UPDATED HEAT-TRANSFER CORRELATIONS FOR SUPERCRITICAL WATER-COOLED REACTOR APPLICATIONS

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Abstract

It is expected that the next generation of water-cooled nuclear reactors will operate at supercritical pressures (~25 MPa) and high coolant temperatures (350–625°C). In support of the development of SuperCritical Water-cooled Reactors (SCWRs), research is currently being conducted for heat-transfer at supercritical conditions. Currently, there are no experimental datasets for heat transfer from power reactor fuel bundles to the fuel coolant (water) available in open literature. Therefore, for preliminary calculations, heat-transfer correlations obtained with bare-tube data can be used as a conservative approach. This paper presents an analysis of experimental supercritical-water data and new supercritical heat-transfer correlations, for water and carbon dioxide, developed as part of a larger project assessing the feasibility of Generation IV SCWR concepts.

1. Introduction

SuperCritical Water-cooled nuclear Reactors (SCWRs) are high-pressure (~25 MPa) and high-temperature (outlet temperatures up to 625°C) reactors that will operate above the thermodynamic critical point of water (22 MPa and 374°C) (see Figure 1) [1], [2]. As part of the Generation-IV International Forum (GIF), SCWR concepts are currently under development worldwide. Figure 2 outlines the difference in the operating conditions (pressures, temperatures and entropies) of current generation reactor systems in comparison to SCWRs. Compared to existing Pressurized Water Reactors (PWRs), SCWRs would involve increasing the coolant pressure from 10 – 16 MPa to about 25 MPa, the inlet temperature to about 350ºC, and the outlet temperature to about 625ºC. The coolant would pass through the pseudocritical region before reaching the channel outlet [1].

1.1 SCWR Concepts

SCWRs can be divided into two subcategories: 1) Pressure-Vessel (PV) reactors, and 2) Pressure-Tube (PT) reactors. Currently, both Canada and Russia are working on the development of PT-reactor concepts. One of the main objectives for developing and utilizing SCWRs is that SuperCritical Water (SCW) Nuclear Power Plants (NPPs) offer an increased thermal efficiency, approximately 45 – 50%, compared to that of current generation NPPs (30 – 35%). Additionally, they allow for a decrease in capital and operational costs.

Generation-IV reactor concepts (see Table 1) under development at AECL [3] and RDIPE [4] have a main design objective of achieving major reductions in unit energy cost relative to existing PWR designs [5]. This approach builds on using existing SCW experience in currently operating fossil-fired thermal power plants. A major contribution to this energy cost reduction would result from boosting the outlet coolant temperature, thereby increasing the thermal efficiency of the NPP. A further benefit of using SCWRs is their ability to facilitate hydrogen co-generation, on an economical scale, through either thermochemical cycles or direct high-temperature electrolysis.

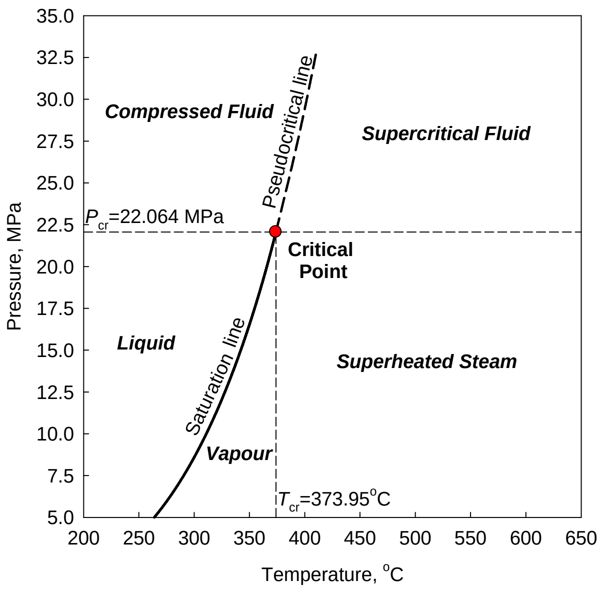


Figure 1 Pressure-Temperature Diagram for Water in Critical Region [2].

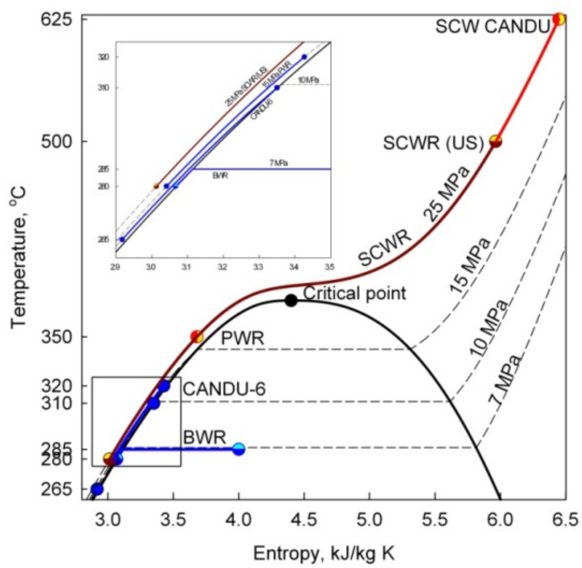


Figure 2 Temperature-Entropy Diagram Comparison of Current Generation Nuclear Reactors and SCWRs [1].

The current Canadian SCWR concept includes a fuel channel comprised only of a pressure tube insulated internally, which would enable the pressure tube to operate at temperatures close to that of the moderator. This fuel-channel design would be used for supercritical water heating from 350 to 625°C. A re-entrant fuel-channel design, allowing the pressure tube to operate at the SCW inlet temperature, might be used for a nuclear steam re-heat at subcritical pressures. The current heat-transfer evaluation has shown that PT SCWRs are feasible. A further study on conceptual thermal-design options for pressure-tube SCWRs can be found in [6].

1.2 Supercritical Fluids

Supercritical fluids have unique properties [7], [8]. It is well established that thermophysical properties of any fluid, including water and carbon dioxide, experience significant changes within critical and pseudocritical regions. Beyond the critical point (22.1 MPa and 374.1°C for water and 7.38 MPa and 31.0°C for carbon dioxide) the fluid resembles a dense gas. Figure 3 illustrates these variations for water passing through the pseudocritical point at 25 MPa, the proposed operating pressure of SCWRs.

The most significant changes in properties occur within ±25°C from the pseudocritical temperature (384.9°C at 25 MPa for Fig. 3). The National Institute of Standards and Technology (NIST) [9] Reference Fluid Properties (REFPROP) software was used to calculate these thermophysical properties. Crossing from high-density fluid to low-density fluid does not involve a distinct phase change at these conditions. Phenomena such as dry-out (critical heat flux) are therefore not applicable. However, at supercritical conditions, a Deteriorated Heat-Transfer (DHT) regime may exist [1].

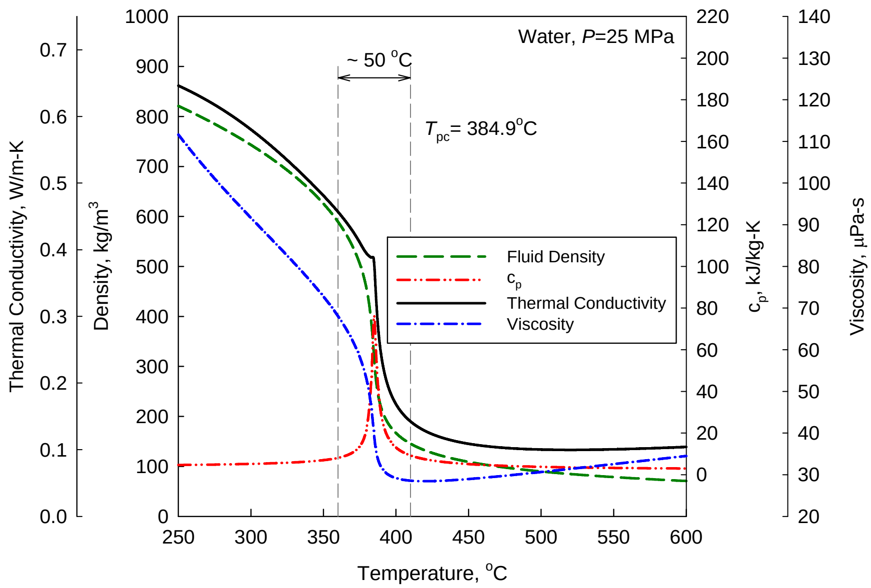


Figure 3 Selected Properties of Supercritical Water at Pseudocritical Point [2].

Table 1. Major parameters of SCW CANDU reactor concept [3].

Thermal power, MW	2540
Electric power, MW	1220
Thermal efficiency, %	48
Pressure, MPa	25
Inlet temperature, °C	350
Outlet temperature, °C	625
Mass flow rate, kg/s	1320
Number of fuel channels	300
Number of fuel elements	43
Maximum cladding temperature, °C	850

In support of developing an SCWR, studies are being conducted into heat transfer at supercritical conditions using carbon dioxide as a modeling fluid as a less expensive alternative to using SCW and to aid in the improvement of fundamental knowledge of the transport processes and handling of supercritical fluids. Table 1 lists parameters of current PT-SCWR concepts being developed by AECL (Canada). Preliminary parameters used for scaling nominal operating conditions of a generic SCWR to carbon dioxide-equivalent values are listed in Table 2.

Table 2. Basic scaling parameters for fluid-to-fluid modeling at supercritical conditions.

Pressure	$\left(\frac{P}{P_{cr}}\right)_{CO_2} = \left(\frac{P}{P_{cr}}\right)_W$
Bulk-fluid temperature (K)	$\left(\frac{T_b}{T_{cr}}\right)_{CO_2} = \left(\frac{T_b}{T_{cr}}\right)_W$

Table 3 lists critical parameters and nominal operating parameters of the SCW CANDU reactor concept in water and CO_2-equivalent values.

Table 3. Critical and nominal operating parameters.

Parameter	**Unit**	**Water**	**CO_2**
Critical parameters			
Critical pressure	MPa	22.1	7.38
Critical temperature	ºC	374.1	31.0
Critical density	kg/m^3	315	468
Operating parameters			
Operating pressure	MPa	25	8.34
Inlet temperature	ºC	350	20
Outlet temperature	ºC	625	150

This work investigates heat transfer at supercritical conditions, for water and using carbon dioxide as a modeling fluid, as part of a larger project assessing the feasibility of Generation IV SCWR concepts. Heat-transfer correlations for SCW and CO_2 were developed. The results are provided and a comparison was conducted for several correlations.

2. Existing Heat-Transfer Correlations

Currently, there is just one SCW heat-transfer correlation for fuel bundles. This correlation was obtained for SCW flowing in a 7-element helically-finned bundle designed by Dyadyakin and Popov [1]. However, heat-transfer correlations for bundles are usually very sensitive to bundle design. Therefore, this correlation cannot be applied to other bundle geometries. To overcome this problem, a wide-range heat-transfer correlation based on bare-tube data can be developed as a conservative approach. This process is based on the fact that Heat Transfer Coefficients (HTCs) in bare tubes are generally lower than those in bundle flow geometries in which heat transfer is enhanced with appendages (endplates, bearing pads, spacers, buttons, etc.).

A number of empirical generalized correlations, based on experimentally obtained datasets, have been proposed to calculate the HTC in forced convection for various fluids, including water, at supercritical pressures. These bare-tube-based correlations are available in various literature sources, however, differences in HTC values can be up to several hundred percent [1].

The most widely used heat-transfer correlation at subcritical pressures for forced convection is the Dittus-Boelter correlation (1930) [10]. McAdams (1942) [11] proposed to use the Dittus-Boelter correlation in the following form for forced-convective heat transfer in turbulent flows at subcritical pressures (this statement was based on the recent study by Winterton [12]):

$$\mathbf{Nu}_\mathrm{b} = 0.0243\,\mathbf{Re}_\mathrm{b}^{0.8}\mathbf{Pr}_\mathrm{b}^{0.4} \tag{1}$$

Later, Eq. (1) was also used at supercritical conditions. However, it was noted that Eq. (1) might produce unrealistic results within some flow conditions, especially near the critical and pseudocritical points, because it is sensitive to properties variations. Therefore, the Dittus-Boelter correlation was used in the following form, for reference purposes:

$$\mathbf{Nu}_\mathrm{b} = 0.023\,\mathbf{Re}_\mathrm{b}^{0.8}\mathbf{Pr}_\mathrm{b}^{0.4} \tag{2}$$

Equation (2) is the most widely used interpretation of the original Dittus-Boelter correlation [14]. An analysis performed by Pioro and Duffey [1] showed that the Bishop et al. correlation was obtained within the same range of operating conditions as those for SCWRs. Bishop et al. (1964) [15] conducted experiments in SCW flowing upward inside bare tubes and annuli within the following range of operating parameters: pressure 22.8 – 27.6 MPa, bulk-fluid temperature 282 – 527ºC, mass flux 651 – 3662 kg/m^{2}s and heat flux 0.31 – 3.46 MW/m^2. Their data for heat transfer in tubes were generalized using the following correlation with a fit of ±15%:

$$\mathbf{Nu}_\mathrm{b} = 0.0069\,\mathbf{Re}_\mathrm{b}^{0.9}\,\overline{\mathbf{Pr}}_\mathrm{b}^{0.66}\left(\frac{\rho_w}{\rho_b}\right)^{0.43}\left(1+2.4\,\frac{D}{x}\right) \tag{3}$$

Equation (3) uses the cross-sectional averaged Prandtl number. The last term in the correlation accounts for the entrance-region effect. In the present comparison, the Bishop et al. correlation was modified and used without the entrance-region term, because this term depends significantly on the particular design of the inlet of the bare test section:

$$\mathbf{Nu}_\mathrm{b} = 0.0069\,\mathbf{Re}_\mathrm{b}^{0.9}\,\overline{\mathbf{Pr}}_\mathrm{b}^{0.66}\left(\frac{\rho_w}{\rho_b}\right)^{0.43} \tag{4}$$

Swenson et al. (1965) [16] found that conventional correlations, which use the bulk-fluid temperature as a basis for calculating the majority of the thermophysical properties, did not work well. They suggested the following correlation in which thermophysical properties are based mainly on a wall temperature:

$$\mathbf{Nu}_\mathrm{w} = 0.00459\,\mathbf{Re}_\mathrm{w}^{0.923}\,\overline{\mathbf{Pr}}_\mathrm{w}^{0.613}\left(\frac{\rho_w}{\rho_b}\right)^{0.231} \tag{5}$$

Jackson (2002) [17] modified the original correlation of Krasnoshchekov et al. (1967) [18] (for details, see [1]), for forced-convective heat transfer in water and carbon dioxide at supercritical pressures, to employ the Dittus-Boelter type form for $\mathbf{Nu}_\mathrm{o}$. Finally, the following correlation was obtained:

$$\mathbf{Nu}_\mathbf{b} = 0.0183\,\mathbf{Re}_\mathbf{b}^{0.82}\mathbf{Pr}_\mathbf{b}^{0.5}\left(\frac{\rho_w}{\rho_b}\right)^{0.3}\left(\frac{\overline{c}_p}{c_{pb}}\right)^{n} \tag{6}$$

Where the exponent n is defined as following:

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

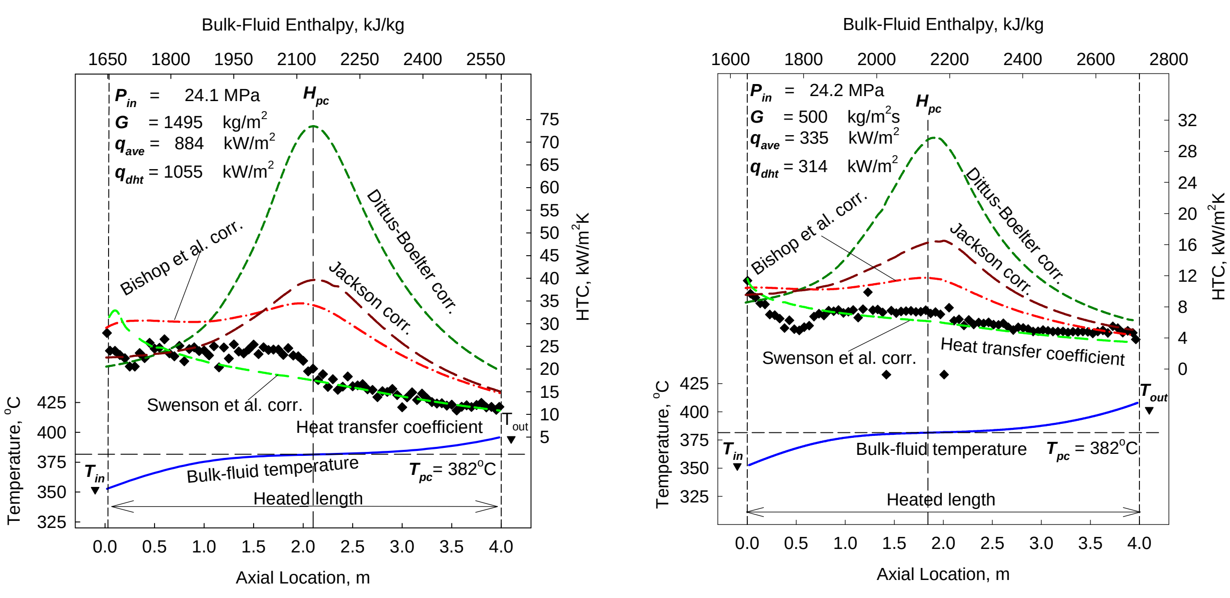
$n = 0.4 + 0.2\left(\dfrac{T_w}{T_{pc}} - 1\right)$ for $T_b < T_{pc} < T_w$; and

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

2.1 Comparison of Existing Heat-Transfer Correlations

Figure 4 shows two sample experimental runs at supercritical pressures and provides experimentally measured HTC values. Also, a comparison between experimental and calculated HTCs using the Dittus-Boelter, modified Bishop et al., Swenson et al. and Jackson correlations are plotted in this figure.

As can be seen from Figure 4, the Dittus-Boelter correlation provides a significant overestimation of the HTC values within the pseudocritical region, and thus, this correlation is unusable within a wide range of parameters. The modified Bishop et al. and Jackson correlations also tend to deviate substantially from the experimental data within the pseudocritical range. The Swenson et al. correlation provides a better fit for the experimental date than the previous three correlations within some flow conditions, but does not closely follow the experimental data within others [19].



(a) **(b)**

Figure 4 Temperature and HTC (Experimental and Calculated Values) Profiles along Heated Length of Bare Vertical Tube: (a) G = 1500 kg/m^{2}s and q = 884 kW/m^2; (b) G = 500 kg/m^{2}s and q = 335 kW/m^2 [19].

It should be noted that all heat-transfer correlations presented in this paper are intended only for use at normal and Improved Heat-Transfer (IHT) regimes. None of the presented correlations can be used for the HTC prediction within the DHT regime. A more thorough discussion and comparison of heat-transfer correlations can be found in [1].

The majority of the reviewed empirical correlations were proposed in the 1960s and 1970s, when experimental techniques were not at the same level (i.e., advanced level) as they are today. Also, thermophysical properties of water have since been updated (for example, a peak in thermal conductivity in critical and pseudocritical points, within a range of pressures from 22.1 to 25 MPa, was not officially recognized until the nineties [1]). Thus, this further emphasizes the necessity of developing a new or an updated correlation based on a new set of heat-transfer data and the latest thermophysical properties of water [9] within the SCWRs operating range.

3. Updated Heat-Transfer Correlation for SCW

3.1 Experimental Data

The experimental SCW data used in the current paper were obtained at the State Scientific Center of Russian Federation – Institute for Physics and Power Engineering Supercritical-Test Facility (Obninsk, Russia) [20]. This set of data was obtained within operating conditions close to those of SCWRs including a hydraulic-equivalent diameter. The supercritical CO_2 data was obtained at the MR-1 loop at the Thermalhydraulics Branch at Chalk River Laboratories. Details of the experimental set-up and procedures can be found in [2] and [21].

3.2 Data Analysis

The objective of this study was to develop updated heat-transfer correlations for the normal and improved heat-transfer regimes. Therefore, data points within the DHT region were removed from the datasets (for details, see Figure 7). This region is subject to future investigations. Also, the very first and last points of most data runs were removed from the supercritical water dataset. Temperatures at these outlying points were likely affected with the test-section clamps, which were at a lower/higher temperature than the heated part of tube.

3.3 Developing the Correlations

It is well established that the general form of a correlation is as follows:

$$y = C_o \times t_1^{C_1} t_2^{C_2} ... t_n^{C_n} \tag{7}$$

where C_o is the constant, t represents the various parameters that affect heat transfer and C_n represents the exponents.

In order to obtain a general empirical form of an equation governing HTCs, a dimensional analysis was conducted. A review of trends in correlating heat-transfer data at supercritical pressures determined that there are nine parameters affecting heat transfer [1] (for details, see [19]). The Buckingham *Π*-Theorem [22], using dimensionless pi-terms, was chosen for this analysis. This theorem is based on dimensional homogeneity, in which dimensionless pi-terms can be formed from the correlation variables. Thus, the following expression was produced for HTCs as a function of the identified heat-transfer parameters:

$$HTC = f\,(D\,,\ \rho_w\,,\ \rho_b\,,\ \mu_w\,,\ \mu_b\,,\ k_w\,,\ k_b\,,\ c_p\,,\ V) \tag{8}$$

The resulting relationship based on this analysis is as follows:

$$\Pi_1 = f\,(\Pi_2,\ \Pi_3,\ \Pi_4,\ \Pi_5,\ \Pi_6)\ , \tag{9}$$

Through consideration of the primary dimensions, six unique dimensionless Π-terms were determined. The resulting relationship is given below:

$$\mathbf{Nu}_b = C \cdot \mathbf{Re}_b^{n_1} \mathbf{Pr}_b^{n_2} \left(\frac{\rho_w}{\rho_b}\right)^{n_3} \left(\frac{\mu_w}{\mu_b}\right)^{n_4} \left(\frac{k_w}{k_b}\right)^{n_5} \tag{10}$$

Equation (10) provided a starting point for the development of a correlation, where HTC can be calculated from the following equation:

$$\mathrm{HTC} = \frac{\mathbf{Nu} \cdot k_b}{D_{hy}}\ , \tag{11}$$

where D_{hy} and k_b denote the hydraulic-equivalent diameter and thermal conductivity of water, respectively. The various coefficients for the resulting relationship needed to be determined for the final correlation.

As a result of the experimental data analysis described, the following preliminary correlation for heat transfer to supercritical water was obtained.

$$\mathbf{Nu}_b = 0.0053\,\mathbf{Re}_b^{0.914} \overline{\mathbf{Pr}}_b^{\,0.654} \left(\frac{\rho_w}{\rho_b}\right)^{0.518} \tag{12}$$

To finalize this correlation, the complete set of primary data and Eq. (12) were fed into the SigmaPlot Dynamic-Fit Wizard to perform final adjustments. The final correlation is as follows:

$$\mathbf{Nu}_b = 0.0061\,\mathbf{Re}_b^{0.904} \overline{\mathbf{Pr}}_b^{\,0.684} \left(\frac{\rho_w}{\rho_b}\right)^{0.564} \tag{13}$$

The test matrix shown in Table 4 provides the range of applicability for the developed correlation. This matrix is the result of comparison with Kirillov et al. [20] experimental data in addition to a comparison with other datasets for supercritical water.

Table 4 Test Matrix for Developed Correlation (Eq. (13)).

Pressure, MPa	Heat Flux, kW/m^2	Mass Flux, kg/m^{2}s	Diameter, mm
22.8 – 29.4	70 – 1250	200 – 1500	3 – 38

Even though the final coefficients slightly deviate from the preliminary correlation, both correlations fit the data in nearly the same manner. Figure 5 provides scatter plots of the experimentally obtained HTC values versus the calculated HTC values for each of the above mentioned correlations. The final correlation (Eq. (13), (Mokry et al. correlation) has an uncertainty of about ±25% for HTC values and about ±15% for calculated wall temperature.

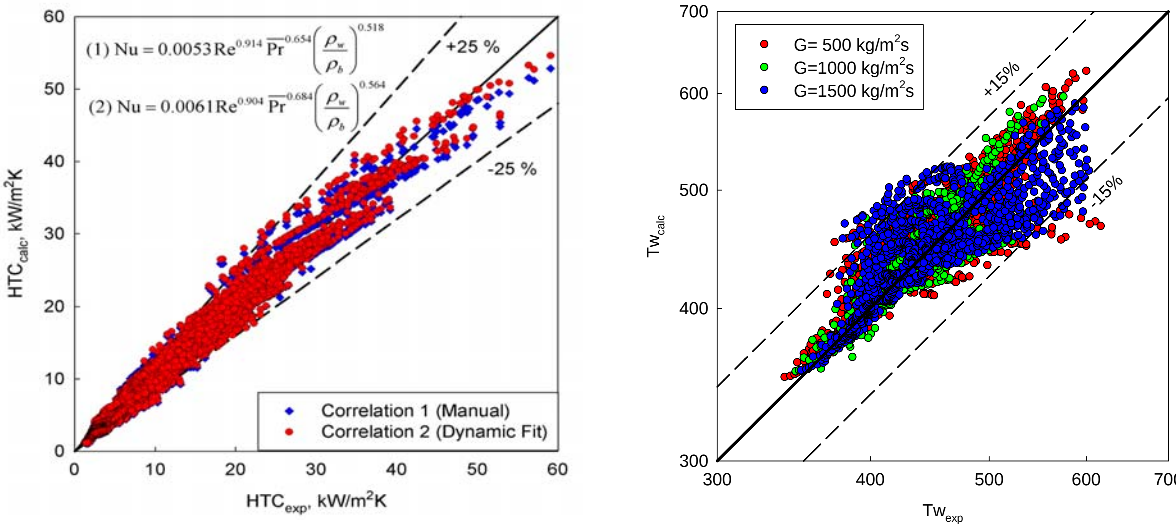


Figure 5 Comparison of Data Fit (Eqs. (12) and (13)) with Experimental Data: (a) for Heat Transfer Coefficient and (b) for wall temperature [19].

In order to evaluate the accuracy of the derived correlation, a comparison of the experimental data with the calculated HTC profiles, using the modified Bishop et al., Dittus-Boelter and the derived correlations was conducted and is shown in Figure 6 and 7. As can be seen from these graphs, neither the modified Bishop et al. nor the Dittus-Boelter correlations provide a good fit for the experimental data, whereas the final Mokry et al. correlation (Eq. (13)) fits the data well and follows trends closely. A comparison between the Mokry et al. correlation (Eq. (13)) and calculations using the CFD Code FLUENT-6.0 can be found in [23].

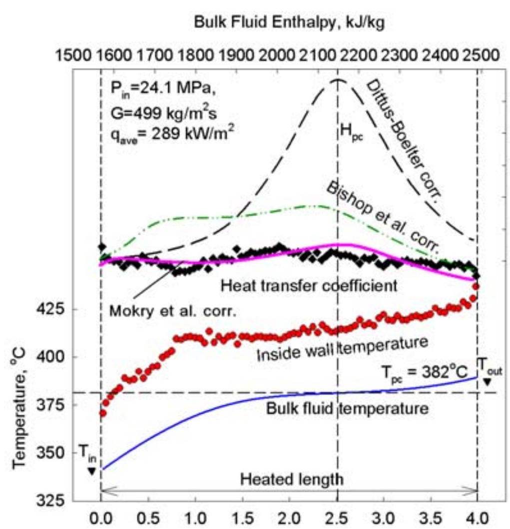


Figure 6 Temperature and Heat Transfer Coefficient Profiles along Heated Length of Bare Vertical Tube: G = 500 kg/m^{2}s and q = 290 kW/m^2 [19].

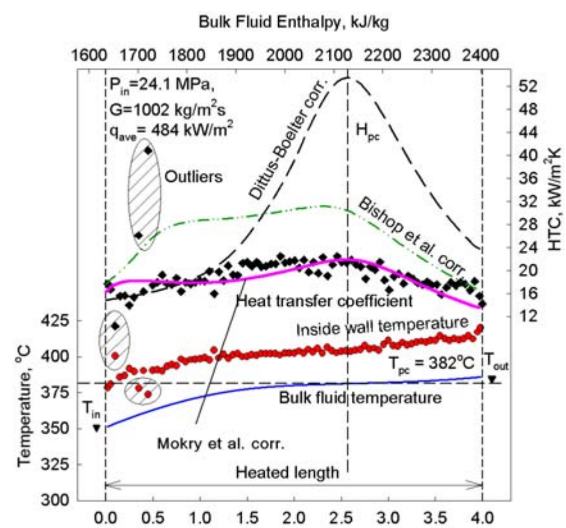


Figure 7 Temperature and Heat Transfer Coefficient Profiles along Heated Length of Bare Vertical Tube: G = 1000 kg/m^{2}s and q = 480 kW/m^2 [19].

An analysis of the plots in Figures 6 and 7 (for more details, see [19]) showed that in general, the final correlation (Eq. (13)) appeared to best fit the general data trends. Deviations in the calculated HTC values from the experimentally determined values were found, for the most part, at the test section inlet. Within this area, however, the flow was likely subject to an entrance effect. There were also slight deviations within the pseudocritical range; however, the most pronounced difference occurred only at data runs with lower mass flux values.

Nevertheless, the derived correlation (Eq. (13)) showed the best fit for the experimental data within a wide range of flow conditions. This correlation has an uncertainty of about ±25% for HTC values and about ±15% for calculated wall temperature. For the final verification of the correlation, a comparison with other datasets was completed (Figures 8 and 9). From the presented figures, it can be seen that the updated correlation (Eq. (13)) closely represents the experimental data and follows trends closely, even within the pseudocritical range.

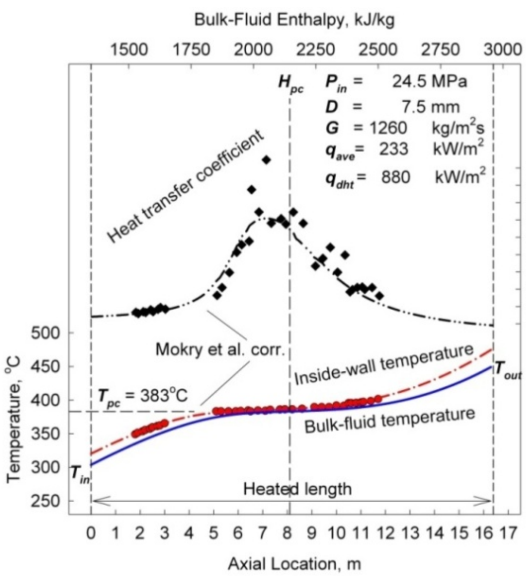


Figure 8 Temperature and Heat Transfer Coefficient Variations at Various Heat Fluxes along a Tube: Nominal Operating Conditions – water, P_{in} = 24.5 MPa, G = 1260 kg/m^{2}s and q_{ave}=233 kW/m^2 [24]

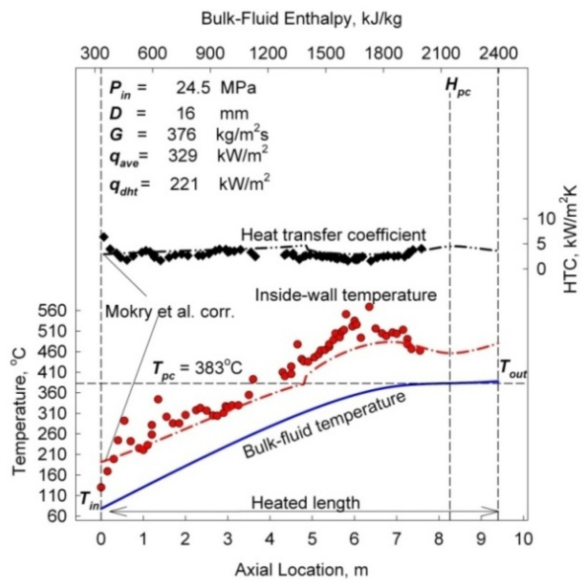


Figure 9 Temperature and Heat Transfer Coefficient Variations at Various Heat Fluxes along a Circular Tube: Nominal Operating Conditions –water, P_{in} = 24.5 MPa, (a) G = 1180 kg/m^{2}s; and (b) G = 376 kg/m^{2}s [25].

4. Updated Heat-Transfer Correlation for $SCCO_2$

Similarly, for the supercritical CO_2 correlation the following preliminary correlation for heat transfer to supercritical carbon dioxide was obtained by the same method:

$$\mathbf{Nu}_b = 0.0345\,\mathbf{Re}_b^{0.77}\,\overline{\mathsf{Pr}}_b^{0.17}\left(\frac{\rho_w}{\rho_b}\right)^{0.47} \qquad (14)$$

To finalize the development of the correlation, the complete set of primary data and Eq. (14) were fed into the SigmaPlot Dynamic Fit Wizard to perform the final adjustments. The final correlation is as follows:

$$\mathbf{Nu}_b = 0.0121\,\mathbf{Re}_b^{0.86}\,\overline{\mathbf{Pr}}_b^{0.23}\left(\frac{\rho_w}{\rho_b}\right)^{0.59} \tag{15}$$

Figure 10 shows a scatter plot of the calculated **Nu** versus the experimental **Nu** according to Eq. (15). The data lie along a 45-degree straight line with a spread of ± 50%. Accounting for the relatively high uncertainty, a more thorough analysis of the experimental data is required.

In order to evaluate the accuracy of the derived correlation, (Eq. (15), Mokry and Pioro correlation) a comparison of the experimental data with the calculated HTC profiles, using the Bringer and Smith correlation (1957) [26], Krasnoshchekov et al. correlation (1964) [18], Jackson correlation (2001) [27] and Swenson correlation (1965)[16] was conducted and is shown in Figures 11 and 12. For further details, see [21].

From Figures 11 and 12, it can be seen that the Jackson correlation tends to over predict HTC values in the pseudocritical region. Similarly, the Krasnoshchekov et al. correlation tends to under predict HTC values in the pseudocritical region. For lower mass flux (~1000 kg/m^{2}s) the Bringer and Smith correlation, Swenson et al. correlation and Mokry and Pioro correlation all followed the general data trends. However, at higher mass flux (~2000 kg/m^{2}s) both the Bringer and Smith and Swenson et al. correlations began to slightly over predict HTC values, whereas the Mokry and Pioro correlation still appears to closely follow the data trends.

Thus, despite the relatively high uncertainty, the obtained correlation for forced-convective heat transfer to supercritical carbon dioxide in a bare vertical tube with upward flow showed a reasonable fit for the analyzed dataset. This correlation can be used for future comparison with other independent datasets and for verification of scaling parameters between water and CO_2.

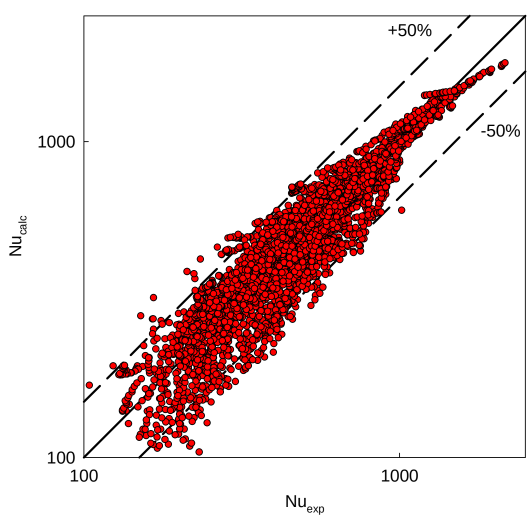


Figure 10 Verification of Final Correlation.

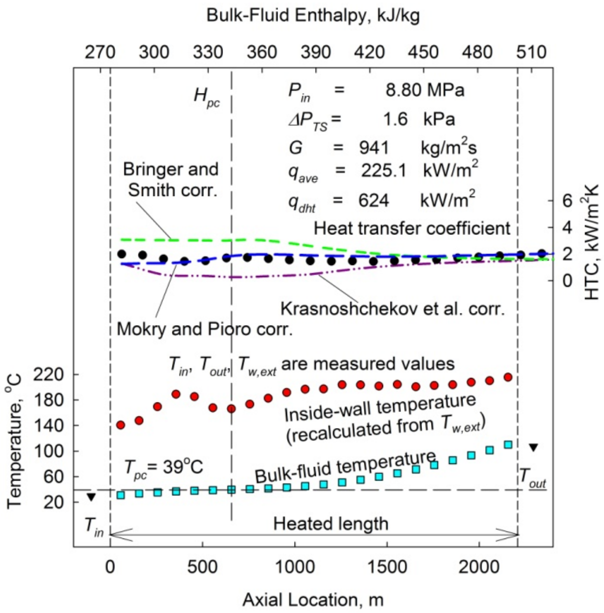


Figure 11a. Temperature Variations for Carbon Dioxide along Test Section at P_{in}=8.80 MPa and G=941 kg/m^{2}s.

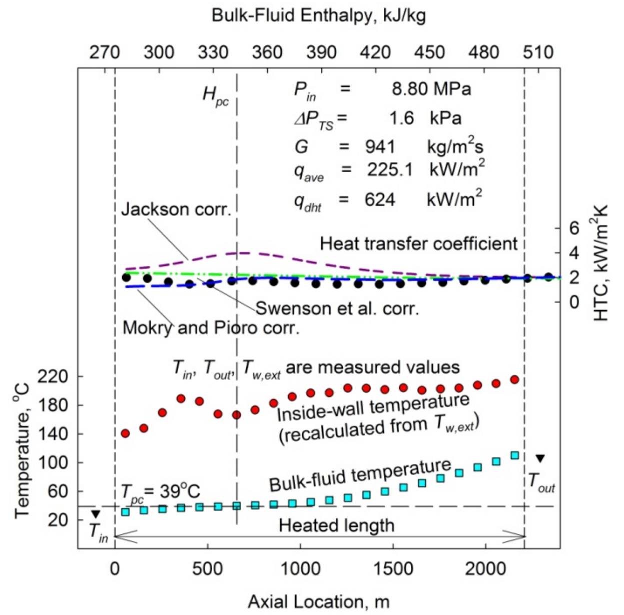


Figure 11b. Temperature Variations for Carbon Dioxide along Test Section at P_{in}=8.80 MPa and G=941 kg/m^{2}s.

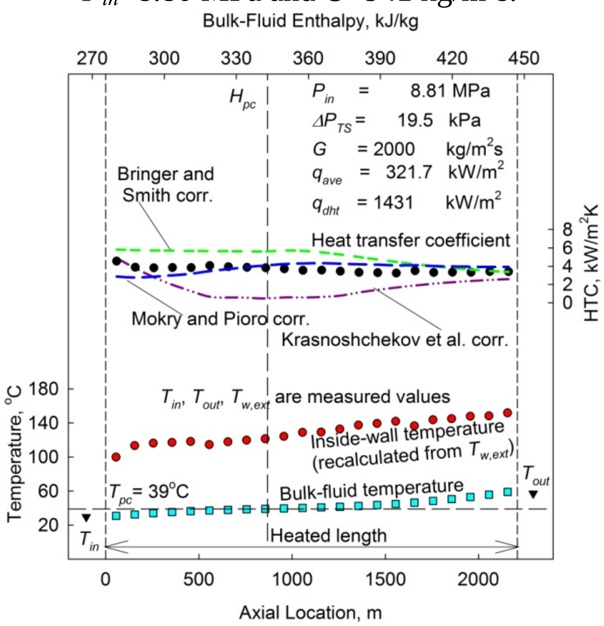


Figure 12a. Temperature Variations for Carbon Dioxide along Test Section at P_{in}=8.81 MPa and G=2000 kg/m^{2}s.

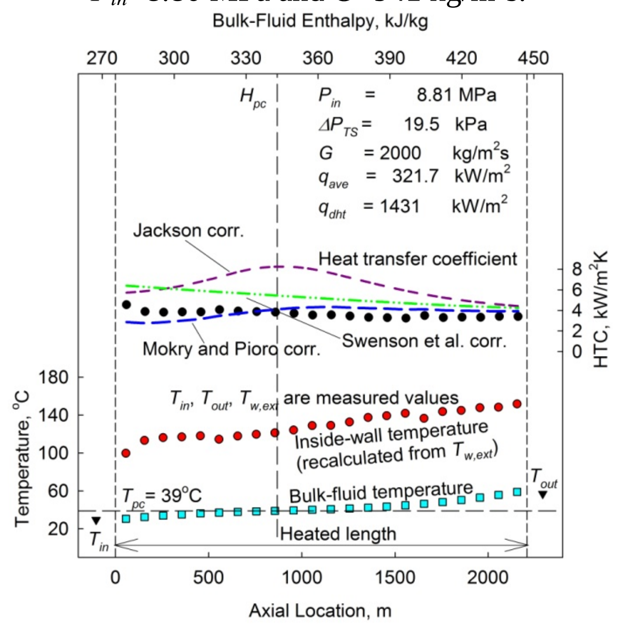


Figure 12b. Temperature Variations for Carbon Dioxide along Test Section at P_{in}=8.81 MPa and G=2000 kg/m^{2}s.

5. Conclusions

Supercritical-water heat-transfer data for a vertical bare circular tube were obtained within the proposed SCWR operating conditions. Supercritical heat transfer was investigated for several combinations of wall and bulk-fluid temperatures, i.e., internal wall temperatures and bulk-fluid temperatures below, at, or above the pseudocritical temperature. The obtained correlation for forced convective heat transfer to supercritical water in a bare vertical tube showed a good fit (±25% for heat transfer coefficient) for the analyzed dataset. In addition, the calculated wall temperatures resulted in a more accurate fit for the analyzed dataset (±15%).

An experimental dataset was analyzed and a heat-transfer correlation for supercritical CO_2 was also developed. In order to evaluate the accuracy of the derived correlation, a comparison of the experimental data with the calculated HTC profiles, using the Bringer and Smith correlation (1957), Krasnoshchekov et al. correlation (1964), Jackson correlation (2001) and Swenson correlation (1965) was conducted. The obtained correlation for forced-convective heat transfer to supercritical carbon dioxide in a bare vertical tube with upward flow showed a reasonable fit for the analyzed dataset.

Therefore, the derived correlations can be used for preliminary HTC calculations in SCWR fuel bundles as a conservative approach, for SCW heat exchangers, for future comparison with other datasets, for verification of computer codes and scaling parameters between SCW and modelling fluids.

ACKNOWLEDGEMENTS

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NOMENCLATURE

c_p specific heat at constant pressure (J/kg·K)

$\bar{c}_p$ average specific heat, J/kg·K, $\left(\frac{H_w - H_b}{T_w - T_b}\right)$

D inner diameter, m

G mass flux, kg/m²s

H enthalpy, J/kg

h heat transfer coefficient, W/m²K

k thermal conductivity, W/m·K

L heated length, m

P pressure, MPa

q heat flux, W/m²

T temperature, °C

Greek letters

μ dynamic viscosity, Pa·s

ρ density, kg/m³

Dimensionless numbers

Nu Nusselt number $\left(\frac{h \cdot D}{k}\right)$

Pr Prandtl number $\left(\frac{\mu \cdot c_p}{k}\right)$

$\overline{\mathbf{Pr}}$ averaged Prandtl number $\bar{c}_p\left(\frac{\mu_b}{k_b}\right)$

Re Reynolds number $\left(\frac{G \cdot D}{\mu}\right)$

Subscripts

ave average

b bulk

cal calculated

cr critical

dht deteriorated heat transfer

exp experimental

ext external

hy hydraulic

in inlet conditions

out outlet conditions

pc pseudocritical

w wall
x axial location, m

Abbreviations

AECL	Atomic Energy of Canada Limited
BWR	Boiling Water Reactor
CANDU	CANada Deuterium Uranium (reactor)
DHT	Deteriorated Heat-Transfer (regime)
GIF	Generation IV International Forum
HTC	Heat Transfer Coefficient
IHT	Improved Heat-Transfer (regime)
NIST	National Institute of Standards and Technology (USA)
NPP	Nuclear Power Plant
PT	Pressure Tube
PV	Pressure Vessel
PWR	Pressurized Water Reactor
RDIPE	Research and Development Institute of Power Engineering (Moscow) (NIKIET in Russian abbreviations)
REFPROP	REFerence PROPerties
SCW	SuperCritical Water
SCWR	SuperCritical Water-cooled Reactor

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