ASSESSMENT OF SUPERCRITICAL HEAT-TRANSFER CORRELATIONS AGAINST AECL DATABASE FOR TUBES

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Abstract

Thermalhydraulic characteristics at supercritical water-flow conditions need to be investigated in support of the fuel-bundle design and qualification, and safety analysis for the supercritical water-cooled reactor (SCWR). An experimental database on supercritical heat transfer for water flow (both upward and downward) in tubes has been compiled from published literature. Four existing supercritical heat transfer correlations were assessed against the AECL database for water flow in tubes. The objective of this paper is to present the database and the assessment results of the existing correlations against the supercritical heat-transfer database.

1. Introduction

One of Canada's GenIV National Program objectives is to develop supercritical heat-transfer (SCHT) prediction methods for use in subchannel and system computer codes in support of the core and fuel design for a CANDU supercritical water-cooled reactor. To achieve this objective, thermalhydraulic characteristics at supercritical conditions for water flow in bundles need to be investigated. However, most experimental data with full-scale bundles or bundle subassemblies are proprietary information and details of these experiments are generally unavailable. Most of the available experimental information is obtained with circular tubes.

Although tube data are not directly applicable to bundle geometries with a large degree of flow and enthalpy imbalances, they provide a fundamental understanding of the SCHT phenomena. The objective of this study is to establish a database for supercritical water flowing in circular tubes. The database has been used to assess existing correlations and improve these correlations to reduce prediction uncertainty, and to analyse heat-transfer deterioration in the vicinity of the critical point.

A large amount of experimental data on SCHT is available for water, carbon dioxide and various types of refrigerants in tubes. Only water fluid data on supercritical heat-transfer are compiled here from available papers. The majority of these papers describe the experimental work for supercritical water flowing in a uniformly heated vertical smooth tube. Few papers perform the studies for the supercritical water in a horizontal tube or a vertical or horizontal bundle. A database has been established through extracting the data points either from graphs or from tables of these reviewed papers. Some researchers' data sets are not included. This is either because the information is insufficient to calculate the local heat-transfer coefficient or the graphs are unclear. The data sets obtained from the horizontal tube flow are also not collected because a non-uniform temperature distribution is displayed around the tube periphery. Significant buoyancy effects in the horizontal tube increase the complexity of heat transfer to supercritical water, and are not accounted for by the heat-transfer correlations that are to be assessed.

There are many SCHT coefficient correlations for tubes available in the literature (Pioro et al.[1]). The majority of these correlations follow a general trend of the experimental data outside the regions of deteriorated or enhanced heat transfer, but are sensitive to significant variations in thermophysical properties near the critical and pseudocritical points. Licht et al. [2] compared four correlations of Dittus and Boelter [3], Krasnoshchekov et al. [4], Jackson [5] and Watts and Chou [6] against their experimental data in circular annular flow, and they suggested that the Jackson correlation was the most accurate one among the correlations. The Dittus-Boelter correlation is a widely used correlation for fluids in subcritical turbulent flow. The Krasnoshchekov correlation is the one from which the Jackson correlation was derived. The correlation of Yang [7] is the newest prediction method derived from the investigation of fluid-to-fluid scaling of supercritical heat transfer. These four correlations of Dittus and Boelter [3], Krasnoshchekov et al. [4], Jackson [5] and Yang [7] were selected for assessment in this study.

The four correlations were analyzed against the database, and the predicted heat-transfer coefficients were compared with those of experiments. It was found that the Jackson correlation has the highest accuracy in predicting heat transfer of supercritical upward flow and downward flow in circular tubes, but it over-predicts the heat transfer. The correlation was modified such that the predicted coefficients were optimized against the database to achieve an overall bias of zero with a minimum standard deviation. Two modified correlations for upward flow and downward flow, respectively, are presented.

2. Experimental data extraction

Many experimental studies are available in the open literature for supercritical water flow in circular tubes. Gudla et al. [8] compiled heat-transfer data obtained at supercritical conditions with water, carbon dioxide, refrigerant R-134a and other fluids. Their data were extracted from the literature and are given in either a graphical form or a tabular form. Based on their data sets and more data sets from the literature, this study presents a compilation of the heat transfer database for supercritical water flowing in vertical circular tubes extracted from 17 papers of Ackerman [9], Alekseev [10], Alferov [11], Glushchenko [12], Goldmann [13], Herkenrath [14], Ishigai et al. [15], Kirillov [16], Krasyakova [17], Lee [18], Ornatskii [19], Razumovskiy [20], Shitsman [21], Shitsman [22], Swenson et al. [23], Vikherv [24] and Yamagata [25]. These data sets have various ranges of operating conditions (pressure, temperature, heat flux and mass flux) and various flow geometries. The ranges of pressure and temperature are presented in Figure 1 showing ranges of the experimental data on non-dimensional temperature versus non-dimensional pressure scale. The heat-transfer coefficient in supercritical water was plotted or tabulated in the literature with parameters of tube inner diameter, pressure, mass flux, bulk temperature and heat flux or tube wall surface temperature (depending on which is known). These six parameters are included in the database.

Each data point is checked carefully for parametric trends. The database for tube flow is composed of 17 data sets that contain 5306 data points covering pressures from 22.5 to 40.5

MPa, mass fluxes from 90 to 2441 kg/m^{2}s, heat fluxes from 76 to 3659 kW/m^2 and tube inner diameters from 1.57 to 38.1 mm. Among the total 5306 data points, 4756 data points are for upward flow, and 550 data points are for downward flow.

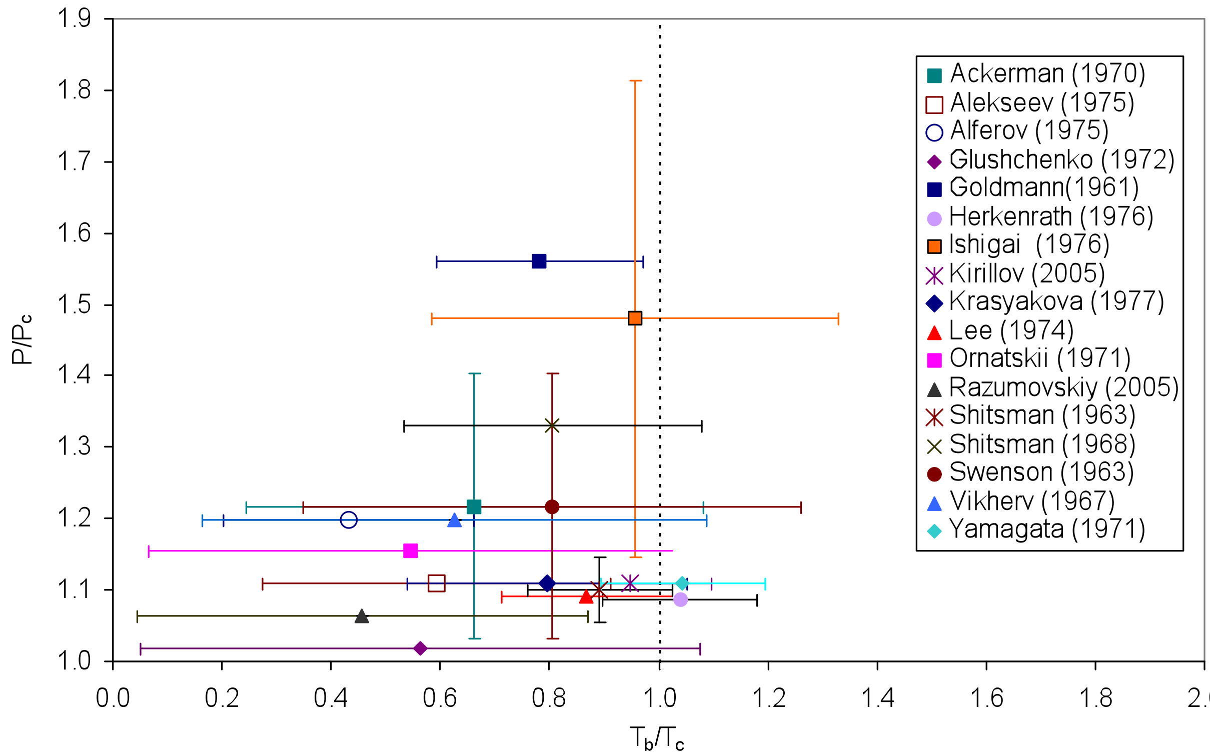

Figure 1 Ranges of processed SCHT water data sets of tube flow.

3. Existing prediction methods for supercritical heat transfer

3.1 The Dittus-Boelter Correlation

The Dittus–Boelter correlation [3] is a widely used correlation for fluids in subcritical turbulent flow. It has a particularly simple form:

$$Nu_b = 0.023\,\mathrm{Re}_b^{\,0.8}\,\mathrm{Pr}_b^{\,0.4} \tag{1}$$

where

$$Nu_b = \frac{1000hD}{k_b} \tag{2}$$

$$\mathrm{Re}_b = \frac{GD}{\mu_b} \tag{3}$$

$$\mathrm{Pr}_b = \frac{C_{pb}\mu_b}{k_b} \tag{4}$$

According to Incropera and DeWitt [26], the Dittus-Boelter correlation is valid for single-phase heat transfer in channels within the following range: $0.7 \leq Pr \leq 160$; $Re_b \geq 10{,}000$; and $L/D \geq 10$.

3.2 The Krasnoshchekov Correlation

Krasnoshchekov and Protopopov [27] proposed a correlation for forced-convective heat transfer in water and carbon dioxide at supercritical pressures. Then, Krasnoshchekov et al. [4] modified this correlation to the following form:

$$Nu = Nu_0 \left(\frac{\rho_w}{\rho_b}\right)^{0.3} \left(\frac{\overline{C_p}}{C_{pb}}\right)^n \tag{5}$$

where

$$Nu_0 = \frac{\frac{\xi}{8} \mathrm{Re}_b \overline{\mathrm{Pr}}}{12.7\sqrt{\frac{\xi}{8}}\left(\overline{\mathrm{Pr}}^{2/3} - 1\right) + 1.07} \tag{6}$$

$$\xi = \frac{1}{\left(1.82 \log_{10} \mathrm{Re}_b - 1.64\right)^2} \tag{7}$$

$$\overline{C_p} = \frac{H_w - H_b}{T_w - T_b} \tag{8}$$

Exponent n is:

$n = 0.4$ for $T_w / T_{pc} \leq 1$ or $T_b / T_{pc} \geq 1.2$
$n = n_1 = 0.22 + 0.18\,(T_w / T_{pc})$ for $1 \leq (T_w / T_{pc}) \leq 2.5$
$n = n_1 + (5 \cdot n_1 - 2)\,(1 - (T_b / T_{pc}))$ for $1 \leq (T_b / T_{pc}) \leq 1.2$

where T_b, T_{pc} and T_w are bulk, pseudocritical and wall temperatures, respectively, and are in K. The friction factor ξ is only valid for smooth tubes.

These equations are valid with the following range of parameters:

$8 \cdot 10^4 < \mathrm{Re}_b < 5 \cdot 10^5$, $0.85 < \overline{\mathrm{Pr}}_b < 65$, $0.90 < \rho_w / \rho_b < 1.0$, $0.02 < \overline{C_p} / C_{pb} < 4.0$, $0.9 < T_w / T_{pc} < 2.5$, $46 < q < 2600$ and $L/D \geq 15$.

3.3 The Jackson Correlation

Jackson [5] modified the original correlation of Krasnoshchekov et al. [4] (Equations (5) and (6)) for forced-convective heat transfer in water and carbon dioxide at supercritical pressure to employ the Dittus-Boelter type form for Nu_0. Finally, he obtained the following correlation:

$$Nu = 0.0183\, \mathrm{Re}_b^{0.82}\, \mathrm{Pr}_b^{0.5} \left(\frac{\rho_w}{\rho_b}\right)^{0.3} \left(\frac{\overline{C_p}}{C_{pb}}\right)^n \tag{9}$$

exponent n is:

$n = 0.4$ for $T_b < T_w < T_{pc}$ and for $1.2 \cdot T_{pc} < T_b < T_w$

$n = 0.4 + 0.2\left(\frac{T_w}{T_{pc}} - 1\right)$ for $T_b < T_{pc} < T_w$

$n = 0.4 + 0.2\left(\frac{T_w}{T_{pc}} - 1\right)\left[1 - 5\left(\frac{T_b}{T_{pc}} - 1\right)\right]$ for $T_{pc} < T_b < 1.2 \cdot T_{pc}$ and $T_b < T_w$

where T_b, T_{pc} and T_w are in K.

3.4 The Yang Correlation

Yang [7] proposed two correlations for normal and deteriorated heat transfer using CO_2 data from upward flow in an 8-mm diameter tube. The authors tested the correlations on available data of supercritical water, and the results agreed well with the experimental data. The criterion to determine normal and deteriorated heat transfer for vertically upward CO_2 flow was suggested as:

$$k_c = \frac{q}{G^{0.94}} \tag{10}$$

where q is heat flux in kW/m^2 and G is mass flux in kg/m^2s. The mode of heat transfer is normal when $k_c \leq 0.27$, and deteriorated when $k_c > 0.27$. Equations (11) and (12) are for normal heat transfer and deteriorated heat transfer in CO_2, respectively.

$$Nu = 0.41179\left(\frac{P}{P_c}\right)^{-0.43274}\left(\frac{T_b}{T_{pc}}\right)^{1.84087}\left(10000\frac{q}{GH_b}\right)^{0.13205}\left(Nu_0\right)^{1.10223}\left(\frac{\mu_b}{\mu_w}\right)^{-0.92839}\left(\frac{k_b}{k_w}\right)^{0.16801}\left(\frac{\overline{C_p}}{C_{pb}}\right)^{0.72487}$$

(normal) (11)

$$Nu = 1.7065\left(\frac{P}{P_c}\right)^{-0.53838}\left(\frac{T_b}{T_{pc}}\right)^{2.46823}\left(10000\frac{q}{GH_b}\right)^{-0.32562}\left(Nu_0\right)^{0.94871}\left(\frac{\mu_b}{\mu_w}\right)^{0.50388}\left(\frac{k_b}{k_w}\right)^{-0.54941}\left(\frac{\overline{C_p}}{C_{pb}}\right)^{0.57156}$$

(deteriorated) (12)

Nu_0 is the reference Nusselt number given as

$$Nu_0 = \frac{\frac{C_f}{8}\mathrm{Re}_b\,\mathrm{Pr}_b}{12.7\sqrt{\frac{C_f}{8}}\left(\mathrm{Pr}_b^{2/3} - 1\right) + 1.07}$$

where

$$C_f = \frac{1}{(1.82\log_{10}\mathrm{Re}_b - 1.64)^2}$$

4. Assessment of the prediction methods

4.1 Assessment with the Correlations

The heat-transfer coefficients of supercritical water for upward flow and downward flow in tubes were predicted with the selected correlations. The predicted coefficients were then compared with the measured (or experimentally-derived) heat-transfer coefficients. Three parameters were used to present the correlation prediction uncertainties – average error, standard deviation (SD), and root-mean-square (RMS) error.

To apply the Yang correlation, the water data are categorized into normal and deteriorated heat transfer using the Yamagata et al. [28] criterion in water for the vertically upward flow in a 10 mm inner diameter tube at pressures of 22.6-29.4 MPa, given as

$$k_w = \frac{q}{G^{1.2}} \tag{13}$$

The mode of heat transfer is normal when $k_w \le 0.2$, and deteriorated when $k_w > 0.2$.

4.2 Assessment Results

The prediction results with percentage of captured data points are tabulated in Table 1 in terms of percentage of captured data points to total data points with accuracies of 10%, 20%, 25% and 30%, respectively.

It can be seen that, among the four correlations, the Jackson correlation has the highest accuracy in predicting heat-transfer of supercritical upward flow and downward flow in circular tubes. The existing Jackson correlation predicted the upward flow database of 4282 data points with an average error of 23.6%, a standard deviation of 32.0%, and an RMS error of 39.7%, and predicted the downward flow database of 550 data points with an average error of 5.0%, a standard deviation of 33.1%, and an RMS error of 33.4%. The existing Jackson correlation over-predicts the heat-transfer coefficient for both upward flow and downward flow, but the amplitude of over-prediction for upward flow is bigger than that for downward flow, because the heat-transfer coefficient for upward flow is lower than that for downward flow, and the existing Jackson correlation does not account for flow direction. The reason for the difference between upward flow and downward flow is that, with higher q/G ratio, acceleration effects cause an impairment in heat transfer in both upward flow and downward flow, whereas buoyancy effects cause an impairment in upward flow and an enhancement in downward flow, as described by Krann et al. [29]. In summary, a modification to the existing Jackson correlation accounting for flow direction is necessary for predicting heat-transfer coefficient more accurately.

Table 1 Prediction Results with Percentage of Captured Data Points

Correlation	Within ±10%	Within ±20%	Within ±25%	Within ±30%
	Percentage of Captured Data Points (%)			
Upward Flow				
Dittus-Boelter	18.8	37.6	43.6	48.3
Krasnoshchekov	16.0	30.5	37.1	44.1
Jackson	29.3	52.7	60.2	67.4
Yang	20.8	42.9	51.1	58.9
Downward Flow				
Dittus-Boelter	34.4	64.5	69.1	72.0
Krasnoshchekov	21.5	55.3	64.4	70.2
Jackson	36.0	75.6	82.7	86.5
Yang	1.5	6.5	11.8	20.4

5. Modifications of the Jackson correlation

5.1 The Modified Jackson Correlation

The Jackson correlation was modified for two flow directions: upward flow and downward flow. The modification was made such that the form of the existing Jackson correlation was preserved while an overall correction factor to the correlation and one of the exponents were modified to remove the prediction biases. The coefficients of this correlation were optimized against the database to achieve an overall bias of zero with a minimum standard deviation. The resultant new Jackson correlations for upward flow and downward flow are expressed as Equations (14) and (15), respectively.

$$Nu = 0.01503\,\mathrm{Re}_b^{0.82}\,\mathrm{Pr}_b^{0.5}\left(\frac{\rho_w}{\rho_b}\right)^{0.3}\left(\frac{\overline{C_p}}{C_{pb}}\right)^{n} \qquad \text{(upward flow)} \quad (14)$$

$$Nu = 0.01763\,\mathrm{Re}_b^{0.82}\,\mathrm{Pr}_b^{0.5}\left(\frac{\rho_w}{\rho_b}\right)^{0.3}\left(\frac{\overline{C_p}}{C_{pb}}\right)^{n} \qquad \text{(downward flow)} \quad (15)$$

exponent n is:

$n = 0.5$ for $T_b < T_w < T_{pc}$ and for $1.2 \cdot T_{pc} < T_b < T_w$

$$n = 0.5 + 0.2\left(\frac{T_w}{T_{pc}} - 1\right) \text{ for } T_b < T_{pc} < T_w$$

$$n = 0.5 + 0.2\left(\frac{T_w}{T_{pc}} - 1\right)\left[1 - 5\left(\frac{T_b}{T_{pc}} - 1\right)\right] \text{ for } T_{pc} < T_b < 1.2 \cdot T_{pc} \text{ and } T_b < T_w$$

5.2 Prediction Uncertainties of the Modified Jackson Correlations

The modified Jackson correlations (i.e., Equations (18) and (19)) were assessed against the database. The assessment results of the original and modified Jackson correlations are tabulated in Table 2. The prediction results with percentage of captured data points are tabulated in Table 3. It can be found that both Equations (18) and (19) improve the prediction accuracies.

The application parametric ranges of the modified correlations are as follows:

<u>Upward flow:</u>

Tube diameter:	1.6 to 38.1 mm
Pressure:	22540 to 40520 kPa
Mass flux:	103 to 2441 kg/m^{2}s
Heat flux:	76 to 3659 kW/m^2
Bulk temperature:	17.4 to 497.0 ^{o}C
Wall temperature:	62.0 to 766.8 ^{o}C

Table 2 Prediction Uncertainties of the Original and Modified Jackson Correlations

Correlation	# of Data Point	Avg. Error (%)	SD (%)	RMS (%)
Upward Flow				
Original Equ. (9)	4282	23.6	32.0	39.7
Modified Equ. (18)	4282	0.0	23.8	23.8
Downward Flow				
Original Equ. (9)	550	5.0	33.1	33.4
Modified Equ. (19)	550	0.0	29.8	29.8

Table 3 Prediction Results with Percentage of Captured Data Points

Correlation	Within ±10%	Within ±20%	Within ±25%	Within ±30%
Upward Flow				
Original Equ. (9)	29.3	52.7	60.2	67.4
Modified Equ. (18)	42.7	72.7	81.6	86.9
Downward Flow				
Original Equ. (9)	36.0	75.6	82.7	86.5
Modified Equ. (19)	38.7	80.4	88.9	91.3

Downward flow:

Tube diameter: 3.0 to 20.0 mm
Pressure: 23500 to 26500 kPa
Mass flux: 90 to 1530 kg/m^2s
Heat flux: 81 to 1630 kW/m^2
Bulk temperature: 23.8 to 476.6 ^oC
Wall temperature: 87.0 to 689.2 ^oC

6. Conclusion

Papers related to heat transfer of water flow at supercritical conditions were reviewed. Those with experimental data of vertical water flow in uniformly heated smooth tubes were chosen to assess the prediction accuracy of selected heat-transfer correlations. Seventeen papers for tube flow were found to have sufficient information for the calculation of heat-transfer coefficient. Subsequently, experimental data were extracted from these papers. All experimental data were checked and only reliable data were included in the database. The tube flow database is composed of 17 data sets containing 5306 data points covering pressures from 22.5 to 40.5 MPa, mass fluxes from 90 to 2441 kg/m^2s, heat fluxes from 76 to 3659 kW/m^2 and tube inner diameters from 1.57 to 38.1 mm.

The existing prediction methods for supercritical heat transfer from external publications were reviewed. The correlations of Dittus-Boelter, Krasnoshchekov, Jackson and Yang were selected and assessed against the data to quantify their prediction accuracy for upward flow and downward flow in tubes. The existing Jackson correlation was found to have the highest accuracy, but it over-predicts the heat transfer, especially for upward flow. Thus modifications to the existing Jackson correlation for upward flow and downward flow, respectively, were made.

First, the existing Jackson correlation was modified against 4282 upward flow data points. This modified correlation predicted the experimental supercritical heat-transfer coefficients with an average error of 0.0% and a standard deviation of 23.8%, and captured 81.6% of the data points within a ±25% accuracy. Secondly, the existing Jackson correlation was modified against 550 downward flow data points. The modified correlation predicted the experimental supercritical heat-transfer coefficients with an average error of 0.0% and a standard deviation of 29.8%, and captured 88.9% of the data points with a ±25% accuracy.

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