A boiling heat transfer correlation for a helically coiled tube

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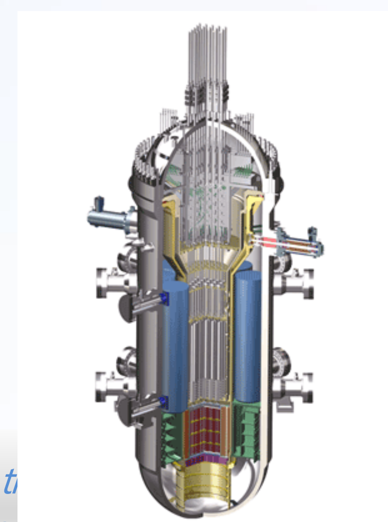
Contents

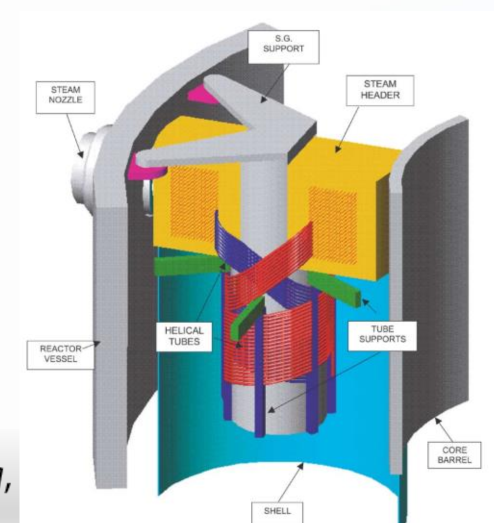
Introduction

- **Accurate simulation of SMR's helical steam generators is vital for optimizing design, ensuring safety, and enhancing efficiency in nuclear power plants.**
- **Precise simulations are key to meeting safety standards and maximizing energy production using SMR's helical steam generators.**
- **Due to the unique flow boiling mechanism in helical coil tubes, understanding their characteristics is essential.**

SMART reactor



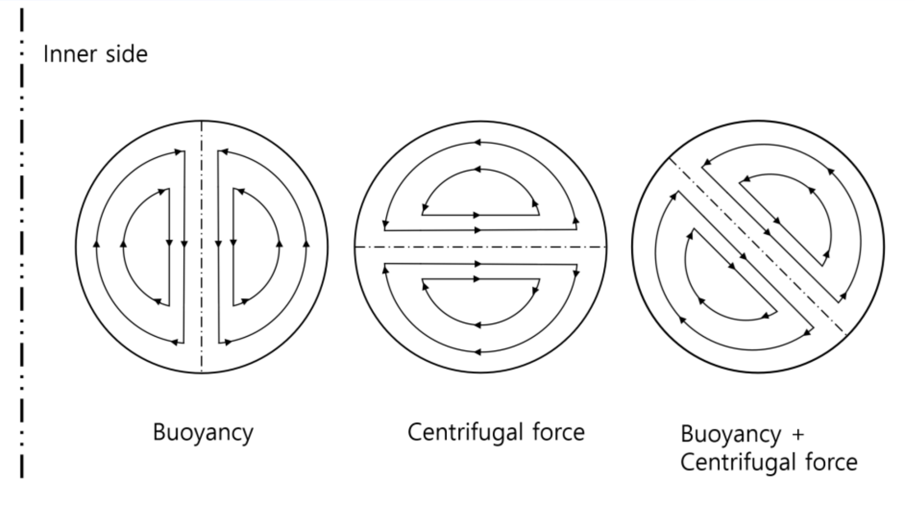
Schematic of IRIS reactor's steam generator



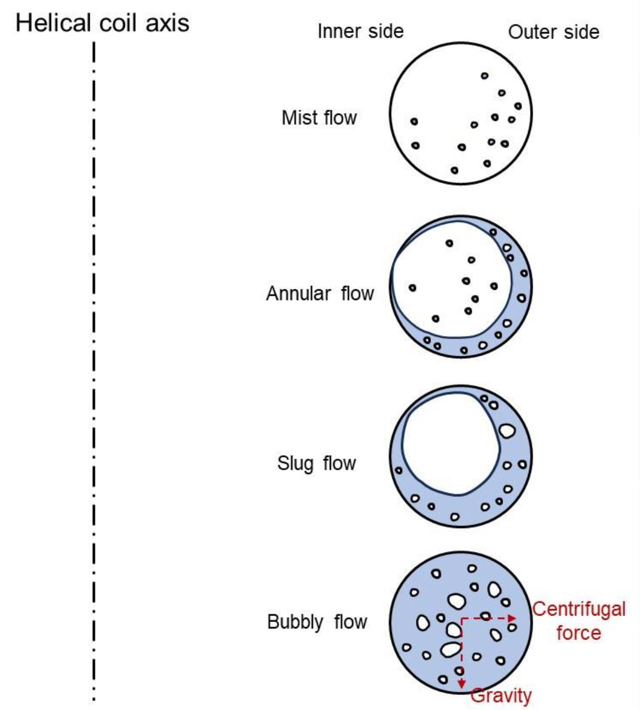
Boiling heat transfer inside a helical coil tube

- **Strengthening centrifugal force intensifies outer-side convection heat transfer**
- **The centrifugal force leads to even distribution of the liquid film and consequently, enhances boiling heat transfer**

Secondary flow effect inside a helical coil tube



Flow regime inside a helical coil tube



Data collection

- A total of 13 sets of experimental data for helically coiled tubes and straight tubes

Investigator(s)	Tube type	d_i (mm)	D_{HC}/d_i (-)	P (MPa)	q (kW/m^2)	G (kg/m^{2}s)	Direction	Data points
Chang (2023)		8.0	81.3	8.0 ~ 14.0	100.0 ~ 300.0	500.0 ~ 1,000.0		36
Hardik (2017)		8.0 / 9.7	14.4/ 17.1	0.14 ~ 0.28	290.0 ~ 620.0	129.0 ~ 400.0		41
Owhadi (1966)		12.5	20.0/ 41.8	0.10 ~ 0.21	60.8 ~ 253.6	77.0 ~ 314.0		235
Santini (2016)	Helically coiled tube	12.5	80.1	2.0 ~ 6.0	46.0 ~ 200.0	200.0 ~ 820.0	Vertical	60
Xiao (2018)		12.5 / 14.5	12.4 /14.4 / 26.2 /30.4	2.0 ~ 7.6	300.0 ~ 400.0	600.0 ~ 800.0		23
Xiao (2018)		14.5	12.4	2.0 ~ 7.6	200.0 ~ 500.0	400.0 ~ 1,000.0		156
Zhao (2003)		9.0	32.4	3.0	70.0 ~ 470.0	400.0 ~ 700.0	Horizontal	73
Mumm (1954)		11.8		0.31 ~ 1.38	157.0 ~ 247.0	339.0 ~ 1,383.0		343
Sani (1960)		18.3		0.11 ~ 0.21	43.0 ~ 15.7	350.0 ~ 1,035.0		254
Schrock (1957)		3.0		0.29 ~ 1.27	306.0 ~ 2,090.0	1,245.0 ~ 2,939.0	Vertical	195
Wright (1961)		18.2		0.10 ~ 0.35	4.74 ~ 157.0	250.0 ~ 1,345.0		907
Bennett (1976)	Straight tube	20.4	-	0.2	136.0 ~ 581.0	115.0 ~ 981.0		257
Hardik (2016)		7.5 / 9.3 / 10.0		0.12 ~ 0.20	400.0 ~ 1,400.0	230.0 ~ 650.0	Horizontal	56

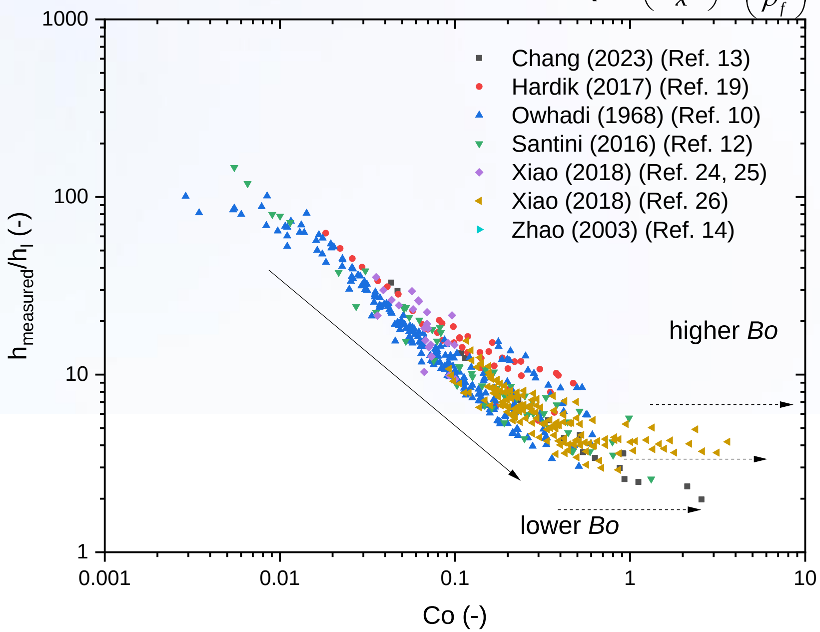
Development of new correlation (1)

- **We plotted the heat transfer coefficient ratios * h_{TP}/h_l against the convection number (*Co*) and the boiling number (*Bo*)**

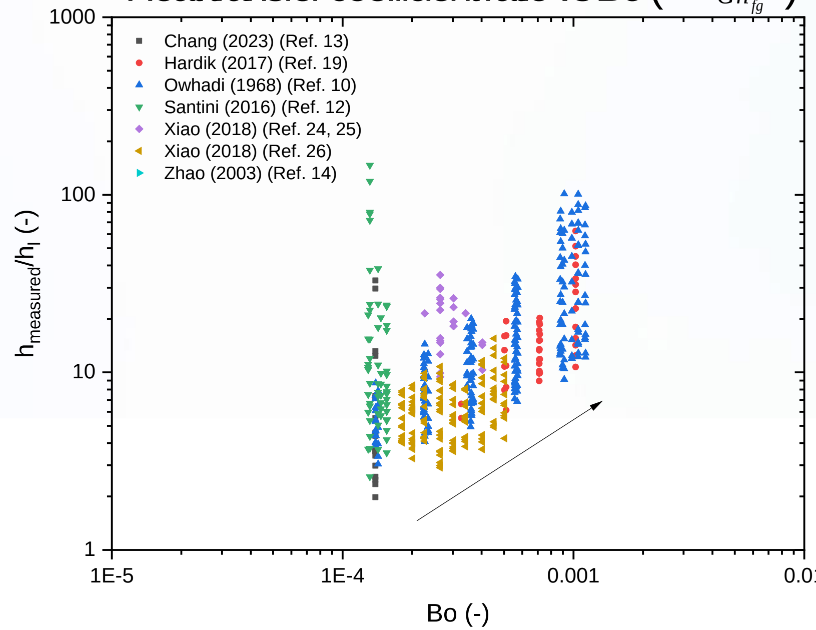
  h_l: single-phase heat transfer coefficient calculated by the Dittus-Boelter equation

- **As *Co* goes up, heat transfer ratio drops, the heat transfer coefficients ratio towards a linear trend**
- **Conversely, under low-quality conditions with higher *Co*, nucleate boiling is significant, leading to a proportional increase in heat transfer with *Bo***

Heat transfer coefficient ratio vs *Co* $\left(= \left(\frac{1-x}{x}\right)^{0.8}\left(\frac{\rho_g}{\rho_f}\right)^{0.5}\right)$

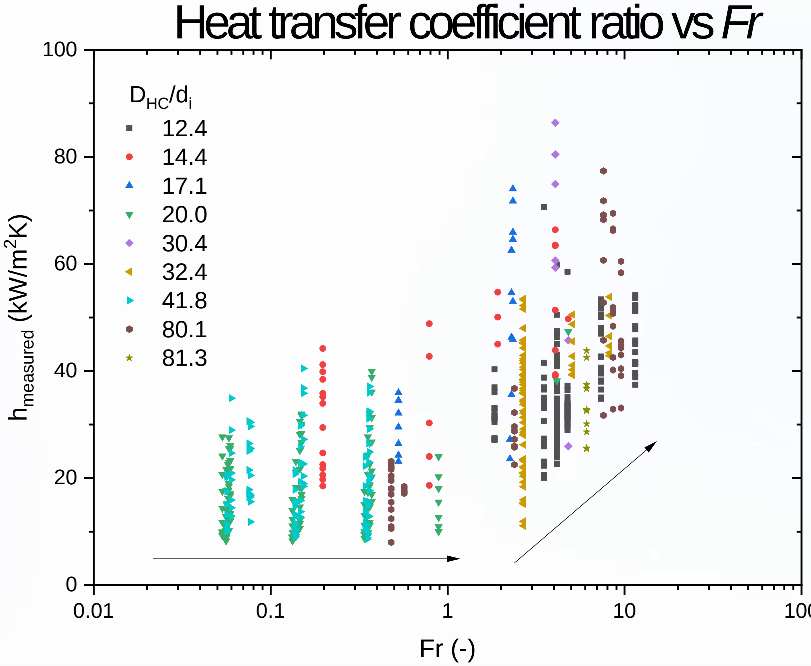


Heat transfer coefficient ratio vs *Bo* $\left(= \frac{q}{Gh_{fg}}\right)$



Development of new correlation (2)

- For *Fr* <1, the flow behavior in a helically coiled tube may be similar to that in an inclined tube
- The greater impact of gravity causes the liquid film to accumulate on the lower side, leading to increased non-uniformity in the circumferential wall temperature
- Despite the increase of *Fr*, the enhancement of the heat transfer coefficient is less sensitive
- However, for *Fr* >1, the turbulence intensifies significantly promoting uniform fluid and wall temperature due to the centrifugal force



Development of new correlation (3)

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

$$N_{CF} = \frac{\rho_{mix} v_{mix}^2 / R_{HC}}{\rho_{mix} g} = \frac{v_{mix}^2}{g R_{HC}} = \frac{G^2}{\rho_{mix}^2 g R_{HC}}$$

- **For the liquid phase, the dimensionless number can be expressed as follows:**

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

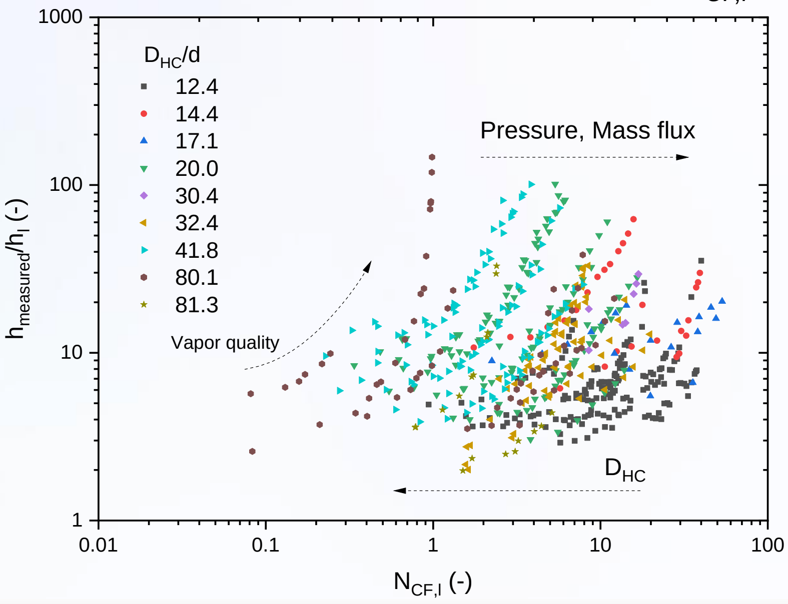
- **In this study, we used a correlation for the slip ratio proposed by Chisholm :**

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

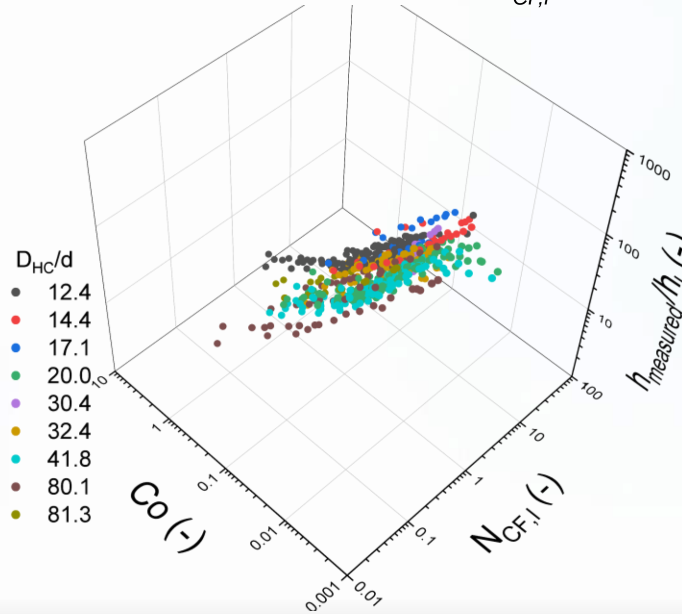
Development of new correlation (4)

- **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**

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



Heat transfer coefficient ratio vs. $N_{CF,l}$ and Co



Development of new correlation (5)

- **We developed a heat transfer correlation for helically coiled tubes by modifying the Kandlikar correlation**

$$h_{TP} = C_1 Co^{C_2} \left(25Fr_l\right)^{C_5} h_l + F_{fluid} C_3 Bo^{C_4} h_l \text{ : Kandlikar correlation}$$

- **All the coefficients for each region were obtained by using a curve-fitting program***
- **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**

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

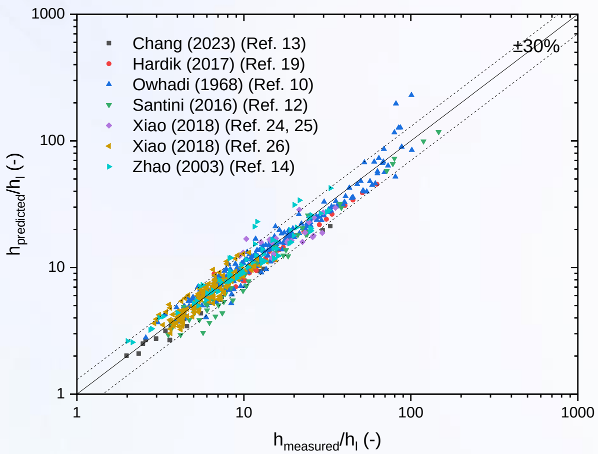
Constant	$Fr < 1$	$Fr \geq 1$
C_1	0.66	0.97
C_2	-0.99	-0.95
C_3	0.103	0.0998
C_4	3330.9	3427.6
C_5	0.92	0.91
C_6	1.40	0.55

*Curve expert professional

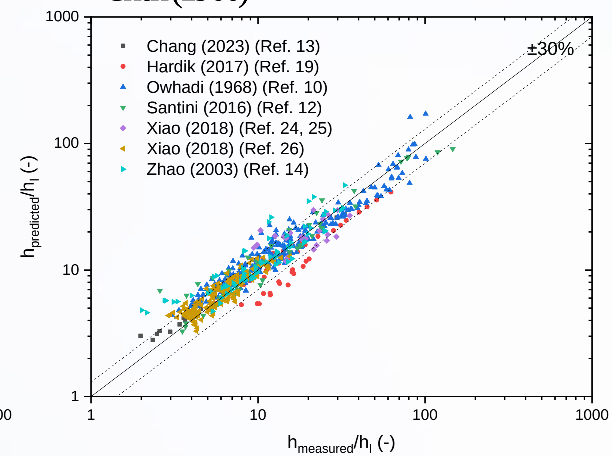
Assessment of new correlation (1)

- **New correlation shows the excellent predictions**
- **Notably, the Shah correlation and the Kandlikar correlation, which were developed for a straight tube, also show good performance**

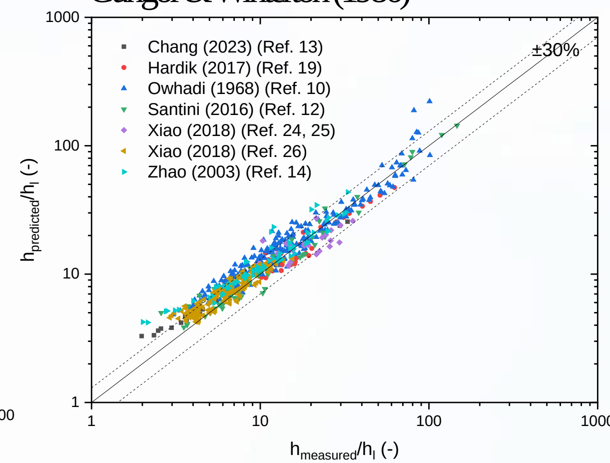
New correlation



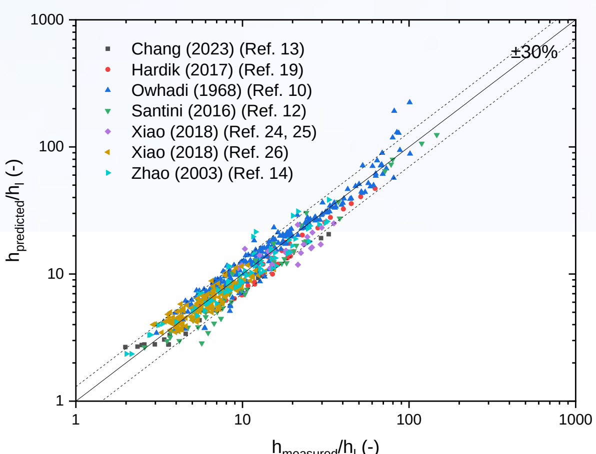
Chen (1966)



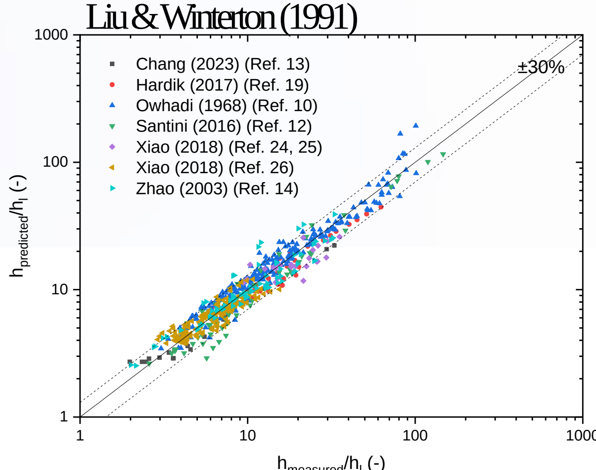
Gungor & Winterton (1986)



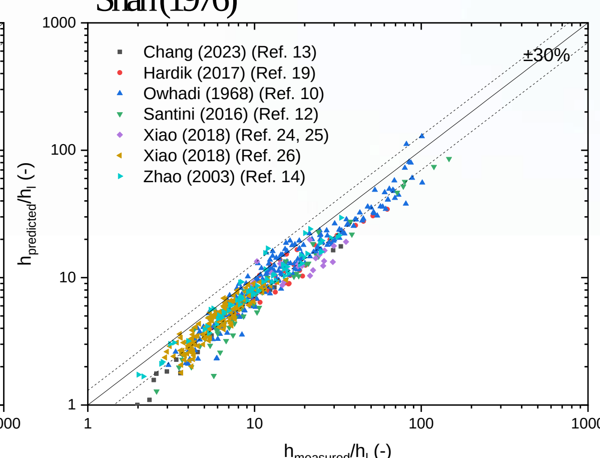
Kandlikar (1990)



Liu & Winterton (1991)



Shah (1976)



Assessment of new correlation (2)

- **New correlation shows better performance than the Shah correlation in terms of the RMSE, MAE, and the percentages within error bands**
- **Shah correlation was the best among the existing correlations**
- **Quantitatively, the new correlation showed a decreased RMSE of 5.2% compared to that of the Shah correlation**

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\frac{\left|h_{measured,i} - h_{predicted,i}\right|}{h_{measured,i}}\right]^2} \qquad \mathrm{MAE} = \frac{1}{N}\sum_{i=1}^{N}\frac{\left|h_{measured,i} - h_{predicted,i}\right|}{h_{measured,i}}$$

Comparison of the new and existing heat transfer correlations

	New correlation	Chen (1966)	Gungor & Winterton (1986)	Kandlikar (1990)	Liu & Winterton (1991)	Shah (1976)	Stenier & Taborek (1992)	Kozeki (1970)	Zhao (2003)	Chen (2011)	Kaji (1998)	Niu (2018)
RMSE (-)	**0.194**	0.287	0.287	0.206	0.357	0.204	0.372	0.287	0.284	0.387	7.193	0.410
MAE (-)	**0.141**	0.202	0.217	0.159	0.279	0.158	0.301	0.211	0.254	0.322	2.756	0.336
Data within ±20% error band (%)	**75.79**	64.68	55.56	67.99	45.11	69.98	38.97	59.87	32.67	34.00	7.79	35.82
Data within ±30% error band (%)	**90.88**	79.44	74.46	90.22	59.54	89.72	58.54	75.46	62.02	50.25	12.11	52.57

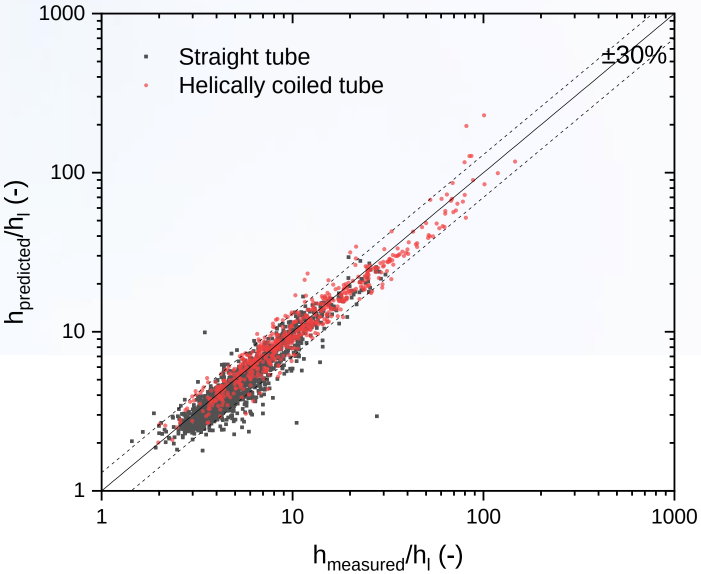
RMSE of the new and the existing correlations for each experiment

	New correlation	Chen (1966)	Gungor & Winterton (1986)	Kandlikar (1990)	Shah (1976)	Stenier & Taborek (1992)
Chang (2023)	0.206 (2nd)	0.190 (1st)	0.301	0.231	0.210	0.617
Hardik (2017)	0.177 (2nd)	0.292	0.199	0.203	0.174 (1st)	0.342
Owhadi(1968)	0.199 (1st)	0.273	0.327	0.225	0.210 (2nd)	0.312
Santini (2016)	0.206 (1st)	0.317	0.216	0.218	0.212 (2nd)	0.433
Xiao (2018)	0.245 (1st)	0.308	0.272	0.258	0.246 (2nd)	0.532
Xiao (2018)	0.151 (1st)	0.191	0.225	0.152 (2nd)	0.161	0.369
Zhao (2003)	0.233 (2nd)	0.438	0.362	0.212 (1st)	0.261	0.391

Assessment of new correlation (3)

- **We also performed quantitative assessment results for experimental data of the straight tube**
- **The proposed correlation showed the best performance among the existing correlations**
- **Although the new correlation was developed for helically coiled tubes, it can be applicable to straight tubes as well**

Predicted vs. measured heat transfer coefficient ratios for the straight and helically coiled tube



Comparison of the new and existing flow boiling heat transfer correlations for straight tube data

	New correlation	Chen (1966)	Gungor & Winterton (1986)	Kandlikar (1990)	Shah (1976)
RMSE (-)	0.181	0.229	0.192	0.188	0.183
MAE (-)	0.370	0.429	0.381	0.377	0.367
Data within ±30 % error band (%)	92.07	80.7.	90.21	90.89	91.57

Conclusions

- The study examined the effects of dimensionless numbers (convection number, boiling number, and Froude number) on boiling heat transfer
- The influence of centrifugal force on boiling heat transfer in helically coiled tubes was confirmed, and a dimensionless centrifugal force number (N_{CF}) was introduced
- A new heat transfer correlation was proposed, which outperformed existing correlations in terms of accuracy
- The new correlation also demonstrated superior performance in straight tube boiling heat transfer applications when compared to existing correlations