Korea
**jjjeong@pusan.ac.kr*

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1. Introduction

The helically coiled tubes are widely employed for heat exchangers in various industries, including chemical, air conditioning, refrigeration, and nuclear engineering, due to its compact geometry and advanced heat transfer performance. Recently, the nuclear industry has shown increasing interest in helical coil heat exchangers, recognizing their numerous advantages. Also, helical coil type heat exchangers have been adopted in various integral reactor designs, such as NuScale and SMART [1, 2]. However, it is still difficult to accurately predict the heat transfer performance of helical coil tube inside because of its complicated boiling mechanism caused by the centrifugal force. Also, previous studies for the development of boiling heat transfer correlation mainly have used experimental data of vertically straight tubes.

This study focuses on developing a boiling heat transfer correlation for a helically coiled tube. We investigated the effects of curvature and centrifugal force on heat transfer, along with the distinctions in flow boiling mechanisms between helically coiled and straight tubes. The effects of key dimensionless parameters, such as the convection, boiling, and Froude numbers, were also investigated. To consider centrifugal force into the heat transfer in a helically coiled tube, we introduced a dimensionless number regarding centrifugal force. The performance of the developed correlation was assessed using data from 7 experiments.

2. Data collection

A total of 7 sets of experimental data were gathered to analyze flow boiling heat transfer in helically coiled tubes using water as the working fluid (see Table 1). 624 data points cover a wide range of pressure, heat flux and mass flux, with vapor qualities spanning 0.005 to 0.95. Also, the experimental database includes diverse tube geometries relevant to the design conditions of integral reactors.

3. Data analysis

In Figs. 1 and 2, the heat transfer coefficient ratios h_{TP}/h_l (the measured two-phase heat transfer coefficient divided by the single-phase heat transfer coefficient calculated by the Dittus-Boelter equation) are plotted against the convection number *Co* and the boiling number *Bo*, showing clear dependences on both parameters, consistent with previous research [2]. As *Co* increases, heat transfer coefficient ratio decreases. In the Fig.1, decreasing *Co* represents increasing vapor quality. When the flow regime changes from bubbly to annular flow, convective boiling heat transfer becomes dominant, and the nucleate boiling becomes relatively less effective. The heat transfer coefficients ratio towards a linear trend. Conversely, at low-quality conditions with higher *Co*, nucleate boiling effect is notable, causing heat transfer to increase proportionally with *Bo* (see Figs. 1 and 2). These results show the dependences for the dimensionless numbers in boiling heat transfer in a helically coiled tube.

Strengthening centrifugal force intensifies outer-side convection heat transfer, as observed in the experiment [3]. The centrifugal force leads to even distribution of the liquid film and, consequently, enhances boiling heat transfer. Thus, investigating the effect of centrifugal force on the helical tube's heat transfer is valuable.

Table 1. Experimental data: helically coiled tube with water

Investigator(s)	Chang [3]	Hardik [4]	Owhadi [5]	Santini [6]	Xiao [7,8]	Xiao [9]	Zhao [10]
d_i (mm)	8	8.0 / 9.7	12.5	12.5	12.5 /14.5	14.5	9
D_{HC}/d_i (-)	81.3	14.4 / 17.1	20.0 / 41.8	80.1	12.4 / 14.4 / 26.2 / 30.4	12.4	32.4
P (MPa)	8	0.14 ~ 0.28	0.1 ~ 0.21	2.0 ~ 6.0	2.0 ~ 7.6	2.0 ~ 7.6	3
q (kW/m^2)	100.0 ~ 300.0	290.0 ~ 620.0	60.8 ~ 253.6	46.0 ~ 200.0	300.0 ~ 400.0	200.0 ~ 500.0	70.0 ~ 470.0
G (kg/m^{2}s)	500~ 1,000.0	129~ 400.0	77.0 ~ 314.0	200 ~ 820.0	600~ 800.0	400 ~ 1,000.0	400 ~ 700.0
Direction	Vertical						Horizontal
Data points	36	41	235	60	23	156	73

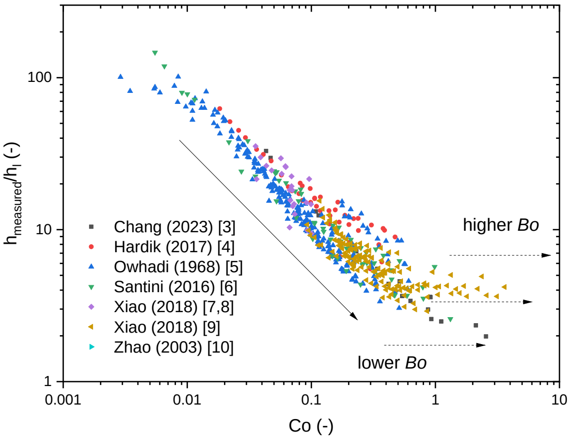

Fig.1 Heat transfer coefficient ratio vs *Co*.

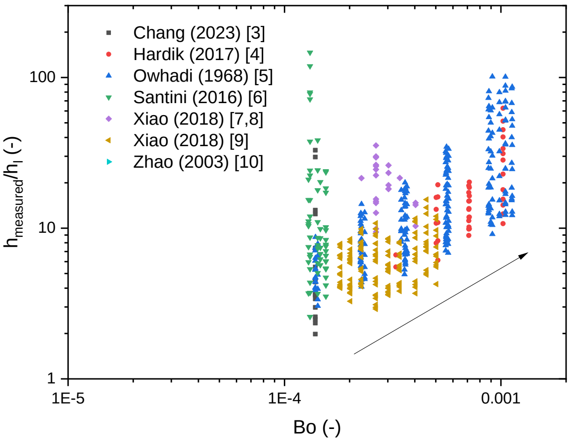

Fig.2 Heat transfer coefficient ratio vs *Bo*.

To observe the effect of centrifugal force, we introduced a dimensionless number, N_{CF}, which represents the centrifugal force on the fluid relative over gravity:

$$N_{CF} = \frac{\rho_{mix} v_{mix}^2 / R_{HC}}{\rho_{mix} g} = \frac{v_{mix}^2}{g R_{HC}},$$
$$= \frac{G^2}{\rho_{mix}^2 g R_{HC}}, \qquad (1)$$

where R_{HC} is the radius of the helical coil. In the case of a straight tube, R_{HC} is infinite. For the liquid phase, the dimensionless number can be expressed as follows:

$$N_{CF,l} = \frac{\rho_l v_l^2 / R_{HC}}{\rho_l g} = \frac{v_l^2}{g R_{HC}},$$
$$= \frac{G_l^2}{\alpha_l^2 \rho_l^2 g R_{HC}},$$
$$= \frac{G^2 (1-x)^2}{\alpha_l^2 \rho_l^2 g R_{HC}}. \qquad (2)$$

The liquid volume fraction, α_l , can be calculated from the definition of vapor quality flowing inside a tube:

$$x = \frac{\alpha_g \rho_g v_g}{\alpha_g \rho_g v_g + \alpha_l \rho_l v_l}. \qquad (3)$$

Then, the liquid fraction can be expressed as:

$$\alpha_l = \frac{(1-x)(\rho_g/\rho_l)S}{x + (1-x)(\rho_g/\rho_l)S}. \qquad (4)$$

By substituting Eq. (4) into Eq. (2), $N_{CF,l}$ is written as:

$$N_{CF,l} = \frac{G^2}{g R_{HC}} \left(\frac{x}{\rho_g} \frac{1}{S} + \frac{1-x}{\rho_l} \right)^2 .. \qquad (5)$$

In this study, we used a correlation for the slip ratio proposed by Chisholm [11]:

$$S = \max \left[1, \sqrt{1 - x\left(1 - \frac{\rho_l}{\rho_g}\right)} \right] . \qquad (6)$$

Fig. 3 shows the heat transfer coefficient ratios in the experiments listed in Table 1 with respect to $N_{CF,l}$. As $N_{CF,l}$ increase, the heat transfer coefficient ratio increases showing that they are strongly dependent on the centrifugal force. When the centrifugal force increases, the secondary flow is enhanced. This leads to reducing the non-uniformity of wall temperature distribution and, in turn, enhancing the boiling heat transfer.

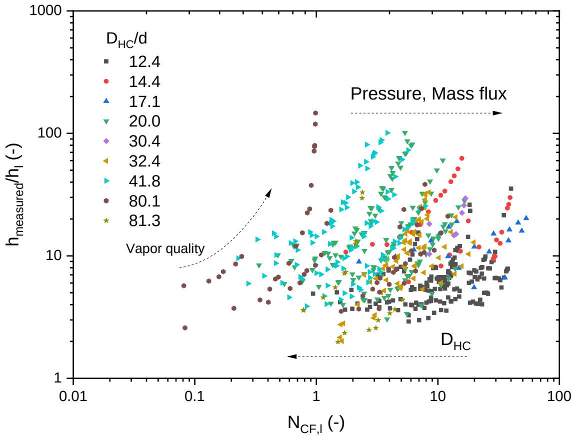

Fig.3 Heat transfer coefficient ratio vs $N_{CF,l}$.

4. Development of a boiling heat transfer correlation for helically coiled tube

We developed a heat transfer correlation for helically coiled tubes. Similar to the Kandlikar correlation [12], new correlation combines convective and nucleate boiling terms. Because the behavior of heat transfer coefficient ratio with $N_{CF,l}$ is similar to that of Co, the proposed correlation simplifies the convective boiling term by combining the $N_{CF,l}$ term with Co term. In this way, the convective heat transfer can be more accurately calculated.

As a result, the form of proposed correlation is as follows:

$$\frac{h_{TP}}{h_l} = C_1 Co^{C_2} \left(1 + 0.1 N_{CF,l}\right)^{C_3} + C_4 Bo^{C_5} + C_6 . \qquad (3)$$

The first term combined with Co and $N_{CF,l}$ takes into account the convective boiling effect, and the second term considers nucleate boiling effect. When a boiling occurs, the two-phase heat transfer coefficient increases rapidly compared to the single-phase heat transfer, so the constant term C_6 was added to consider the discontinuity. Using the 624 experimental data points in Table 1, the constants in Eq. (3) were obtained from a curve fitting program, CurveExpert Professional [13]. Table 2 presents constants of the proposed correlation.

Table 2. Constants in the proposed correlation.

Constant	$Fr < 1$	$Fr > 1$
C_1	0.66	0.97
C_2	-0.99	-0.95
C_3	0.103	0.0998
C_4	3330.9	3427.6
C_5	0.92	0.91
C_6	1.40	0.55

We assessed the performance of the proposed correlation with existing correlations. Fig. 4 compares the predicted and measured heat transfer coefficient ratios. The new correlation showed excellent results, despite some challenging overpredictions, which were common for most correlations.

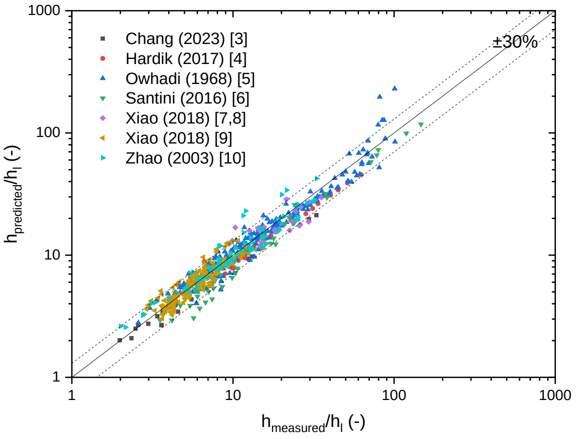

Fig.4 Predicted vs measured heat transfer coefficient ratio for helically coiled tube.

For a quantitative comparison, we compared the root mean square error (RMSE), mean absolute error (MAE), and percentages within ±20% and ±30% error bands of the new model with two well-known correlations, the Kandlikar and Shah correlations. Table 3 shows that the new one is better than the other existing ones.

For the assessment against boiling heat transfer in straight tubes, we used a total 2,012 of experimental data listed in Table 4. Fig. 5 presents comparison of the predicted and measured heat transfer coefficient ratio of the new correlation for boiling heat transfer in both straight and helically coiled tubes.

Remarkably, despite being developed solely from helical tube data, the new correlation showed its suitability for straight tubes. Most predicted value showed good agreement within ±30% error, showing its versatile application for both tube types.

Table 3. Performance of proposed and existing correlations

	New correlation	Kandlikar (1990)	Shah (1976)
RMSE (-)	0.194	0.207	0.205
MAE (-)	0.141	0.161	0.159
Data within ±20% error band (%)	75.79	67.66	69.80
Data within ±30% error band (%)	90.88	90.26	89.44

Table 4. Experimental data: straight tube with water

Investigator(s)	Mumm [14]	Sani [15]	Schrock [16]	Wright [17]	Bennett [18]	Hardik [19]
d_i (mm)	11.8	18.3	3	18.2	20.4	7.5 / 9.3 / 10.0
Direction	Vertical					Horizontal
P (MPa)	0.31 ~ 1.38	0.11 ~ 0.21	0.29 ~ 1.27	0.10 ~ 0.35	0.2	0.12 ~ 0.20
q (kW/m^2)	157.0 ~ 247.0	43.0 ~ 157.0	306.0 ~ 2,090.0	4.74 ~ 157.0	136.0 ~ 581.0	400.0 ~ 1,345.0
G (kg/m^{2}s)	339.0 ~ 1,383.0	350.0 ~ 1,035.0	1,245.0 ~ 2,939.0	250.0 ~ 1,345.0	115.0 ~ 981.0	230.0 ~ 650.0
Data points	343	254	195	907	257	56

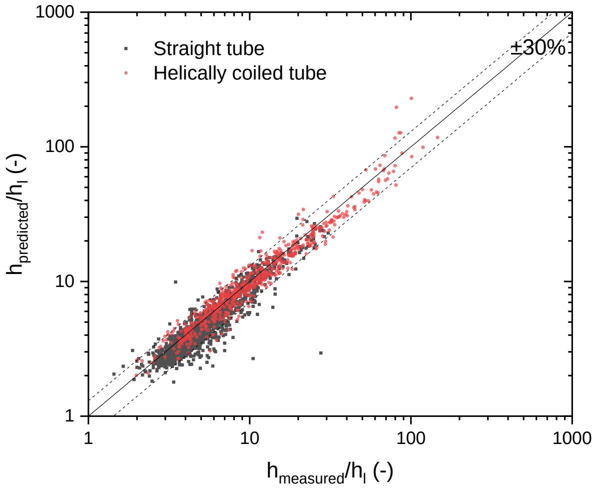

Fig.5 Predicted vs measured heat transfer coefficient ratio for helically coiled and straight tube.

5. Conclusion

In this study, we have developed a new correlation for a helically coiled tube under saturated flow boiling condition. We analyzed experimental data of boiling heat transfer and confirmed the importance of centrifugal force on boiling heat transfer in a helical tube. Thus, we introduced a new dimensionless number, $N_{CF,l}$, which represents the centrifugal force in a helically coiled tube over gravity, into a new boiling heat transfer correlation. The proposed correlation showed excellent performance. It was also shown that it can be applied to straight tubes as well. Therefore, this correlation is strongly recommended for the design and analysis of helical coil steam generators for SMRs.

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Nomenclature

Bo	boiling number, $\frac{q}{Gh_{fg}}$ (-)
Co	convection number, $\left(\frac{1-x}{x}\right)^{0.8}\left(\frac{\rho_g}{\rho_f}\right)^{0.5}$ (-)
d_i	inner diameter of the tube (m)
D_{HC}	diameter of helical coil (m)
Fr	Froude number, $\frac{G}{\sqrt{gd_i}}$ (-)
G	mass flux,
R_{HC}	radius of helical coil (m)
S	slip ratio, v_g/v_l (-)