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Assessment of Convective Heat Transfer Correlations Against an Expanded Database for Different Fluids at Supercritical Pressures

Canadian Nuclear Laboratories (CNL) has recently expanded the supercritical heat transfer (SCHT) databank with additional data provided by the Nuclear Power Institute of China (NPIC). These additional data cover flow conditions beyond the current databank, and are applicable for improving or validating existing correlations. The expanded databank comprises more than 41,000 points of heat-transfer measurements with different fluids flowing vertically upward in tubes, annuli, and bundles at supercritical (SC) pressures. It has been applied in assessing the prediction accuracy of 24 heat-transfer correlations, which were derived from experimental data obtained with water or nonaqueous fluids (such as carbon dioxide) flowing in tubes. For the correlation assessment, a sensitivity analysis has been performed by applying the measured wall temperature as an independent parameter. The assessment against the bundle data was based on cross-sectional-averaged flow conditions and the hydraulic diameter. The iterative approach (i.e., without prior knowledge of the wall temperature) overpredicted the wall temperature, which is conservative in safety analyses.
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1 Introduction

Development and safety analysis of supercritical water-cooled reactors (SCWRs) require predictions of heat transfer during normal operation and postulated accident scenarios. Experimental data are the basis for development of a theoretical model or a correlation. However, reliable water data are still scarce and cover only a limited range of flow conditions, particularly for the rod-bundle geometry. Recently, a number of experiments have been performed using surrogate fluids, such as carbon dioxide (CO_2) and refrigerants (Refrigerant–12 and Refrigerant–22). With the low critical pressures and temperatures of these fluids compared to those of water, these experiments were able to cover a wide range of flow conditions.

Unlike the change of thermo-physical properties at low subcritical pressures, properties at the vicinity of the critical (or pseudo-critical) point are highly dependent on temperature (T) and to a much less extent on pressure (P). Although the maximum change occurs at the critical point, these properties generally decrease with increasing pressure. However, the change remains obvious at pseudo-critical point.[2] The implications on momentum and energy transport include significant differences in velocity and temperature fields in the radial direction from those for uniform properties at low-subcritical pressures. And, under certain flow conditions, buoyancy, and acceleration effects, attributed mainly to large changes in density, start influencing heat transfer. Besides the nonlinear dependence of fluid's thermophysical properties with temperature, buoyancy in the momentum equation implicitly incorporates wall temperature (T_w) dependence. Therefore, momentum and energy equations become strongly coupled. The description and solution of the turbulent mixed-convection flow are further complicated. An example of this intricacy would be the case of application of correlations to data. Churkin and Deev [1] discussed the unavoidable issues in convergence of iterative solutions, which leads some studies to directly applying correlations to data (especially, for example, for a case of application of a large number of correlations to a large size database) without the iteration for T_w. This complication calls for the need for development of accurate correlations with a different formulation of the convective heat transfer at near critical and supercritical (SC) pressure. Several reviews of convective heat transfer correlations at SC pressure have been published. For example, the studies [2–7] presented overviews and assessments of supercritical heat transfer (SCHT) correlations against both SC water and SC CO_2 data for tube. References [8–10] and recently [11], based on their rod-bundle water data, presented a more up-to-date assessment of correlations. The present study focuses on evaluation of correlations independently against the expanded databank, regardless of heat transfer mode.

2 Canadian Nuclear Laboratories Databank

Canadian Nuclear Laboratories' (CNL) heat transfer database consists of measurements obtained with water, CO_2, refrigerants, and helium in different flow channels including round tubes, annuli, and bundle subassemblies at SC pressures. Table 1 lists the range of flow conditions, heat flux (q), and geometric parameters of the recently compiled rod-bundle data. The listed flow conditions correspond to the cross-sectional average values. CNL and Nuclear Power Institute of China (NPIC) collaborated in the framework of thermal-hydraulics and safety assessment in support of SCWR concept development. NPIC has performed a number of heat transfer experiments with tubes, annuli, and bundles in water or carbon dioxide flow at SC pressures. An exchange of SCHT databases for tubes was made between CNL and NPIC to consolidate data [16]. Table 2 lists the number of the data contributed by NPIC and the total number of data in the updated CNL databases for water and CO_2 flows in tubes. Figure 1 shows the overall ranges of the reduced pressure, P/P_c, and Reynolds number, Re, for tube databases for water and CO_2 flows.

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[2]Pseudo-critical point refers to the thermodynamic state of a fluid when its pressure and temperature become equal to or larger than the critical values, and is characterized by a maximum specific heat for a given pressure.

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Table 1 Flow conditions and numbers of the recently compiled bundle data

Dataset	P (MPa)	G (kg/m^2 s)	q (kW/m^2)	d_{hy} (mm)	Heated length (m)	Fluid	Data number
Eter et al. [12]	7.7–8.4	330–1170	56–175	4.03	1.500	CO_2	1155
Gu et al. [13]	23–26	400–1200	300–1000	5.40	0.833	Water	348
Wang et al. [11]	23–28	350–1000	200–1000	4.32	0.600	Water	291
Wang et al. [14]	Same as above						353
Richards [15]	4.6	515–1000	33–96	4.70	1.000	R–12	129

Table 2 Number of data in the CNL tube database

Tube	Water	CO_2
NPIC contribution	342	4487
Updated CNL database	26,641	19,975

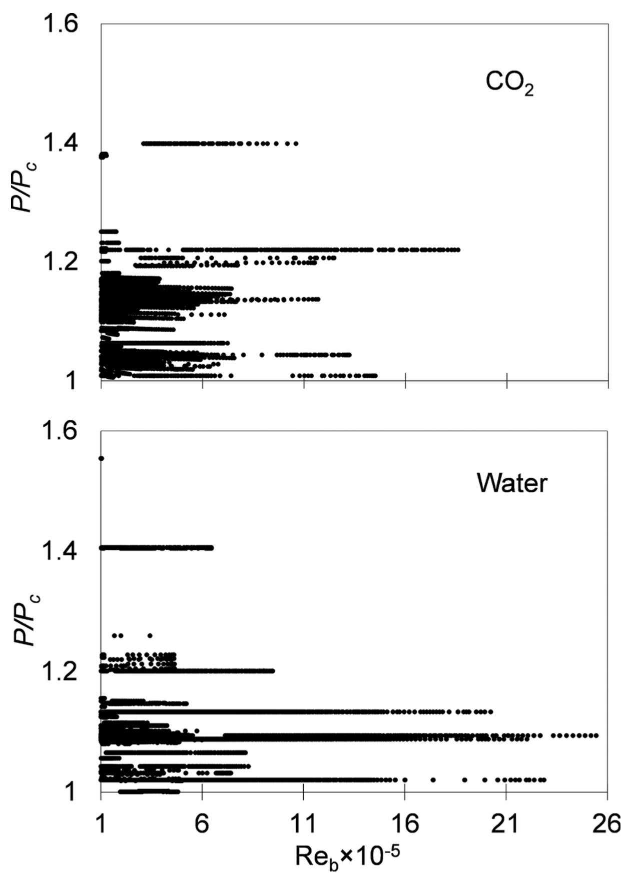

Fig. 1 Spread of the water and CO_2 databases for tube over reduced pressure and Reynolds number

Data screening: The compiled data were subjected to quality assurance tests and screening. Those not meeting the following criteria have been excluded from the databank for the present study:

- Fluid: Data for fluids other than water, CO_2, R–12, and R–22 were excluded from this study.
- Flow direction: Data for flows other than vertical upward were also excluded.
- Flow geometry: This study is interested in round tube, concentric circular annulus, and rod-bundle subassemblies; other flow geometries were removed from the correlation assessment database.
- Thermal development region: Data collected at $z/d < 30$ were left out.
- Tube diameter: Round tubes with sizes $d < 2$ mm were also excluded.
- Duplicates, outliers, and heat balance inconsistencies.

3 Single-Phase and Supercritical Heat Transfer Correlations

3.1 Tube Data-Based Correlations for Water Flow. Single-phase and SCHT correlations were compiled and described in Zahlan et al. [17]. Recently developed SCHT correlations have also been included in the assessment. The Appendix lists the form of all assessed correlations. Wang et al. [18] at CNL compiled a round tube database for SCHT to water and CO_2. The CNL water database included more than 5000 data points for vertical flow. Wang et al. [18] modified the Jackson's [19] correlation using a subset of the CNL water database. They proposed a correlation for upward flow and a correlation for downward flow. Five correlations including the proposed ones were assessed against the CNL database. The results showed that the proposed two correlations provided the closest agreement with the data. Wang and Li [9] applied the heat transfer deterioration (HTD) criterion suggested by Yamagata et al. [20] to screen datasets of Yamagata et al. [20], Kirillov et al. [21], and Zhu et al. [22]. They compiled 1916 data points for normal heat transfer (NHT) in tubes with vertical-upward flow of water. These data were applied in deriving a new correlation (based on a modification of the correlation of Hu [23]) and assessing 15 heat-transfer correlations. The assessment was based on the Nusselt number rather than the heat-transfer coefficient or the T_w. Chen and Fang [10] compiled 5366 data points from 13 different sources for water flowing vertically upward in tubes. They categorized each data point into one of three heat transfer modes (i.e., normal, enhanced, or deteriorated heat transfer) and assessed selected correlations against their database. Identification of the heat transfer mode of the data was based on the ratio of experimental to predicted heat transfer coefficient (HTC, h) using the Dittus–Boelter correlation [24]. Chen and Fang [10] proposed a general form of a SCHT correlation with eight dimensionless groups. Using regression analysis software, the number of dimensionless groups was reduced, and numerical coefficients and exponents of the general form of the correlation were found and optimized based on the experimental data using the least squares method. Similar to the correlation of Kuang et al. [25], the correlation includes both q and T_w as independent parameters.

3.2 Tube Data-Based Correlations for Carbon Dioxide Flow. Krasnoschekov and Protopopov [26] modified their previously derived correlation [27] based on CO_2 data. The modified correlation was recommended for the following ranges:

$$8 \times 10^4 < \mathbf{Re_b} < 5 \times 10^5$$

$$0.85 < \mathbf{Pr_b} < 65, 0.9 < \frac{\mu_b}{\mu_w} < 3.6, 0.09 < \frac{\rho_w}{\rho_b} < 1.0$$

$$0.02 < \frac{\overline{c_p}}{c_{pb}} < 4$$

and

$$46 < q < 2600 \mathrm{kW/m^2}$$

Jackson proposed many correlations for SCHT, e.g., see Refs. [19,28]; the original version was based on the Krasnoschekov and

Protopopov [26] correlation. Later, Wang et al. [18] modified Jackson's correlation [19] based on CNL data compilation for CO_2. Gupta et al. [29] proposed three correlations for NHT based on the experimental data collected at Chalk River Laboratories by Pioro and Khartabil [30] with the CO_2 loop. In each of these three correlations, Nusselt, Reynolds, and Prandtl numbers are evaluated at one of the three fluid temperatures, bulk fluid (T_b), fluid at the wall (T_w), or film temperature (T_{film}), which is defined as the arithmetic average between T_b and T_w. Gupta et al. [29] showed that the correlation evaluated at T_w had the best agreement with the data. Yang [31] modified the Petukhov et al. correlation [32] based on the CO_2 data collected at CNL by Pioro and Khartabil [30] and proposed two correlations, one for NHT and the other one for HTD. The Appendix lists the CO_2 data-based SCHT correlations.

3.3 Rod-Bundle Data-Based Correlations. Dyadyakin and Popov [33] reported the first correlation for a seven-rod bundle in water flow. Spacing between rods was maintained with a helical spacer. Richards [15] analyzed an experimental dataset of SCHT measurements in a seven-rod bundle cooled with Refrigerant–12 (R–12) flowing vertically upward. Richards [15] applied selected correlations for tube and rod bundle to the seven-rod bundle database and proposed a correlation. The correlation was restricted to NHT of R–12 in a seven-rod bundle flow channel. The correlation is applicable to $G < 1200\,\text{kg/m}^2$ s and bulk fluid temperature (T_b) 70–140 °C. Wang et al. [11] conducted an experimental study of SCHT to water flowing vertically upward through a 2 × 2 rod bundle, which was inserted into a square channel with rounded corners. They assessed eight correlations and modified the Jackson's correlation [19] with their collected rod bundle data. The modified exponent in the density ratio, however, is much higher than the corresponding one in the original correlation, which can be sensitive at the pseudocritical point and create scatter in the correlation trend. These correlations and their database-characteristics are listed in the Appendix.

4 Correlation Assessment

Twenty-four correlations were applied to the round tube, annulus, and rod bundle databases. Thermophysical properties were estimated from the NIST Software [34]. The HTC was calculated from the Nusselt number of the correlations. Based on the calculated HTC, q and T_b, T_w was estimated for each correlation. For correlations requiring T_w as an independent parameter, the experimental T_w was applied. This approach is reasonable to establish the closeness of the correlation to the measurement. However, it is not appropriate in design and safety analyses where the T_w is not known a priori. A sensitivity analysis has been performed to understand the implication of the iterative approach in establishing the wall-temperature prediction.

The correlation providing the best agreement with wall-temperature measurements, through the direct use of the T_w, was applied iteratively to the water database for NHT in tubes [35]. Based on the independent flow parameters and q (i.e., P, G, q and T_b), the calculation started with two assumed values for T_w ($>T_b$) following the Secant method. Using NIST Software [34], the assumed T_w values with the pressure were used to calculate the values of the T_w-based thermophysical properties in the correlation. HTC value was determined from the Nusselt number of the correlation. The values of HTC, q, and T_b are used to determine new values of T_w. The algorithm stops when the assumed and determined values of T_w nearly coincide. Otherwise, this procedure is repeated using the updated values of T_w. Under certain conditions, the procedure resulted in convergence issues and in more than one solution. These issues are attributed to the strong nonlinear dependence of thermophysical properties in the correlation on local temperature (as indicated in Churkin and Deev [1]). The challenge at this moment is to identify the most relevant solution and to reduce the prediction uncertainty.

4.1 Correlations' Application to the Extended Databank. *Round tube and annulus databases*: As discussed earlier, the present evaluation of correlations used the entire databases. The round tube database covered the two fluids water and CO_2 while the annulus database was for water only.

Rod bundle database: Rod bundle flow is very different from a simple tube flow. Estimation of bulk fluid enthalpy (H_b) and mass flux (G), for each subchannel, is usually performed with a subchannel code. A different method from subchannel analysis, for rod bundle subassemblies, is based on parameters averaged over the flow cross section and is called cross section average-parameter method [36]. H_b and G are reduced to rod bundle cross section average parameters, which are calculated based on total power and mass flow rate through all subchannels without the consideration of imbalance in flow properties between the subchannels. Thus, heat transfer in a rod bundle is simplified to an equivalent circular tube case rather than an individual subchannel. T_w of interest is the mean temperature and HTC is the average in a cross section based on equivalent hydraulic diameter (d_{hy}). Cross-section average calculation of heat transfer enables the use of tube-based correlations, for instance for preliminary thermal-hydraulic analysis of flows in rod bundles.

4.2 Uncertainty Assessment. Heat-transfer correlations are applied in predicting the cladding temperature in SCWR fuel assemblies. Therefore, the assessment examines the prediction accuracy of T_w through the expression of prediction error, e, in terms of the difference in predicted and measured T_w, respectively, $T_{w,\text{cor}}$ and $T_{w,\text{exp}}$, i.e.,

$$e = 100\,\frac{T_{w,\text{cor}} - T_{w,\text{exp}}}{T_{w,\text{exp}}}\,\% \tag{1}$$

where T_w is measured in °C. The average e_{avg} and standard deviation σ values of e were calculated for all cases. Percentages of data predicted within the error ranges of $\pm 5\%$ (e_5), $\pm 10\%$ (e_{10}), $\pm 15\%$ (e_{15}), $\pm 20\%$ (e_{20}), and $> |\pm 20\%|$ $(e_{>20})$ were also calculated for each correlation.

5 Results of Correlation Assessment

In total, eight tables of uncertainty numbers are presented, Tables 3–10. The tables show the assessment results for all tabulated correlations against all databases—regardless of applicable fluid or heat transfer mode.

5.1 Against Round Tube and Annulus Databases. *Results for the round tube database*: The results of the assessment of all correlations against the water database for tube, with a total number of 20,825 data points of screened data, are presented in Table 3. The table shows that the Chen and Fang [10] correlation has by far the lowest average error and standard deviation and the highest percentage of data predicted within the specified error ranges, discussed in Sec. 4.2. This correlation showed also a similar performance for the CO_2 database (Table 4) with 16,796 data points. The standard deviation for the Chen and Fang [10] correlation for the tube database for water and CO_2 was less than 6%.

Iteration results: Chen and Fang [10] correlation was applied to the water database for NHT for tube with 8373 data points. From this database, 110 data points showed issues in convergence. Results showed that average error and standard deviation in terms of T_w were 5.0% and 10.0%, respectively. However, the direct application of the correlation to the same database showed that the average error and standard deviation were 0.0% and 1.0%, respectively. The correlation dependency on T_w is highly nonlinear close to pseudo-critical temperature (T_{pc}), which is believed to be the cause of the convergence issues in iteration. The overprediction of the wall temperature using the iterative approach is considered conservative for design and safety analyses. However,

Table 3 Correlation uncertainty against water database for tube (20,825)

Correlation	e_{avg} (%)	σ (%)	e_5 (%)	e_{10} (%)	e_{15} (%)	e_{20} (%)	$e_{>20}$ (%)
Bishop et al. [37]	−2.3	4.9	85	95	97	98	2
Swenson et al. [38]	−0.3	5.5	88	96	98	98	2
Chen and Fang [10]	0.0	2.3	96	99	100	100	0
Wang and Li [9]	−0.5	4.8	91	96	98	98	2
Gupta et al. [39]	1.9	6.4	84	94	97	98	2
Gupta et al. [29]	3.3	10.0	33	73	91	96	4
Krasnoschekov and Protopopov [26]	−3.0	6.0	78	92	96	98	2
Yamagata et al. [20]	−4.0	7.9	58	84	92	96	4
Wang et al. [18]; Water	−0.5	5.5	86	95	97	98	2
Wang et al. [18]; CO_2	−5.6	6.6	62	87	94	96	4
Watts and Chou [40]	−1.6	5.4	85	95	97	98	2
Yang [31]; NHT	8.8	54.4	71	82	88	91	9
Yang [31]; HTD	9.5	33.1	64	84	89	91	9
Griem [41]	−1.9	5.8	82	93	96	98	2
Koshizuka and Oka [42]	−2.8	20.4	62	83	91	94	6
Jackson [19]	−3.5	5.9	74	91	96	98	2
Jackson [28]	−1.3	5.8	83	94	97	98	2
Mokry et al. [43]	0.4	4.8	90	96	98	98	2
Kuang et al. [25]	1.0	7.2	79	92	97	98	2
Cheng et al. [44]	−1.9	6.8	78	91	95	97	3
Sieder and Tate [45]	−7.8	7.8	45	71	86	93	7
Gnielinski [46]	−6.2	7.7	52	76	89	94	6
Dittus and Boelter [24]	−6.1	7.5	53	78	90	95	5

Table 4 Correlation uncertainty against CO_2 database for tube (16,796)

Correlation	e_{avg} (%)	σ (%)	e_5 (%)	e_{10} (%)	e_{15} (%)	e_{20} (%)	$e_{>20}$ (%)
Bishop et al. [37]	−5.0	12.8	33	65	81	89	11
Swenson et al. [38]	−3.6	13.9	39	63	79	88	12
Chen and Fang [10]	0.5	5.8	76	92	98	99	1
Wang and Li [9]	−1.2	14.7	37	67	83	91	9
Gupta et al. [39]	5.2	17.1	41	67	80	88	12
Gupta et al. [29]	16.9	20.3	17	34	52	64	36
Krasnoschekov and Protopopov [26]	−5.5	13.3	40	61	74	84	16
Yamagata et al. [20]	−16.0	22.8	12	28	47	60	40
Wang et al. [18]; water	4.9	14.2	44	67	79	88	12
Wang et al. [18]; CO_2	−15.6	10.7	9	24	47	70	30
Watts and Chou [40]	−1.6	11.4	45	69	84	92	8
Yang [31]; NHT	21.3	26.5	8	19	33	46	54
Yang [31]; HTD	1.6	22.1	26	50	69	79	21
Griem [41]	5.9	18.4	27	50	67	78	22
Koshizuka and Oka [42]	−22.7	23.6	13	31	42	50	50
Jackson [19]	−6.5	13.0	37	60	73	83	17
Jackson [28]	4.4	14.7	38	63	78	86	14
Mokry et al. [43]	5.5	17.9	40	69	81	87	13
Kuang et al. [25]	11.5	29.1	28	51	65	72	28
Cheng et al. [44]	4.0	204.5	25	44	59	71	29
Sieder and Tate [45]	−22.4	20.1	21	38	48	54	46
Gnielinski [46]	−20.5	22.4	25	41	50	55	45
Dittus and Boelter [24]	−16.2	22.2	25	42	52	59	41

further analyses are needed to establish the general trend over the entire database.

Results for the annulus database: Table 5 presents uncertainty numbers of all correlations applied to the concentric circular annulus database for water with 1078 data points, collected by Licht et al. [47]. Results of the assessment of correlations for this database show that the Jackson's [19] correlation had the best agreement with the data.

5.2 Against Rod Bundle Database. Error analysis of the correlations against the bundle data was based on average wall temperature, because most of the data (for different rod bundles) were reported in terms of average T_w and not maximum T_w. Also, for general temperature representation and correlation assessment based on different subchannels and spacers, the average wall temperature was deemed more meaningful than the maximum wall temperature. The latter was reported to be affected by spacer design and measurement location. However, if studying a specific spacer design, the correlations' assessment would be more useful based on the maximum wall temperature.

Water database: Correlations were also assessed against the rod bundle databases for water. The single-phase correlation of Dittus–Boelter [24], twenty SC heat transfer correlations for tube, and three correlations for rod bundle were applied to the plain (no spacers in the heated length) 2×2 rod bundle database (639 data points). The best estimation of the experimental data (Table 6) was also achieved by the Chen and Fang [10] correlation, followed by the Bishop et al. [37] and Griem [41] correlations. Similarly, the correlations were applied to the wire-wrapped rod bundle database with 372 data points. Table 7 shows the results of this assessment. The Chen and Fang [10] correlation had the best

Table 5 Correlation uncertainty against water database for annulus (1078)

Correlation	e_{avg} (%)	σ (%)	e_5 (%)	e_{10} (%)	e_{15} (%)	e_{20} (%)	$e_{>20}$ (%)
Bishop et al. [37]	0.9	2.2	97	99	100	100	0
Swenson et al. [38]	2.1	3.1	91	97	99	100	0
Chen and Fang [10]	1.0	2.5	95	98	99	100	0
Wang and Li [9]	2.6	3.9	90	96	98	99	1
Gupta et al. [39]	4.1	4.6	73	94	97	98	2
Gupta et al. [29]	5.2	7.4	51	72	91	96	4
Krasnoschekov and Protopopov [26]	2.3	2.3	93	98	100	100	0
Yamagata et al. [20]	2.9	5.1	73	90	97	99	1
Wang et al. [18]; water	3.4	2.4	84	98	100	100	0
Wang et al. [18]; CO_2	−1.6	2.0	95	99	100	100	0
Watts and Chou [40]	2.7	2.2	89	98	100	100	0
Yang [31]; NHT	6.2	5.9	45	84	91	96	4
Yang [31]; HTD	7.5	8.7	47	78	86	93	7
Griem [41]	2.1	2.4	92	98	100	100	0
Koshizuka and Oka [42]	−0.4	4.1	91	96	97	99	1
Jackson [19]	1.1	1.9	97	100	100	100	0
Jackson [28]	2.9	2.2	87	99	100	100	0
Mokry et al. [43]	3.7	5.0	77	93	97	97	3
Kuang et al. [25]	5.6	8.5	67	82	93	95	5
Cheng et al. [44]	2.6	3.9	88	95	98	100	0
Richards [15]	−0.3	9.6	51	83	90	97	3
Wang et al. [11]	14.0	42.9	73	77	81	84	16
Dittus and Boelter [24]	−0.1	4.0	91	96	98	99	1

Table 6 Correlation uncertainty against 2 × 2 rod bundle database for water (639)

Correlation	e_{avg} (%)	σ (%)	e_5 (%)	e_{10} (%)	e_{15} (%)	e_{20} (%)	$e_{>20}$ (%)
Bishop et al. [37]	−0.1	0.9	100	100	100	100	0
Swenson et al. [38]	1.4	1.5	99	100	100	100	0
Chen and Fang [10]	0.0	0.5	100	100	100	100	0
Wang and Li [9]	0.7	1.0	100	100	100	100	0
Gupta et al. [39]	2.5	2.5	88	98	100	100	0
Gupta et al. [29]	3.7	4.7	59	91	99	100	0
Krasnoschekov and Protopopov [26]	−0.4	1.1	99	100	100	100	0
Yamagata et al. [20]	−0.6	2.8	90	100	100	100	0
Wang et al. [18]; water	0.9	1.0	100	100	100	100	0
Wang et al. [18]; CO_2	−2.5	1.7	90	100	100	100	0
Watts and Chou [40]	0.0	1.0	100	100	100	100	0
Yang [31]; NHT	3.9	5.5	77	91	95	97	3
Yang [31]; HTD	2.9	6.4	83	94	96	97	3
Griem [41]	0.1	0.9	100	100	100	100	0
Koshizuka and Oka [42]	−0.8	1.7	97	100	100	100	0
Jackson [19]	−0.8	1.2	99	100	100	100	0
Jackson [28]	0.3	1.0	100	100	100	100	0
Mokry et al. [43]	1.2	1.2	99	100	100	100	0
Kuang et al. [25]	0.2	1.8	96	100	100	100	0
Cheng et al. [44]	0.5	1.7	97	100	100	100	0
Dyadyakin and Popov [33]	1.8	2.8	88	98	100	100	0
Richards [15]	−4.3	3.7	66	92	98	100	0
Wang et al. [11]	2.3	7.1	87	91	93	95	5
Dittus and Boelter [24]	−1.6	2.3	90	99	100	100	0

agreement with the database for wire-wrapped 2 × 2 rod bundle followed by the Wang et al. [18] correlation, originally developed based on CO_2 data.

CO_2 database: The results for the CO_2 database (three-rod bundle with spacers) with 1155 data points are presented in Table 8. Here, the uncertainty numbers are larger than the ones reported earlier for the plain and spacer-equipped rod bundle water data. The best agreement with the data was obtained by the Chen and Fang [10] correlation followed by the Wang et al. [18] correlation for water.

R–12 and R–22 databases: These databases are for the seven- and three-rod bundle subassemblies, respectively. The results for the seven-rod bundle are presented in Table 9, and Table 10 presents the results for the three-rod bundle. For these two databases, Chen and Fang [10] showed the closest agreement with the experimental data.

5.3 Graphical Comparison of Best-Estimate Correlations Against Data.

Best-estimate correlations are those correlations which approximated experimental data closer than others in terms of the different uncertainty numbers, described in Sec. 4.1. The comparison between correlations and experiment is presented in Figs. 2–5. Representative tests were selected for these figures.

Table 7 Correlation uncertainty against wire-wrapped rod bundle database for water (2 × 2-/3-rod; 353/19 data points, respectively)

Correlation	e_{avg} (%)	σ (%)	e_5 (%)	e_{10} (%)	e_{15} (%)	e_{20} (%)	$e_{>20}$ (%)
Bishop et al. [37]	1.5	2.9	94	97	99	100	0
Swenson et al. [38]	3.3	3.4	81	96	98	99	1
Chen and Fang [10]	0.5	1.7	97	99	99	100	0
Wang and Li [9]	2.7	4.2	91	97	97	98	2
Gupta et al. [39]	5.4	6.9	66	87	95	97	3
Gupta et al. [29]	5.2	6.3	48	83	94	98	2
Krasnoschekov and Protopopov [26]	0.9	2.5	94	98	99	100	0
Yamagata et al. [20]	0.5	5.3	82	95	98	98	2
Wang et al. [18]; water	2.5	2.6	94	97	99	100	0
Wang et al. [18]; CO_2	−1.9	1.9	93	100	100	100	0
Watts and Chou [40]	1.3	2.3	95	98	100	100	0
Yang [31]; NHT	7.3	12.6	67	80	86	91	9
Yang [31]; HTD	7.7	17.4	67	80	87	91	9
Griem [41]	1.6	2.7	95	97	99	100	0
Koshizuka and Oka [42]	0.4	4.1	92	97	98	99	1
Jackson [19]	0.3	2.1	95	99	100	100	0
Jackson [28]	1.6	2.2	96	98	100	100	0
Mokry et al. [43]	3.4	5.1	84	95	97	97	3
Kuang et al. [25]	3.0	9.5	90	95	96	96	4
Cheng et al. [44]	1.7	3.1	89	97	100	100	0
Dyadyakin and Popov [33]	4.1	4.2	71	91	97	99	1
Richards [15]	−5.0	5.4	62	88	94	97	3
Wang et al. [11]	4.0	14.7	83	90	93	95	5
Dittus and Boelter [24]	−1.0	3.0	89	98	99	100	0

Table 8 Correlation uncertainty against three-rod bundle database for CO_2 (1155)

Correlation	e_{avg} (%)	σ (%)	e_5 (%)	e_{10} (%)	e_{15} (%)	e_{20} (%)	$e_{>20}$ (%)
Bishop et al. [37]	−7.0	6.8	32	69	90	96	4
Swenson et al. [38]	−0.8	8.8	41	73	92	98	2
Chen and Fang [10]	0.6	4.5	73	97	100	100	0
Wang and Li [9]	1.3	6.4	62	88	96	99	1
Gupta et al. [39]	11.3	8.2	20	47	74	87	13
Gupta et al. [29]	19.8	11.8	10	19	34	54	46
Krasnoschekov and Protopopov [26]	−14.8	7.2	8	27	52	76	24
Yamagata et al. [20]	−32.2	19.2	4	11	23	35	65
Wang et al. [18]; water	−2.0	6.1	57	88	98	100	0
Wang et al. [18]; CO_2	−23.7	6.6	0	0	7	28	72
Watts and Chou [40]	−8.2	6.4	27	61	86	96	4
Yang [31]; NHT	22.1	19.1	9	20	30	38	62
Yang [31]; HTD	2.8	17.2	18	36	58	78	22
Griem [41]	−1.1	9.3	38	71	90	97	3
Koshizuka and Oka [42]	−39.8	12.7	0	0	1	5	95
Jackson [19]	−16.7	7.7	5	21	45	68	32
Jackson [28]	−5.2	6.7	46	76	92	98	2
Mokry et al. [43]	9.5	9.8	37	61	78	87	13
Kuang et al. [25]	10.5	18.3	23	49	66	75	25
Cheng et al. [44]	−0.5	21.7	18	34	52	68	32
Dyadyakin and Popov [33]	1.0	14.9	29	55	71	81	19
Richards [15]	−32.7	11.6	0	1	5	14	86
Wang et al. [11]	92.2	99.6	1	6	11	18	82
Dittus and Boelter [24]	−35.0	14.9	2	4	9	18	82

Figures 2, 3, and 5 are composed of two plots showing the HTC and the T_b. The HTC plot is positioned on the top of the T_w plot in a vertical configuration. Where applicable, T_{pc} was presented on the plots with a straight dash-dotted line. Figure 4 shows standard deviation variation with reduced pressure and reduced temperature for the best-estimate correlations, assessed against the water database for tube.

Plots of correlations against tube and annulus databases: Figure 2 shows the results of the application of 4 different correlations to the water database for tube geometry. This figure compares heat transfer as predicted by the best-estimate correlations against two different experiments. One dataset was collected with the SC water experimental facility at NPIC, while the second dataset was reported by Jackson [48].[3] Chen and Fang [10] correlation almost followed the experimental trend. Figure 3 presents a similar comparison for the carbon dioxide database for tube geometries. The left top plot of this figure shows some scatter in HTC as predicted by the Chen and Fang [10], Wang et al. [18], and Watts and Chou [40] correlations. The correlation scatter resembles the scatter of the experimental data by Zahlan et al. [35,49]. The right-hand side plots of Fig. 3 show a maximum in HTC at

[3]This dataset reports measurements of natural convection heat transfer at University of Manchester.

Table 9 Correlation uncertainty against seven-rod bundle database for R–12 (129)

Correlation	e_{avg} (%)	σ (%)	e_5 (%)	e_{10} (%)	e_{15} (%)	e_{20} (%)	$e_{>20}$ (%)
Bishop et al. [37]	−0.7	6.1	70	91	95	99	1
Swenson et al. [38]	0.9	5.5	68	93	98	100	0
Chen and Fang [10]	−0.7	4.5	75	95	100	100	0
Wang and Li [9]	1.6	5.3	66	95	98	100	0
Gupta et al. [39]	5.5	5.6	29	75	99	100	0
Gupta et al. [29]	7.6	8.5	30	57	77	95	5
Krasnoschekov and Protopopov [26]	0.3	6.8	63	88	94	99	1
Yamagata et al. [20]	−2.1	7.9	55	78	92	97	3
Wang et al. [18]; water	4.9	6.3	36	81	95	100	0
Wang et al. [18]; CO_2	−5.7	5.2	57	83	94	98	2
Watts and Chou [40]	1.9	5.9	60	89	98	100	0
Yang [31]; NHT	22.6	21.0	10	31	44	57	43
Yang [31]; HTD	−2.7	6.2	60	87	97	98	2
Griem [41]	5.0	8.2	33	68	89	99	1
Koshizuka and Oka [42]	−8.6	8.7	39	68	87	91	9
Jackson [19]	−0.3	6.9	64	88	94	98	2
Jackson [28]	4.5	7.3	37	74	91	99	1
Mokry et al. [43]	4.9	5.7	46	82	96	100	0
Kuang et al. [25]	6.9	11.6	50	66	70	80	20
Cheng et al. [44]	9.3	9.3	15	47	84	89	11
Dyadyakin and Popov [33]	1.6	6.1	67	88	97	99	1
Richards [15]	−5.6	8.2	51	71	86	95	5
Wang et al. [11]	13.1	21.7	40	64	75	81	19
Dittus and Boelter [24]	−4.0	9.7	41	77	91	91	9

Table 10 Correlation uncertainty against three-rod bundle database for R–22 (192)

Correlation	e_{avg} (%)	σ (%)	e_5 (%)	e_{10} (%)	e_{15} (%)	e_{20} (%)	$e_{>20}$ (%)
Bishop et al. [37]	−2.5	3.8	80	94	98	100	0
Swenson et al. [38]	−0.7	4.8	83	94	97	99	1
Chen and Fang [10]	−0.4	1.3	98	100	100	100	0
Wang and Li [9]	−1.8	3.7	83	96	98	100	0
Gupta et al. [39]	2.4	3.3	84	97	100	100	0
Gupta et al. [29]	7.5	5.8	22	67	93	97	3
Krasnoschekov and Protopopov [26]	−3.0	4.3	78	93	96	100	0
Yamagata et al. [20]	−5.1	5.3	64	83	94	98	2
Wang et al. [18]; water	0.0	3.7	89	97	99	100	0
Wang et al. [18]; CO_2	−7.9	6.2	41	76	86	93	7
Watts and Chou [40]	−2.4	4.1	82	94	97	100	0
Yang [31]; NHT	13.4	10.6	12	50	77	83	17
Yang [31]; HTD	−4.0	6.1	69	86	92	97	3
Griem [41]	1.3	3.6	90	98	100	100	0
Koshizuka and Oka [42]	−5.2	4.9	56	86	96	99	1
Jackson [19]	−3.3	4.1	78	93	96	100	0
Jackson [28]	−0.4	3.7	89	96	99	100	0
Mokry et al. [43]	−0.4	3.0	93	97	100	100	0
Kuang et al. [25]	−2.8	4.0	82	93	97	100	0
Cheng et al. [44]	−0.4	4.6	83	95	99	99	1
Dyadyakin and Popov [33]	0.3	7.5	44	82	97	98	2
Richards [15]	−12.3	10.1	26	57	71	81	19
Wang et al. [11]	1.3	10.1	67	83	91	92	8
Dittus and Boelter [24]	−4.3	4.8	66	89	96	99	1

the pseudo-critical temperature as demonstrated by the NPIC data. Figure 4 shows variation of σ with reduced pressure and reduced T_b for the best-estimate correlations applied to the water database for round tube. Performance of the correlations varied along the reduced pressure. Unlike the other two correlations presented in Fig. 4, the Chen and Fang [10] correlation showed the lowest values of σ with P/P_c and T_b/T_c. In the lowest T_b/T_c (liquid-like regions), the correlations showed high σ, which almost decreased with increasing the reduced T_b.

Plots of correlations against rod bundle databases: Turbulent flow and convective heat transfer in rod bundle geometries differ from those in circular tubes. Nevertheless, a preliminary estimation of heat transfer in subchannels can be done with tube-based correlations. Figure 5 shows the variation of HTC and T_w versus T_b for the best-estimate correlations against two sets of data collected at similar flow conditions for 2×2 rod bundles. In Fig. 5, a comparison of the experimental heat transfer in a plain 2×2 rod bundle, from the data by Wang et al. [11], and the corresponding

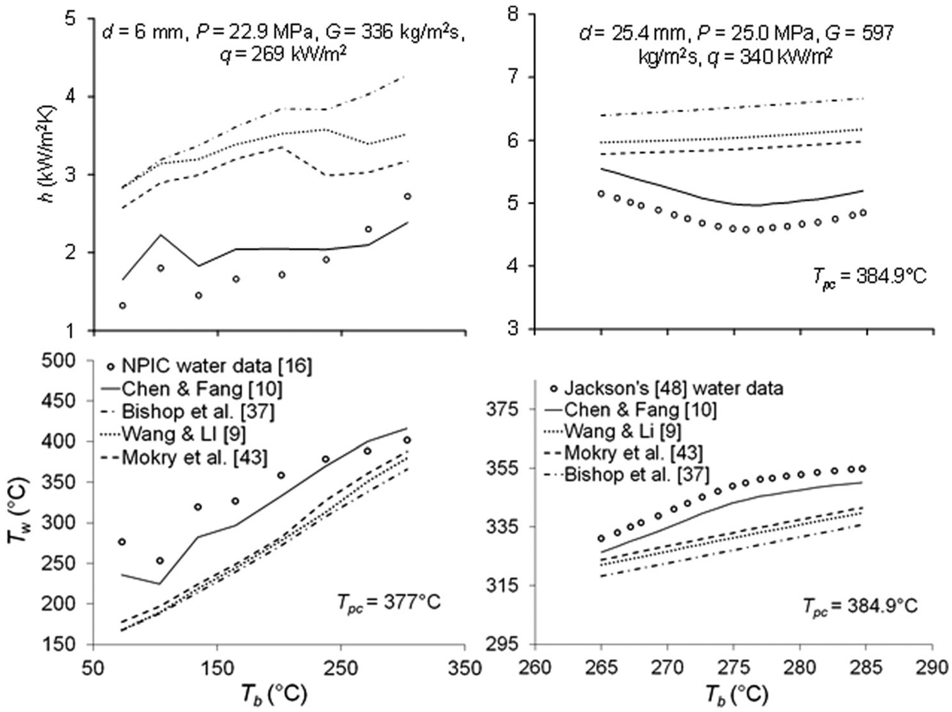

Fig. 2 Comparison of experimental *h* and T_w versus T_b and best-estimate circular tube correlations for water

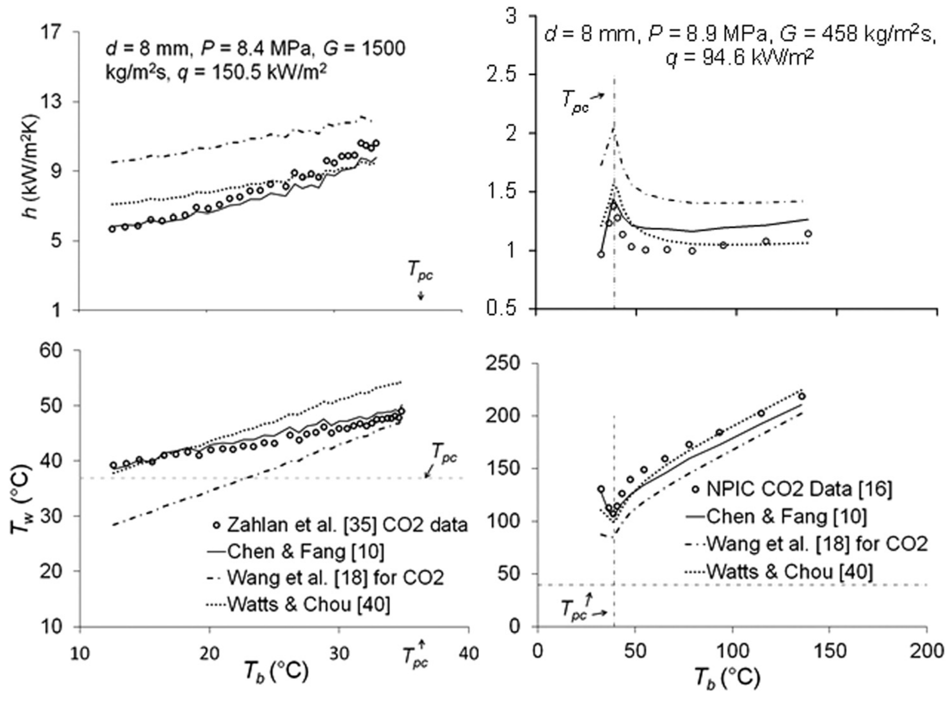

Fig. 3 Comparison of experimental *h* and T_w versus T_b and best-estimate circular tube correlations for CO_2

one in a wire-wrapped 2×2 rod bundle, from the data by Wang et al. [14] is presented. Although more information is needed about the location of the wire wrap along the heated length, one observation can be reported here about the wire wrap effect on SCHT in the 2×2 rod bundle, which is the local increase in HTC just upstream of T_{pc}. The best-estimate correlations based on the plain rod bundle data are the Chen and Fang [10], the Griem [41] and the Bishop et al. [37] correlations. Another observation is that the correlations approximated closer experimental heat transfer in the plain rod bundle than that in the wire-wrapped rod bundle.

6 Conclusions and Final Remarks

CNL and NPIC have shared their databases of SCHT for tube geometries. The CNL databases were expanded by adding

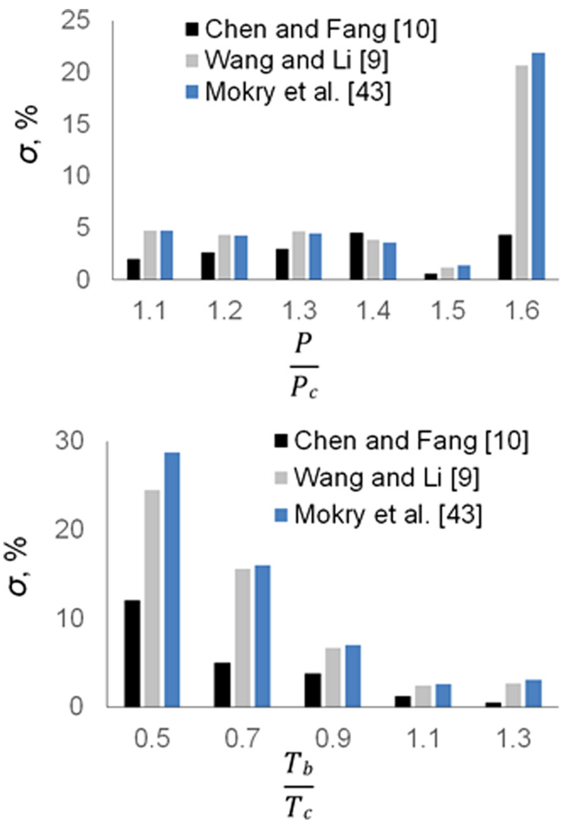

Fig. 4 Variation of σ with reduced pressure and reduced T_b for the best-estimate correlations, applied to the water database for round tube

compiled and original experimental data obtained in the data exchange.

A diversified databank of experimental heat transfer and correlations for the SC pressure region has been compiled at CNL. The databank covers different flow geometries including tube, annulus, and rod bundle, and different fluids including water, CO_2, R–12, and other fluids.

In this paper, a correlation assessment was performed against the CNL expanded databank. In total, 24 correlations were applied to the expanded CNL databases for tube, annulus, and rod bundle. This application was independent of the correlations' limitation in terms of range of flow conditions, applicable heat transfer mode, and type of fluid for a correlation database.

Uncertainty analysis of the assessed correlations revealed best-estimate correlations, which were presented in tables and graphs. Chen and Fang [10] correlation showed the best approximation of the experimental T_w; however, it has a strong functional dependence on both T_w and q, and the estimated HTC/T_w by the correlation followed the scatter of the data. The correlation is sensitive to small changes in T_w especially near critical and pseudocritical temperatures; this dependency might lead to convergence issues when applied in system codes.

Chen and Fang [10] correlation was applied iteratively to the water database of NHT for tubes. The calculated average error and standard deviation of the correlation were 5.0% and 10.0%, respectively.

Correlations for circular tube geometry were also applied to the data for noncircular geometry. The application was based on the cross section average parameter concept and d_{hy}. The agreement between correlations and plain rod bundle data was reasonable, and better than that between the correlations and the data for rod bundle with spacers.

Although the Chen and Fang [10] correlation shed light on the correlations' parameters best-describing SCHT, improvements are still required. To avoid divergence issues, a correlation trend is desired to be free from scatter, similar to the corresponding

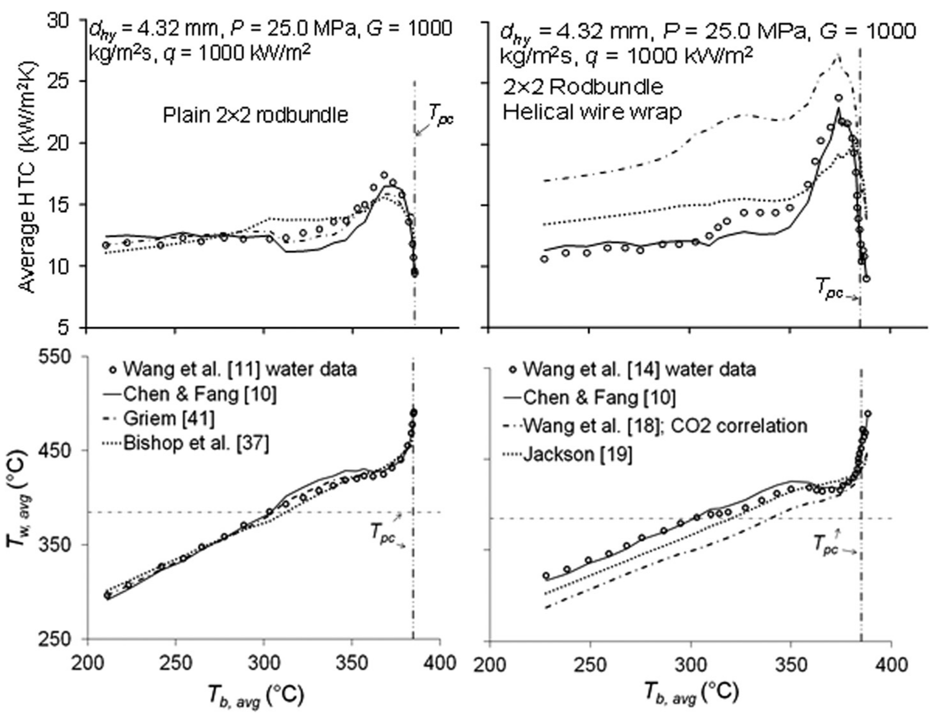

Fig. 5 Comparison of experimental h and T_w versus T_b and best-estimate correlations for water in 2 × 2 rod bundle

physical phenomena. The challenge at this moment is to optimize the solution, which will also reduce prediction uncertainty.

Reliable new data for convective heat transfer to water are still required for SCWR. Finally, it was found that most of the existing data are for tubes, and rod bundle data are particularly scarce.

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Nomenclature

c_p = specific heat at constant pressure, J/kg K
$\overline{c_p}$ = averaged specific heat within the range of $(T_w - T_b)$; $((H_w - H_b)/(T_w - T_b))$, J/kg K
d, D = tube inner diameter, m
e = a measure of deviation of predicted wall temperature from corresponding measurement $(= 100((T_{w,\mathrm{cor}} - T_{w,\exp})/T_{w,\exp})\%)$
e_5, e_{10}, etc. = percentage of data within specified error range ($\pm 5\%$, $\pm 10\%$, etc.)
f = friction factor; $\left(\frac{\tau_w}{\frac{G^2}{8\ \rho}}\right)$, τ_w is the wall sear stress (Pa)
g = gravitational acceleration, m/s^2
G = mass flux (kg/m^2 s)
h = heat transfer coefficient, W/m^2 K
H = specific enthalpy (J/kg)
k = thermal conductivity, W/m K
P = pressure, Pa
q = heat flux, W/m^2
T = temperature, °C or K
z = axial distance from the inlet of the heated section, m

Greek Symbols

β_b = thermal expansion coefficient, $\beta_b = (-1/\rho)(\partial\rho/\partial T)_P$, 1/K
μ = dynamic viscosity, Ns/m^2 = kg/ms
ν = kinematic viscosity, m^2/s
ρ = fluid density, kg/m^3
σ = standard deviation $\left(= 100\sqrt{\left(\sum_{i=1}^{n}(e_i - e_{\mathrm{avg}})^2\right)/n}\%\right)$, n is number of data points

Subscripts

ac = acceleration
avg = average
b = bulk
c = critical
cor = correlation
exp = experimental
h = heated
hy = hydraulic
pc = pseudo-critical
q = heat flux
sel = selected
w = wall

Dimensionless Numbers

$\mathbf{Gr}^*$ = modified Grashof number based on q $(=(g\beta_b q d^4/k_b\nu_b^2))$
Nu = Nusselt number $(=hd/k)$
Pr = Prandtl number $(=\mu c_p/k)$
$\overline{\mathbf{Pr}}$ = averaged Prandtl number $(=(H_w - H_b)\mu_b/(k_b \times (T_w - T_b)))$
$\boldsymbol{Q_b^*}$ = thermal loading group $(= \beta_b q d/k_b)$
Re = Reynolds number $(=GD/\mu)$
$\boldsymbol{\pi_{ac}}$ = nondimensional acceleration number $(=(q/G)(\beta_b/c_p))$
$\boldsymbol{\pi_q}$ = nondimensional heat flux number $(=(q/G)(\beta/c_p))$

Abbreviations

HTC = heat transfer coefficient
HTD = heat transfer deterioration
NHT = normal heat transfer
NPIC = Nuclear Power Institute of China
SC = supercritical
SCHT = supercritical heat transfer
SCWR = supercritical water-cooled reactor

Appendix: Assessed Correlations

Table 11 Single-phase correlations—based on water data

Author	Single-phase correlations
Dittus and Boelter [24]	$\mathbf{Nu_b} = 0.023\mathbf{Re_b}^{0.8}\mathbf{Pr_b}^{0.4}$
Sieder and Tate [45]	$\mathbf{Nu_b} = 0.027\mathbf{Re_b}^{0.8}\mathbf{Pr_b}^{1/3}\left(\frac{\boldsymbol{\mu_b}}{\boldsymbol{\mu_w}}\right)^{0.14}$
Gnielinski [46]	$\mathbf{Nu_b} = \frac{\left(\frac{f}{8}\right)(\mathbf{Re_b} - 1000)\mathbf{Pr_b}}{1 + 12.7\left(\frac{f}{8}\right)^{1/2}\left(\mathbf{Pr_b}^{2/3} - 1\right)}\left(\frac{\mathbf{Pr_b}}{\mathbf{Pr_w}}\right)^{0.11}\left(1 + \left(\frac{d}{z}\right)^{2/3}\right)$ where the Filonenko [50] friction factor $f = 1/(1.82\log_{10}[\mathbf{Re_b}] - 1.64)^2$ and $\left(\frac{T_b}{T_w}\right)^{0.45}$ **replaces** $\left(\frac{\mathbf{Pr_b}}{\mathbf{Pr_w}}\right)^{0.11}$ **for** $\boldsymbol{T_b > T_{pc}}$

Table 12 Correlations for SCHT to water

Author	Correlation
Mokry et al. [43]	$\mathbf{Nu_b} = 0.0061\mathbf{Re_b}^{0.904}\overline{\mathbf{Pr}}_\mathbf{b}^{0.684}\left(\frac{\rho_w}{\rho_b}\right)^{0.564}$
Gupta et al. [39]	$\mathbf{Nu_{film}} = 0.0041\mathbf{Re_{film}}^{0.9284}\overline{\mathbf{Pr}}_\mathbf{film}^{0.7516}\left(\frac{\rho_w}{\rho_b}\right)^{0.2585}\left(\frac{\mu_w}{\mu_b}\right)^{0.3452}$ $\mathbf{Nu_w} = 0.0033\mathbf{Re_w}^{0.941}\overline{\mathbf{Pr}}_\mathbf{w}^{0.764}\left(\frac{\rho_w}{\rho_b}\right)^{0.156}\left(\frac{\mu_w}{\mu_b}\right)^{0.398}$ $\mathbf{Nu_{w,entry}} = \mathbf{Nu_w}\left(1+\exp\left(-\frac{z}{24\boldsymbol{d}}\right)\right)^{0.3}$
Wang and Li [9]	$\mathbf{Nu_b} = 0.00684\ \mathbf{Re_b}^{0.89765}\ \overline{\mathbf{Pr}}_\mathbf{b}^{0.68625}\left(\frac{\rho_w}{\rho_b}\right)^{0.31142}\left(\frac{k_w}{k_b}\right)^{0.26185}$
Wang et al. [18]	$\mathbf{Nu_b} = 0.01503\mathbf{Re_b}^{0.82}\mathbf{Pr_b}^{0.5}\left(\frac{\rho_w}{\rho_b}\right)^{0.3}\left(\frac{\overline{c_p}}{c_{pb}}\right)^{\boldsymbol{n}}$ $\boldsymbol{n} = \begin{cases} 0.5 & \boldsymbol{T_b} < \boldsymbol{T_w} < \boldsymbol{T_{pc}} \text{ or } 1.2\boldsymbol{T_{pc}} < \boldsymbol{T_b} < \boldsymbol{T_w} \\ 0.5+0.2\left(\frac{\boldsymbol{T_w}}{\boldsymbol{T_{pc}}}-1\right) & \boldsymbol{T_b} < \boldsymbol{T_{pc}} < \boldsymbol{T_w} \\ 0.5+0.2\left(\frac{\boldsymbol{T_w}}{\boldsymbol{T_{pc}}}-1\right)\left[1-5\left(\frac{\boldsymbol{T_b}}{\boldsymbol{T_{pc}}}-1\right)\right] & \boldsymbol{T_{pc}} < \boldsymbol{T_b} < 1.2\boldsymbol{T_{pc}} \text{ and } \boldsymbol{T_b} < \boldsymbol{T_w} \\ T \text{ in } K & \end{cases}$
Bishop et al. [37]	$\mathbf{Nu_b} = 0.0069\mathbf{Re_b}^{0.9}\overline{\mathbf{Pr}}_\mathbf{b}^{0.66}\left(\frac{\rho_w}{\rho_b}\right)^{0.43}\left(1+2.4\frac{\boldsymbol{d}}{z}\right)$
Swenson et al. [38]	$\mathbf{Nu_w} = 0.00459\mathbf{Re_w}^{0.923}\overline{\mathbf{Pr}}_\mathbf{w}^{0.613}\left(\frac{\rho_w}{\rho_b}\right)^{0.231}$
Yamagata et al. [20]	$\mathbf{Nu_b} = 0.0135\mathbf{Re_b}^{0.85}\mathbf{Pr_b}^{0.8}\boldsymbol{F_c}$ $\boldsymbol{F_c} = \begin{cases} 1 & E > 1 \\ 0.67\mathbf{Pr_{pc}}^{-0.05}\left(\frac{\overline{c_p}}{c_{pb}}\right)^{\boldsymbol{n}_1} & 0 < E < 1 \\ \left(\frac{\overline{c_p}}{c_{pb}}\right)^{\boldsymbol{n}_2} & E < 0 \end{cases}$ $\boldsymbol{E} = \frac{\boldsymbol{T_{pc}}-\boldsymbol{T_b}}{\boldsymbol{T_w}-\boldsymbol{T_b}}$ $\boldsymbol{n}_1 = -0.77\left(1+\frac{1}{\mathbf{Pr_{pc}}}\right)+1.49;\ \text{and}\ \boldsymbol{n}_2 = 1.44\left(1+\frac{1}{\mathbf{Pr_{pc}}}\right)-0.53$
Watts and Chou [40]	$\mathbf{Nu_0} = 0.021\mathbf{Re_b}^{0.8}\overline{\mathbf{Pr}}_\mathbf{b}^{0.55}\left(\frac{\rho_w}{\rho_b}\right)^{0.35}$ for NHT $\mathbf{Nu_b} = \mathbf{Nu_0}f\left(\frac{\overline{\mathbf{Gr_b}}}{\mathbf{Re_b}^{2.7}\overline{\mathbf{Pr}}_\mathbf{b}^{0.5}}\right)$ $\mathbf{Gr_b^{**}} = \frac{\overline{\mathbf{Gr_b}}}{\mathbf{Re_b}^{2.7}\overline{\mathbf{Pr}}_\mathbf{b}^{0.5}},\ \overline{\mathbf{Gr_b}} = \frac{[\rho_b-\rho_{\text{avg}}]gd^3}{\rho_b\nu_b^2}$, for this study $\rho_{\text{avg}} = \frac{1}{T_w-T_b}\int_{T_b}^{T_w}\rho(T)dT$ $f(\mathbf{Gr_b^{**}}) = \begin{cases} (1-3000\mathbf{Gr_b^{**}})^{0.295}, & 10^{-5} \le \mathbf{Gr_b^{**}} \le 10^{-4} \\ (7000\mathbf{Gr_b^{**}})^{0.295}, & \mathbf{Gr_b^{**}} > 10^{-4} \end{cases}$, NHT: $\mathbf{Gr_b^{**}} < 10^{-5}$
Griem [41]	$\mathbf{Nu_b} = 0.0169\mathbf{Re_b}^{0.8356}\mathbf{Pr_{sel}}^{0.432}\boldsymbol{\Phi}$, where $\mathbf{Pr_{sel}} = c_{p\text{sel}}\mu_b\bar{k},\ \bar{k} = \frac{k_b+k_w}{2}$ $\boldsymbol{\Phi} = \begin{cases} 0.82 & H_b < 1540 \\ 0.82+9\times10^{-4}(H_b-1540) & 1540 \le H_b \le 1740 \\ 1.0 & H_b > 1740 \end{cases}$ H_b in kJ/kg
Koshizuka and Oka [42]	$\mathbf{Nu_b} = 0.015\mathbf{Re_b}^{0.85}\mathbf{Pr_b}^{\phi}$ $\varphi = 0.69-\frac{8.1\times10^4}{q_p}+10^{-3}f_cq$ $f_c = \begin{cases} 2.9\times10^{-8}+\frac{0.11}{q_p} & H_b < 1.5\times10^6 \\ -8.7\times10^{-8}-\frac{0.65}{q_p} & 1.5\times10^6 \le H_b \le 3.3\times10^6 \\ -9.7\times10^{-7}+\frac{1.3}{q_p} & 3.3\times10^6 < H_b \le 4\times10^6 \\ & q_p = 200G^{1.2} \end{cases}$ H_b in J/kg and q in W/m^2

Table 12 (continued)

Author	Correlation
Kuang et al. [25]	$\mathbf{Nu_b} = 0.0239\mathbf{Re_b}^{0.759}\overline{\mathbf{Pr_b}}^{0.833}\left(\frac{k_w}{k_b}\right)^{0.0863}\left(\frac{\mu_w}{\mu_b}\right)^{0.832}\left(\frac{\rho_w}{\rho_b}\right)^{0.31}(\mathbf{Gr_b^*})^{0.014}(\pi_{ac})^{-0.021}$ The acceleration number π_{ac} is defined as $\pi_{ac} = \frac{q}{G}\frac{\beta_b}{c_p}$ and $\mathbf{Gr_b^*} = \frac{g\beta_b q d^4}{k_b \nu_b^2}$
Cheng et al. [44]	$F = \frac{\mathbf{Nu_b}}{\mathbf{Nu_0}} = \min(F_1, F_2),\ \mathbf{Nu_0} = 0.023\mathbf{Re_b}^{0.8}\mathbf{Pr_b}^{1/3}$ $F_1 = 0.85 + 0.776(\pi_A \times 10^3)^{2.4},\ F_2 = \frac{0.48}{(\pi_{ac,pc} \times 10^3)^{1.55}} + 1.21\left(1 - \frac{\pi_{ac}}{\pi_{ac,pc}}\right)$
Chen and Fang [10]	$\mathbf{Nu_b} = 0.46\ \mathbf{Re_b}^{0.16}\left(\frac{\mathbf{Pr_w}}{\mathbf{Pr_b}}\right)^{0.1}\left(\frac{\nu_w}{\nu_b}\right)^{-0.55}\left(\frac{\overline{c_p}}{c_{pb}}\right)^{0.88}\left(\frac{\mathbf{Gr_b^*}}{\mathbf{Gr_b}}\right)^{0.81}$

Table 13 Rod-bundle correlations and main characteristics of their databases

Author	Correlation	Database
Richards [15]	$\mathbf{Nu_b} = 9.23\mathbf{Re_b}^{0.3}\mathbf{Pr_w}^{1.1}\left(\frac{c_{pw}}{c_{pb}}\right)^{0.165}$	R-12, seven-rod bundle with grid spacers, vertical upward flow
Wang et al. [11]	$\mathbf{Nu_b} = 0.01\ \mathbf{Re_b}^{0.88}\ \mathbf{Pr_b}^{0.64}\left(\frac{\rho_{\text{film}}}{\rho_b}\right)^{1.76}\left(\frac{\overline{c_p}}{c_{pb}}\right)^{0.49}$	Water, plain 2 × 2 rod bundle, vertical upward flow
Dyadyakin and Popov [33]	$\mathbf{Nu_b} = 0.021\ \mathbf{Re_b}^{0.8}\overline{\mathbf{Pr_b}}^{0.7}\left(\frac{\rho_w}{\rho_b}\right)^{0.45}\left(\frac{\mu_b}{\mu_{inlet}}\right)^{0.2}\left(\frac{\rho_b}{\rho_{inlet}}\right)^{0.1} \times \left(1 + 2.5\frac{d_{hy}}{z}\right)$	Water, tight seven-element bundle, helically wrapped

Table 14 Correlations for SCHT to CO_2

Author	Correlation
Krasnoschekov and Protopopov [26]	$\mathbf{Nu_b} = \mathbf{Nu_0}\left(\frac{\rho_w}{\rho_b}\right)^{0.3}\left(\frac{\overline{c_p}}{c_{pb}}\right)^{n},\ \mathbf{Nu_0} = \frac{\left(\frac{f}{8}\right)\mathbf{Re_b Pr_b}}{12.7\left(\frac{f}{8}\right)^{1/2}(\mathbf{Pr_b}^{2/3}-1)+1.07}$ f is the Filonenko [50] friction factor described earlier $n = \begin{cases} 0.4 & \frac{T_w}{T_{pc}} \le 1 \text{ or } \frac{T_b}{T_{pc}} \ge 1.2 \\ n_1 = 0.22 + 0.18\frac{T_w}{T_{pc}} & 1 \le \frac{T_w}{T_{pc}} \le 2.5 \\ n_1 + (5n_1 - 2)\left(1 - \frac{T_b}{T_{pc}}\right) & 1 \le \frac{T_b}{T_{pc}} \le 1.2 \end{cases}$, T in K
Jackson [19,28]	$\mathbf{Nu_b} = 0.0183\mathbf{Re_b}^{0.82}\mathbf{Pr_b}^{0.5}\left(\frac{\rho_w}{\rho_b}\right)^{0.3}\left(\frac{\overline{c_p}}{c_{pb}}\right)^{n}$, Jackson's [19] $\mathbf{Nu_b} = 0.021\mathbf{Re_b}^{0.8}\mathbf{Pr_b}^{0.4}\left(\frac{\rho_w}{\rho_b}\right)^{0.3}\left(\frac{\overline{c_p}}{c_{pb}}\right)^{n}$, Jackson's [28] $n = \begin{cases} 0.4 & T_b < T_w < T_{pc} \text{ or } 1.2T_{pc} < T_b < T_w \\ 0.4 + 0.2\left(\frac{T_w}{T_{pc}} - 1\right) & T_b < T_{pc} < T_w \\ 0.4 + 0.2\left(\frac{T_w}{T_{pc}} - 1\right)\left[1 - 5\left(\frac{T_b}{T_{pc}} - 1\right)\right] & T_{pc} < T_b < 1.2T_{pc} \text{ and } T_b < T_w \end{cases}$ T in K
Gupta et al. [29]	$\mathbf{Nu_b} = 0.01\mathbf{Re_b}^{0.89}\overline{\mathbf{Pr_b}}^{-0.14}\left(\frac{\rho_w}{\rho_b}\right)^{0.93}\left(\frac{k_w}{k_b}\right)^{0.22}\left(\frac{\mu_w}{\mu_b}\right)^{-1.13}$ $\mathbf{Nu_{film}} = 0.0043\mathbf{Re_{film}}^{0.94}\left(\frac{\rho_w}{\rho_b}\right)^{0.57}\left(\frac{k_w}{k_b}\right)^{-0.52}$

Table 14 (continued)

Author	Correlation
	$\mathbf{Nu_w} = 0.0038\mathbf{Re_w^{0.96}}\overline{\mathbf{Pr_w}}^{-0.14}\left(\frac{\rho_w}{\rho_b}\right)^{0.84}\left(\frac{k_w}{k_b}\right)^{-0.75}\left(\frac{\mu_w}{\mu_b}\right)^{-0.22}$, authors showed that the previous correlation had best agreement with data
Wang et al. [18]	$\mathbf{Nu_b} = 0.0324\mathbf{Re_b^{0.79}}\mathbf{Pr_b^{0.66}}\left(\frac{\rho_w}{\rho_b}\right)^{0.38}\left(\frac{\overline{c_p}}{c_{pb}}\right)^{n}$ $n = \begin{cases} 0.66 & T_b < T_w < T_{pc} \text{ or } 1.2T_{pc} < T_b < T_w \\ 0.66 + 0.2\left(\frac{T_w}{T_{pc}} - 1\right) & T_b < T_{pc} < T_w \\ 0.66 + 0.2\left(\frac{T_w}{T_{pc}} - 1\right)\left[1 - 5\left(\frac{T_b}{T_{pc}} - 1\right)\right] & T_{pc} < T_b < 1.2T_{pc} \text{ and } T_b < T_w \end{cases}$ T in K
Yang [31]	$\mathbf{Nu_b} = 0.41179\mathbf{Nu_0}^{1.10223}\left(\frac{P}{P_c}\right)^{-0.43274}\left(\frac{T_b}{T_{pc}}\right)^{1.84087}\left(10^4\frac{q}{GH_b}\right)^{0.13205}\left(\frac{\mu_b}{\mu_w}\right)^{-0.92839}\left(\frac{k_b}{k_w}\right)^{0.16801}\left(\frac{\overline{c_p}}{c_{pb}}\right)^{0.72487}$ and for HTD: $\mathbf{Nu_b} = 1.7065\mathbf{Nu_0}^{0.94871}\left(\frac{P}{P_c}\right)^{-0.53838}\left(\frac{T_b}{T_{pc}}\right)^{2.46823}\left(10^4\frac{q}{GH_b}\right)^{-0.32562}\left(\frac{\mu_b}{\mu_w}\right)^{0.50388}\left(\frac{k_b}{k_w}\right)^{-0.54941}\left(\frac{\overline{c_p}}{c_{pb}}\right)^{0.57156}$

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