DEVELOPMENT OF HEAT-TRANSFER CORRELATION FOR WATER FLOWING IN VERTICAL BARE TUBES AT SUPERCRITICAL CONDITIONS

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ABSTRACT

This paper presents an in-depth analysis of heat-transfer correlation for water flowing in bare vertical tubes at supercritical conditions. A large dataset within conditions similar to those of SuperCritical Water-cooled Nuclear Reactors (SCWRs) was obtained from the Institute for Physics and Power Engineering (Obnisk, Russia).

A dimensional analysis was conducted using the Buckingham *Π*-theorem to derive a general form of empirical supercritical-water heat-transfer correlation for the Nusselt number, which was finalized based on the experimental data obtained at the normal heat-transfer regime. The new correlation showed the best fit for the experimental dataset within a wide range of flow conditions.

1. INTRODUCTION

SuperCritical Water-cooled nuclear Reactors (SCWRs) are a high-pressure (~25 MPa) and high-temperature (up to 625°C) reactor concepts, which are intended to operate above the thermodynamic critical point of water (~ 22.1 MPa and 374°C). SCWRs can be divided into two classes: 1) Pressure-Vessel (PV) reactors, and 2) Pressure-Tube (PT) reactors. Currently, Canada and Russia are working on development of PT-reactor concepts. The main objectives for developing SCWRs is that SuperCritical Water (SCW) Nuclear Power Plants (NPP) can significantly increase the thermodynamic efficiency of the plant (~45 − 50%) compared to that of current NPPs (~30 − 35%). Additionally, they allow for a decrease in capital and operation costs.

An important aspect in the PT-SCWR reactor concept is calculations of the Heat Transfer Coefficient (HTC) in fuel bundles. However, this task is very complicated, because heat transfer at supercritical pressures is influenced by significant changes in thermophysical properties of coolant at these conditions. The most significant properties variations occur within critical and psedocritical points [1].

1.1 General Definitions of Selected Terms Related to Fluids at Critical and Supercritical Pressures

Prior to discussing the correlations and calculations of HTC, it is necessary to define a few terms, which are listed below [1] (also, in addition, see Figure 1).

Compressed fluid is a fluid at a pressure above the critical pressure, but at a temperature below the critical temperature.
Critical point is the point in which a distinction between the liquid and gas phases disappears, i.e., both phases have the same temperature, pressure and density. The *critical point* is characterized by the phase-state parameters T_{cr}, P_{cr} and ρ_{cr},, which have unique values for each pure substance.

Deteriorated heat transfer is characterized with lower values of the wall heat transfer coefficient compared to those at the normal heat transfer; and hence has higher values of wall temperature within some part of a test section or within the entire test section.
Improved heat transfer is characterized with higher values of the wall heat transfer coefficient compared to those at the normal heat transfer; and hence lower values of wall temperature within some part of a test section or within the entire test section. In our opinion, the improved heat-transfer regime or mode includes peaks or “humps” in the heat transfer coefficient near the critical or pseudocritical regions.
Near-critical point or critical region is actually a narrow range around the critical point where all the thermophysical properties of a pure fluid exhibit rapid variations.
Normal heat transfer can be characterized in general with wall heat transfer coefficients similar to those of subcritical convective heat transfer far from the critical or pseudocritical regions, when are calculated according to the conventional single-phase Dittus-Boelter type correlations.
Pseudocritical point (characterized with P_{pc} and T_{pc}) is a point at a pressure above the critical pressure and at a temperature ($T_{pc} > T_{cr}$) corresponding to the maximum value of the specific heat for this particular pressure.
<u>Supercritical fluid</u> is a fluid at pressures and temperatures that are higher than the critical pressure and critical temperature.
Superheated steam is a steam at pressures below the critical pressure, but at temperatures above the critical temperature.

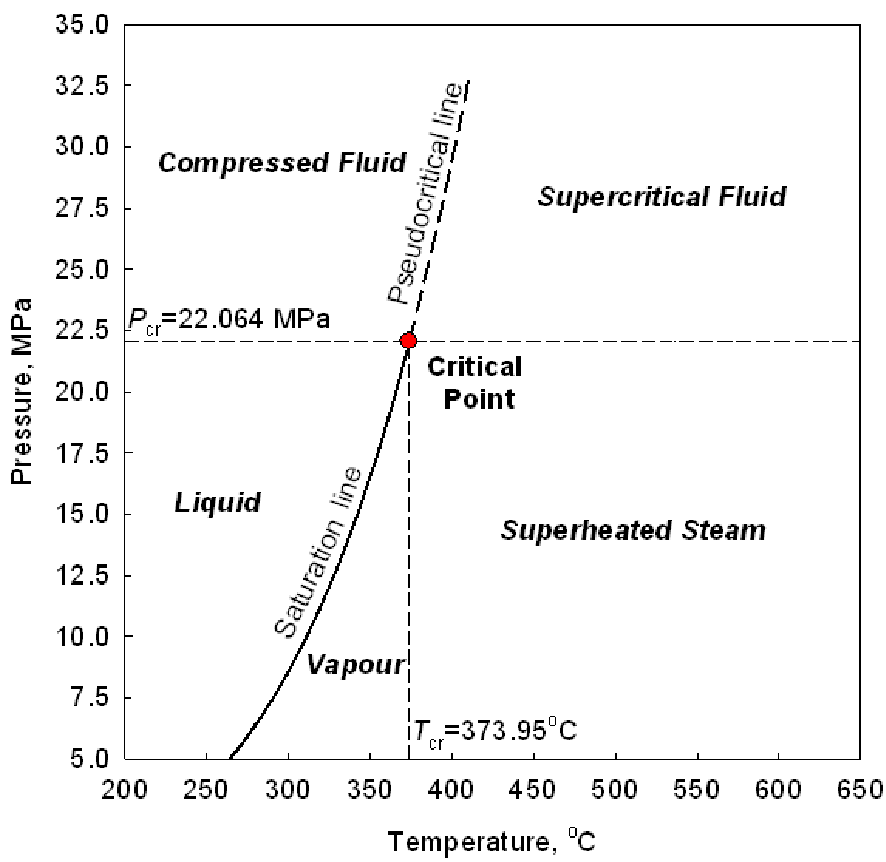

Figure 1: Pressure-Temperature diagram for water [2].

1.2 Supercritical Fluids

Supercritical fluids have unique properties. An interesting thing to note is that, there are very significant changes in the properties of water within the range of ±25°C from the pseudocritical temperature (384.9°C at P = 25 MPa). The NIST REFPROP software [3] was used to calculate some of the thermophysical properties (see Figure 2) at 25 MPa, the proposed operating pressure for SCWRs.

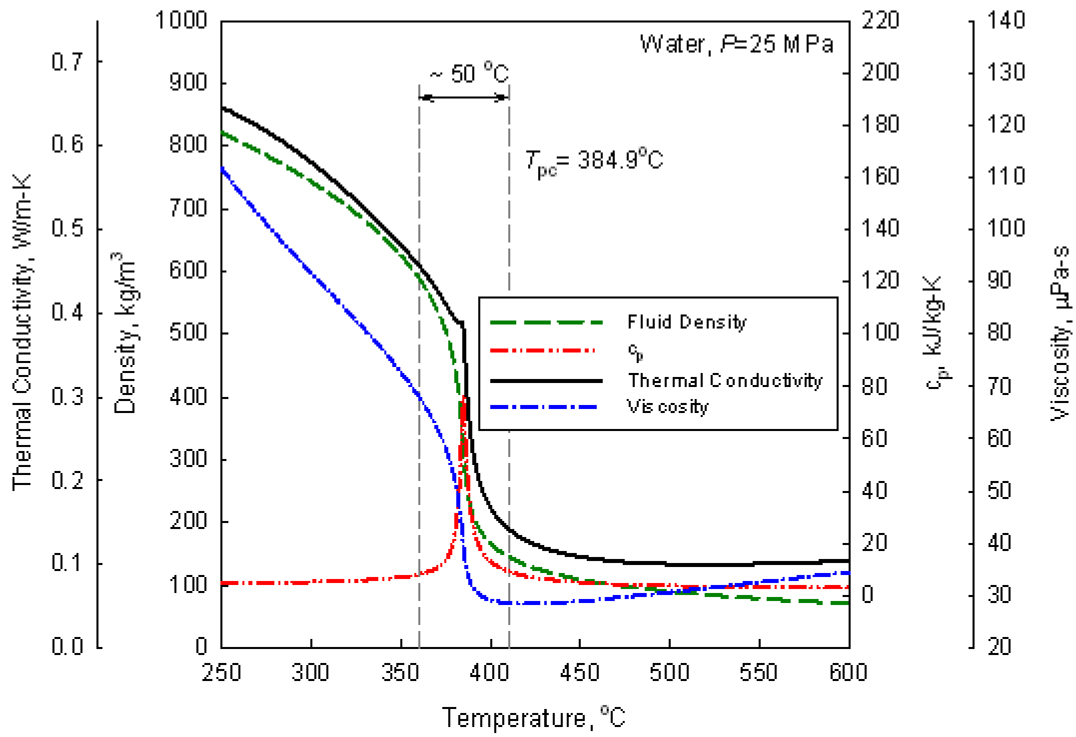

Figure 2: Thermophysical properties of supercritical water within pseudocritical point.

1.3 SCWR Concepts

As part of the Generation IV International Forum (GIF), SCWR concepts (see Table 1), which include PV and PT reactor options, are currently under development worldwide. Canada is working on development of a PT-reactor concept – SCW CANDU reactor (see Table 1 and Figure 3) [1, 4−6].

The current Canadian SCWR concept includes a fuel channel comprised of a pressure tube insulated internally, which would enable the pressure tube to operate at temperatures close to that of the moderator [1]. As discussed earlier such a design can result in increased thermodynamic efficiency.

2. BACKGROUND

Currently, there is just one SCW heat-transfer correlation for fuel bundles developed by Dyadyakin and Popov [1]. This correlation was obtained in a 7-element helically-finned bundle. However, heat-transfer correlations for bundles are usually quite sensitive to a particular bundle design. Therefore, this correlation cannot be applied to other bundle geometries.

To overcome this problem, wide-range heat-transfer correlations based on bare-tube data can be developed as a conservative approach. This approach is based on the fact that HTCs in bare tubes are generally lower than those in bundle geometries, where heat transfer is enhanced with appendages (endplates, bearing pads, spacers, button, etc.). A number of empirical generalized correlations have been proposed to calculate the HTC in forced convection for various fluids including water at supercritical pressures. However, differences in calculated HTC values can be up to several hundred percent [1].

Table 1: Major parameters of SCW CANDU (Canada) and SCW VVER-SCP (Russia) nuclear-reactor concepts.

Parameters	SCW CANDU®	VVER-SCP
Reactor type	PT	PV
Reactor spectrum	Thermal	Fast
Thermal power, MW	2540	3830
Electric power, MW	1220	1700
Thermal efficiency, %	48	44
Pressure, MPa	25	25
Inlet temperature, °C	350	280
Outlet temperature, °C	625	530
Flowrate, kg/s	1320	1860
Number of fuel channels	300	241
Number of fuel elements in a bundle	43	252
Length of a bundle string, m	6	4

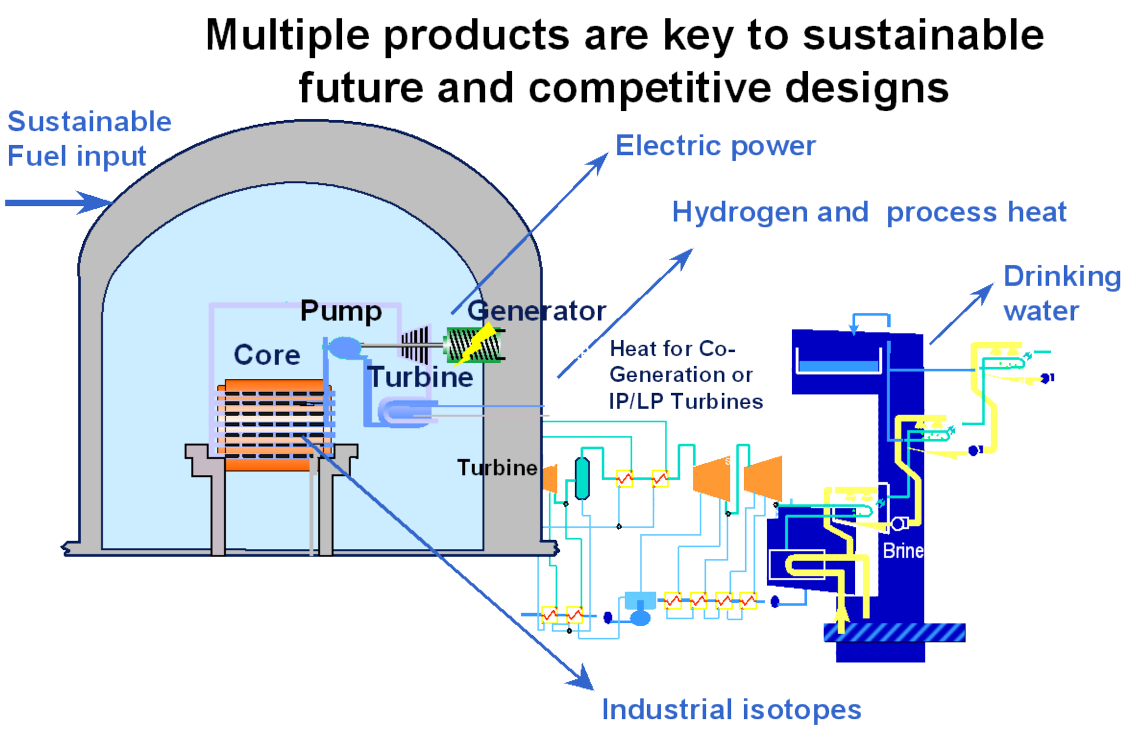

Figure 3: SCW CANDU reactor schematic (courtesy of Dr. R. Duffey, AECL) [1].

2.1 Experimental Data

The experimental 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) [1], [7]-[9]. This set of data was obtained within operating conditions close to those of SCWRs including a hydraulic-equivalent diameter.

The data for this study was obtained within the following conditions: Vertical stainless steel (12Cr18Ni10Ti) smooth tube: D = 10 mm, δ_w = 2 mm, and L_h = 4 m; tube internal-surface roughness R_a = 0.63 – 0.8 μm; and upward flow. Table 2 lists test-matrix parameters, and Table 3 – their uncertainties.

Table 2: Test matrix.

P	T_{in}	T_{out}	T_w	q	G
MPa	°C	°C	°C	kW/m^2	kg/m^{2}s
24	320–350	380–406	<700	70–1250	200, 500; 1000; 1500

Table 3: Uncertainties of primary parameters.

Parameter	Uncertainty
Test-section power	±1.0%
Inlet pressure	±0.25%
Wall temperature	±3.0%
Mass-flow rate	±1.5%
Heat loss	≤3.0%

2.2 Existing Correlations

The most widely used heat-transfer correlation at subcritical pressures for forced convection is the Dittus-Boelter correlation [10]. McAdams [11] proposed the use of the Dittus-Boelter correlation in the following form for forced-convective heat transfer in turbulent flows at subcritical pressures.

$$\mathrm{Nu_b} = 0.0243\ \mathbf{Re_b^{0.8}}\ \mathbf{Pr_b^{0.4}} \tag{1}$$

Equation (1) was later used at supercritical conditions. According to Schnurr et al. [12], Eq. (1) showed good agreement with experimental data of supercritical water flowing inside circular tubes at a pressure of 31 MPa with low heat fluxes. However, it was soon noted that Eq. (1) can produce unrealistic results within some flow conditions, especially within the critical and pseudocritical rnages, because it is very sensitive to properties variations. Nonetheless, the Dittus-Boelter correlation has been used extensively as a basis for development of various supercritical heat-transfer correlations.

An analysis performed by Pioro and Duffey [1] showed that the two following correlations: 1) Bishop et al. [13] and 2) Swenson et al. [14]; were obtained within the same range of operating conditions as those for SCWRs.

Bishop et al. [13] conducted experiments in supercritical water flowing upward inside bare tubes and annuli within the following range of operating parameters: P=22.8 – 27.6 MPa, T_b = 282 – 527°C, G =

651–3662 kg/m^{2}s and q = 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%:

$$\mathrm{Nu_b} = 0.0069\, \mathbf{Re_b^{0.9}}\, \overline{\mathbf{Pr_b}}^{0.66} \left(\frac{\rho_w}{\rho_b}\right)^{0.43} \tag{2}$$

Swenson et al. [14] found that conventional correlations, which use a bulk-fluid temperature as a basis for calculating the majority of thermophysical properties, did not work well. They suggested the following correlation in which the majority of thermophysical properties are based on a wall temperature:

$$\mathrm{Nu_w} = 0.00459\, \mathbf{Re_w^{0.923}} \overline{\mathbf{Pr_w}}^{0.613} \left(\frac{\rho_w}{\rho_b}\right)^{0.231} \tag{3}$$

Equation (3) was obtained within the following range: Pressure 22.8 − 41.4 MPa, bulk-fluid temperature 75 − 576ºC, wall temperature 93 − 649ºC and mass flux 542 − 2150 kg/m^{2}s; and predicts the experimental data within ±15%. It should be noted that all heat-transfer correlations presented in this paper are intended only for the normal heat-transfer regime calculations.

3. DEVELOPING NEW CORRELATION

Many other similar correlations were developed applicable to various flow conditions (refer to [1] for more details). However, majority of these empirical correlations were proposed in the sixties-seventies when experimental techniques were not so advanced as of today. Also, thermophysical properties of water have been updated since that time (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]). Therefore, most of these correlations did not fit the experimental data with the desired accuracy (Figure 4.). It was hence, necessary to develop a new or an updated correlation with the latest thermophysical properties of water [2] within the SCWRs operating range.

Mokry et al. [2, 15, 16] used the Bishop et al. correlation as a starting point to come up with the following updated correlation.

$$\mathrm{Nu_b} = 0.0061\, \mathbf{Re_b^{0.904}} \overline{\mathbf{Pr_b}}^{0.684} \left(\frac{\rho_w}{\rho_b}\right)^{0.564} \tag{4}$$

Equation (4) showed the best fit for the recent experimental dataset within the most operating conditions. This correlation has uncertainty about ±25% for HTC values and about ±15% for calculated wall temperature.

However, it was found [15, 16] that the Swenson et al correlation, which uses a different approach in terms of calculating thermophysical properties based on a wall temperature instead of a bulk-fluid temperature, can predict experimental data even better within some operating conditions compared to the Mokry et al. correlation. Therefore, it was decided to develop an updated Swenson et al. correlation using the same set of experimental data.

3.1 Dimensional Analysis

A dimensional analysis was performed in order to obtain a general empirical form of a correlation for the HTC calculations. It is well known that HTC is not an independent variable, and that HTC values are affected with mass flux, inside diameter, heat flux, thermophysical properties variations, etc.. Therefore, a set of the most important variables, which affects the HTC, were identified based on theoretical and experimental HTC studies at supercritical pressures. Table 4 lists parameters identified as essential for the analysis of heat-transfer processes for forced convection at supercritical conditions.

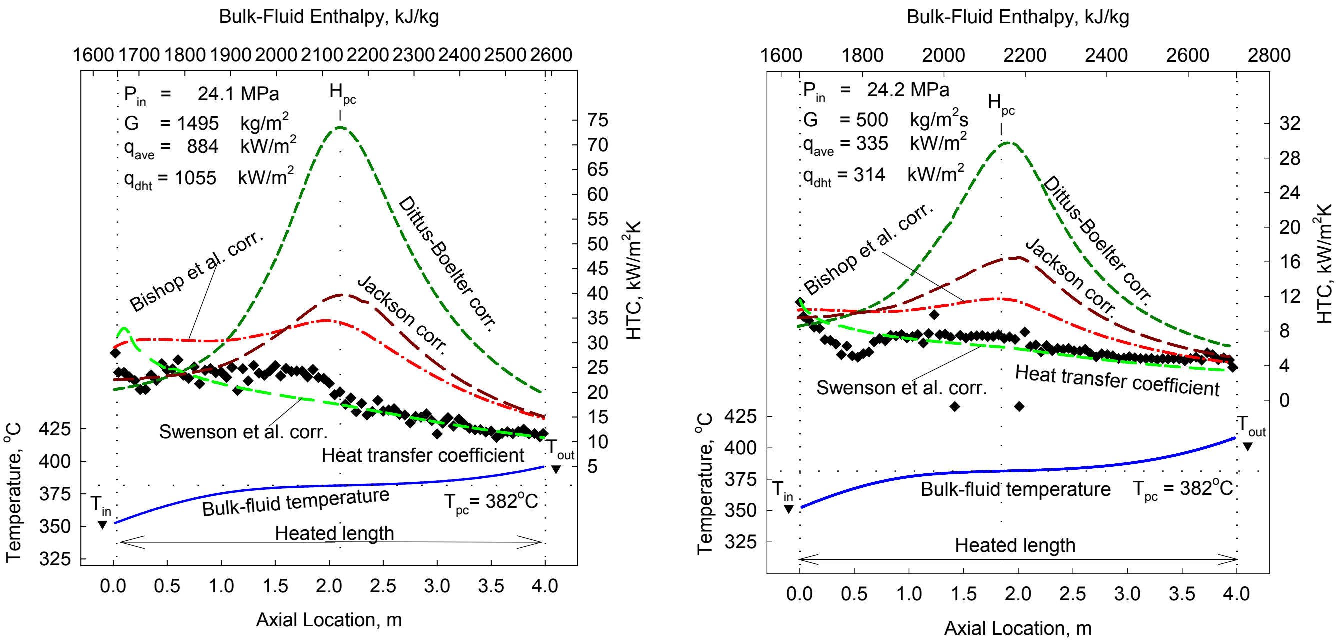

Figure 4: Comparison of HTC values calculated through various correlations with experimental data of 4-m circular tube (D = 10 mm): P_{in} ~ 24.0 MPa and G = 1500 and 500 kg/m^{2}s.

Table 4: Description of Various Heat-Transfer Parameters.

Variable	Description	SI units	Dimensions (M, L, T, K)
HTC	Heat transfer coefficient	W/m^{2}K	MT^{-3}K^{-1}
D	Inside diameter of tube	m	L
k_b	Thermal conductivity of fluid at T_b	W/m·K	MLT^{-3}K^{-1}
k_w	Thermal conductivity of fluid at T_w	W/m·K	MLT^{-3}K^{-1}
ρ_b	Density of fluid at T_b	kg/m^3	ML^{-3}
ρ_w	Density of fluid at T_w	kg/m^3	ML^{-3}
μ_b	Viscosity of fluid at T_b	Pa·s	ML^{-1}T^{-1}
μ_w	Viscosity of fluid at T_w	Pa·s	ML^{-1}T^{-1}
c_p	Specific heat	J/kg·K	L^{2}T^{-2}K^{-1}
V	Velocity	m/s	LT^{-1}

The Buckingham Π-Theorem for dimensional analysis [17] was used to produce the following expression for HTC as a function of the identified heat-transfer parameters.

$$HTC = f\,(D\,,\, k_b\,,,\, k_w\,,\, \rho_w\,,\, \rho_b\,,\, \mu_w\,,\, \mu_b\,,\, c_p\,,\, V) \tag{5}$$

Through consideration of the primary dimensions (mass, length, time and temperature), six unique dimensionless *Π*-terms were determined (see Table 5).

Table 5: *Π*-Terms of Empirical Correlation.

***Π*-terms**	**Dimensionless group**	**Name**
Π_1	$\frac{HTC\ D}{k_w}$	Nusselt number, $\mathrm{Nu_w}$
Π_2	$\frac{\rho\ V\ D}{\mu_w}$	Reynolds number, $\mathbf{Re_w}$
Π_3	$\frac{c_p\ \mu_w}{k_w}$	Prandtl number, , $\mathbf{Pr_w}$
Π_4	$\frac{k_w}{k_b}$	Thermal conductivity ratio
Π_5	$\frac{\mu_w}{\mu_b}$	Viscosity ratio
Π_6	$\frac{\rho_w}{\rho_b}$	Density ratio

The resulting relationship based on this analysis is as follows:

$\Pi_1 = f\,(\Pi_2, \Pi_3, \Pi_4, \Pi_5, \Pi_6)$ or

$$\mathrm{Nu_w} = \mathrm{C}\ \mathbf{Re_w^{n_1}}\ \mathbf{Pr_w^{n_2}}\ \left(\frac{k_w}{k_b}\right)^{n_3} \left(\frac{\mu_w}{\mu_b}\right)^{n_4} . \left(\frac{\rho_w}{\rho_b}\right)^{n_5} \qquad (6)$$

3.2 Finalizing Correlation

The coefficients *C*, n_1, n_2, etc. were then determined using statistical techniques. Some restraints put on values of these coefficients and plotting techniques were employed to obtain a preliminary correlation. To finalize the correlation, the complete set of primary data was coupled with the preliminary correlation using the SigmaPlot Dynamic Fit Wizard to perform the final adjustments. The final correlation is as follows:

$$\mathrm{Nu_w} = 0.004\ \mathbf{Re_w^{0.923}}\ \overline{\mathbf{Pr}}_{\mathbf{w}}^{-0.773} \left(\frac{\mu_w}{\mu_b}\right)^{0.366} \left(\frac{\rho_w}{\rho_b}\right)^{0.186} \qquad (7)$$

Equation (7) has uncertainty about ±25% for HTC values and about ±15% for calculated wall temperature.

3.3 Verifying New Correlation

Figure 5 shows a scatter plot of the experimental values for wall temperature versus the calculated values using Equation (7).

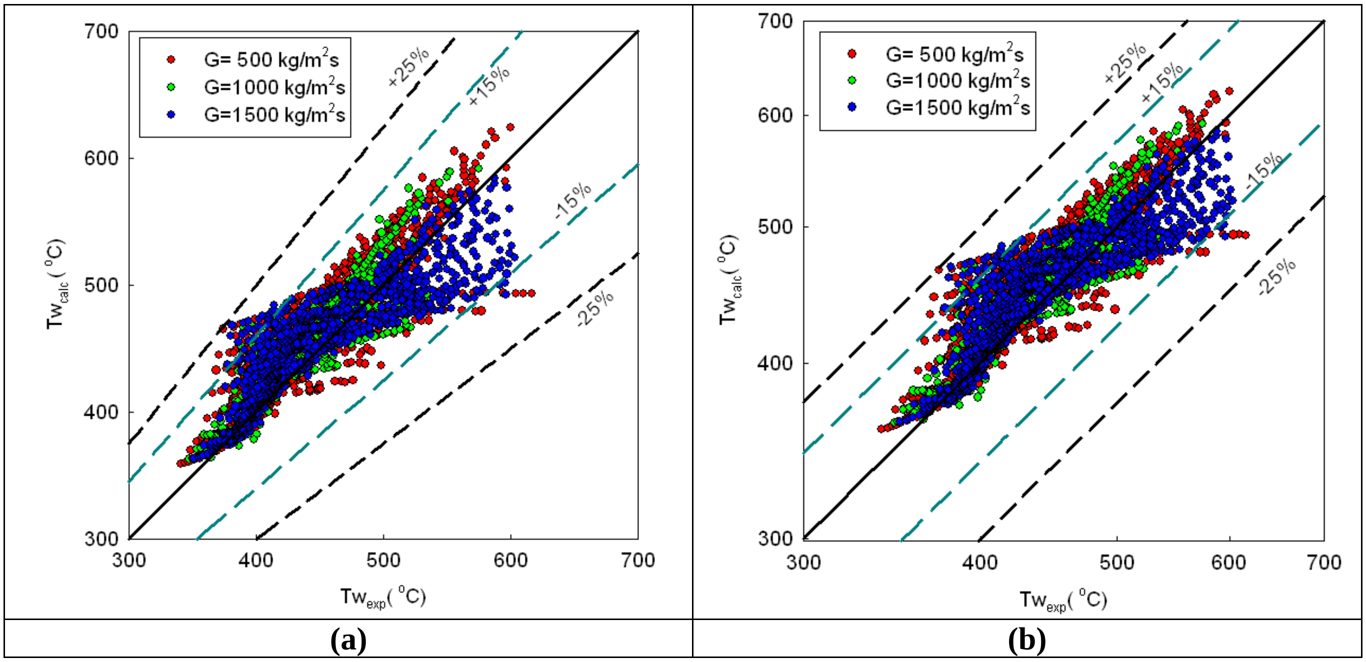

Figure 5: Comparison of data fit with experimental data for wall temperatures: (a) normal scale and (b) log-log scale.

From Figure 5 it is clear that the wall temperatures calculated by the new correlation fall within ±15% for the calculated wall temperatures. Figures (6)–(8) show some additional comparisons of data calculated through Equation (7) with experimental data.

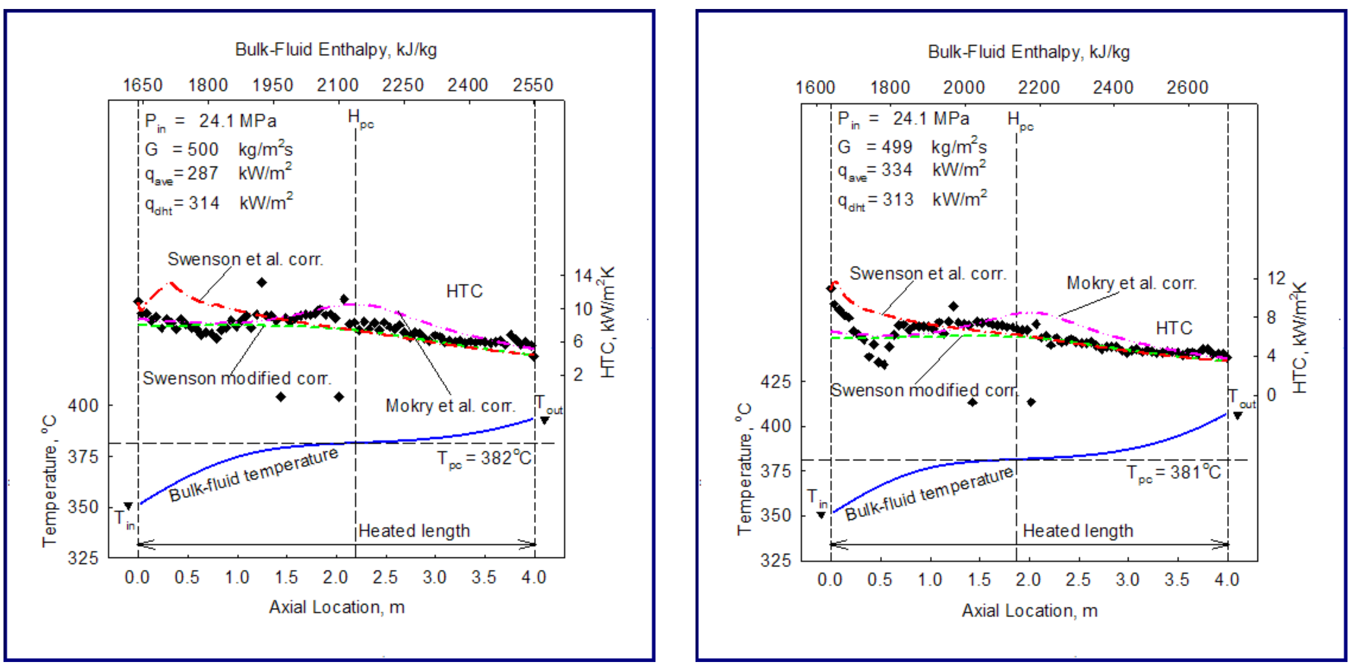

Figure 6: HTC variations at various heat fluxes along 4-m circular tube (D = 10 mm): P_{in} = 24.0 MPa and G = 500 kg/m^{2}s.

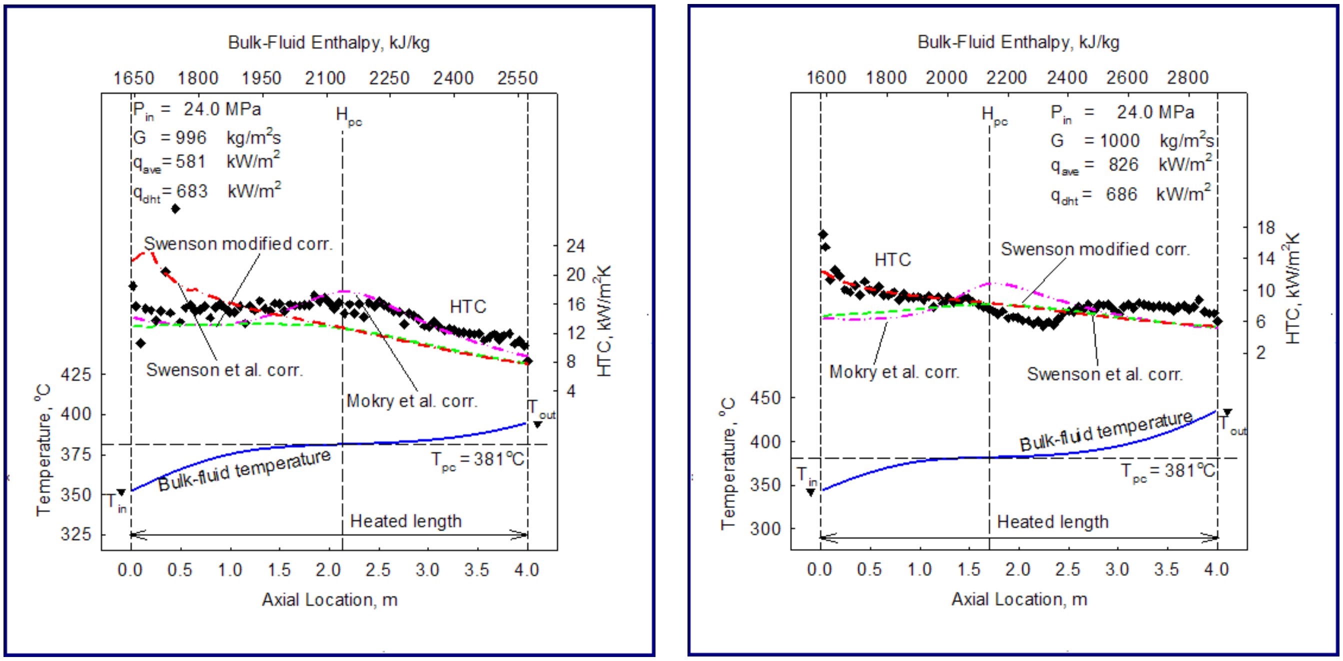

Figure 7: HTC variations at various heat fluxes along 4-m circular tube (*D* = 10 mm): P_{in} = 24.0 MPa and G = 1000 kg/m^{2}s.

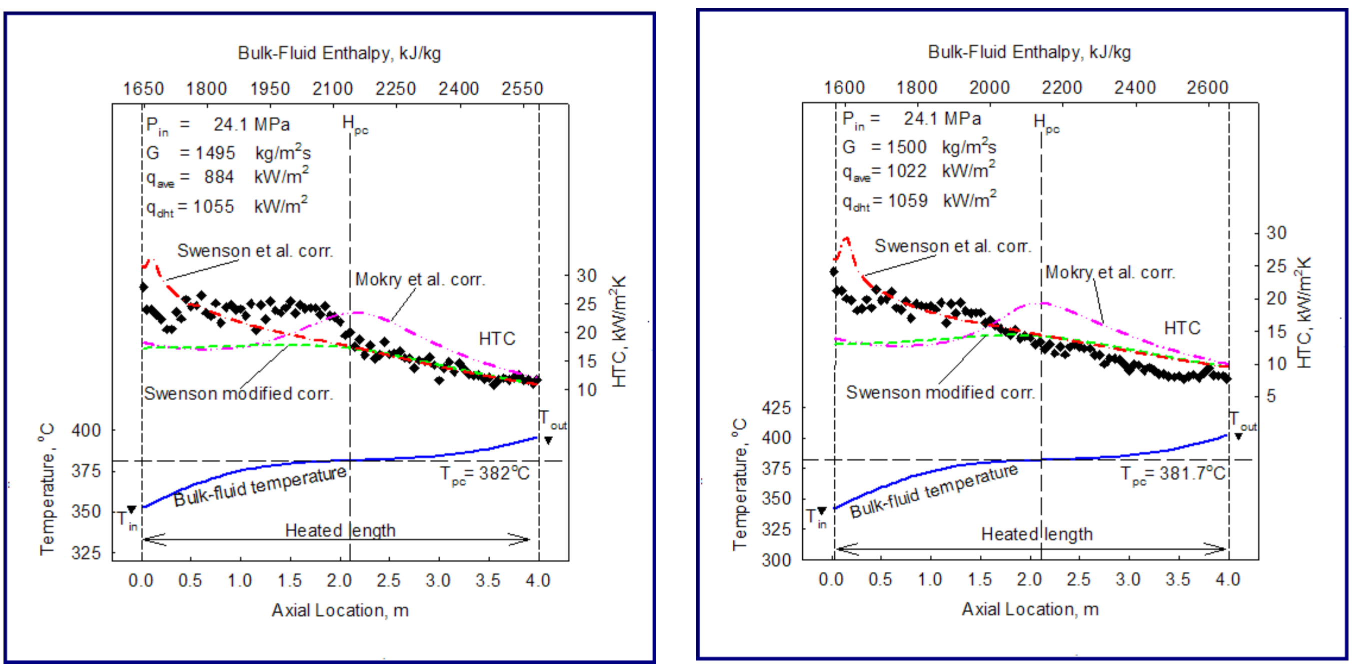

Figure 8: HTC variations at various heat fluxes along 4-m circular tube (*D* = 10 mm): P_{in} = 24.0 MPa and G = 1500 kg/m^{2}s.

4. CONCLUSIONS

The following supercritical-water heat-transfer dataset obtained in a vertical bare tube was used for development of a new heat-transfer correlation and its comparison with the experimental data, with other correlations from the open literature: P = 24 MPa, T_{in} = 320 −3 50ºC, G = 200 − 1500 kg/m^{2}s and $q \leq$ 1250 kW/m^2. This dataset was obtained within the SCWR operating conditions.

The comparison showed that the Dittus-Boelter correlation significantly overestimates experimental HTC values within the pseudocritical range. The Bishop et al. and Jackson correlations tended also to deviate substantially from the experimental data within the pseudocritical range. The Swenson et al. correlation provided a better fit for the experimental data than the previous three correlations within some flow conditions, but does not follow up closely the experimental data within others. Mokry et al. correlation showed the best fit for the experimental data within a wide range of flow conditions. This correlation has uncertainty of about ±25% for HTC values and about ±15% for calculated wall temperature.

However, the Mokry et al. correlation is also not a perfect one and does not predict experimental trends closely with some operating conditions. Therefore, the Swenson et al. correlation approach, which uses thermophysical properties based on a wall temperature instead of a bulk-fluid temperature, was used to develop a new correlation. Based on the dimensional analysis a new correlation was developed, which shows similar uncertainties as that of the Mokry et al. correlation: ±25% for HTC values and about ±15% for calculated wall temperature. Therefore, the new correlation can be used in addition to the Mokry et al. correlation for preliminary HTC calculations in SCWR fuel bundles, for future comparison with other datasets and for verification of computer codes and scaling parameters between water and modelling fluids.

Future work on this topic includes adding an entrance-effect term into the correlation, correlating larger supercritical-water datasets with the proposed correlation, and developing a correlation for supercritical-water bundle data.

6. NOMENCLATURE

C	constant
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	inside diameter, m
f	function
G	mass flux, kg/m^{2}s
H	enthalpy, J/kg
h	heat transfer coefficient, W/m^{2}K
k	thermal conductivity, W/m·K
L	length, m
P	pressure, Pa
q	heat flux, W/m^2
R_a	surface roughness, µm
T	temperature, ºC
V	velocity, m/s
x	axial location, m

<u>Greek letters</u>

μ	dynamic viscosity, Pa·s
ρ	density, kg/m^3
δ	thickness, mm

<u>Dimensionless numbers</u>

Nu	Nusselt number $\left(\frac{h \cdot D}{k}\right)$
Pr	Prandtl number $\left(\frac{\mu \cdot c_p}{k}\right)$
$\overline{\mathbf{Pr}}$	average cross-sectional Prandtl number $\left(\frac{\mu \cdot \bar{c}_p}{k}\right)$

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

Subscripts

ave	average
b	bulk
calc	calculated
cr	critical
dht	deteriorated heat-transfer
exp	experimental
h	heated
in	inlet
out	outlet
pc	pseudocritical
w	wall

Abbreviations:

AECL	Atomic Energy Canada Limited
CANDU	CANada Deuterium Uranium (reactor)
HTC	Heat Transfer Coefficient
ID	Inside Diameter
NIST	National Institute of Standards and Technology
NPP	Nuclear Power Plant
PT	Pressure Tube (reactor)
PV	Pressure Vessel (reactor)
SCW	SuperCritical Water
SCWR	SuperCritical Water Reactor
VVER-SCP	Water Water Power Reactor of SuperCritical Pressure (in Russian abbreviations)

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