A Study of Selected Forced-Convection SuperCritical-Water Heat-Transfer Correlations for Vertical Bare Tubes Based On a Wide-Range Dataset

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ABSTRACT

This paper presents an extensive study of heat-transfer correlations applicable to supercritical-water flow in vertical bare tubes. A comprehensive dataset was collected from 33 papers by 27 authors, including more than 125 graphs and wide range of parameters. The parameters range was as follows: pressures 22.5 − 34.5 MPa, inlet temperatures 85 – 350ºC, mass fluxes 250 – 3400 kg/m^{2}s, heat fluxes 75 – 5,400 kW/m^2, tube heated lengths 0.6 − 27.4 m, and tube inside diameters 2 – 36 mm.

This combined dataset was then investigated and analyzed by calculating Heat Transfer Coefficients (HTCs) and wall temperatures using various correlations and comparing them with the corresponding experimental results. Three correlations were used in this comparison: original Bishop et al., Mokry et al. (modified Bishop et al.) and Gupta et al. (modified Swenson et al).

The main objectives of this study were a selection of the best supercritical-water bare-tube correlation for HTC calculations in: 1) fuel bundles of SuperCritical Water-cooled Reactors (SCWRs) as a preliminary and conservative approach; 2) heat exchangers in case of indirect-cycle SCW Nuclear Power Plants (NPPs); and 3) heat exchangers in case of hydrogen co-generation at SCW NPPs from SCW side.

The comparison showed that in most cases, the Bishop et al. correlation deviates significantly from the experimental data within the pseudocritical region and actually, underestimates the temperature in the most cases. On the other hand, the Mokry et al. and Gupta et al. correlations showed a relatively better fit within the most operating conditions. In general, the Gupta et al. correlation showed slightly better fit with the experimental data than the Mokry et al. correlation.

1. INTRODUCTION

1.1. SCWR concept

New Nuclear Power Plants (NPPs) with Generation IV water-cooled reactor concepts being developed at AECL (Canada) [1] and at IPPE (Russia) [2] have the main design objective of achieving higher thermal efficiencies comparable with that of advanced thermal power plants (43 − 50%) [3−5]. The major contribution to this thermal-efficiency increase would come from boosting the outlet coolant temperature and operating pressure above the critical parameters of water (625ºC and 22.1 MPa).

SuperCritical Water-cooled nuclear Reactors (SCWRs) are high-pressure (~25 MPa) and high-temperature (outlet temperatures up to 625°C) concepts that will be put into operation within next 15 − 20 years.

In this case, the coolant will pass through the pseudocritical point before reaching the outlet of the fuel channel. At these extreme conditions, three regimes of forced-convection heat transfer to water might exist. These regimes depend on heat flux per mass-flux ratio and are as the following: (1) Normal Heat-Transfer (NHT) regime characterized by Heat Transfer Coefficients (HTCs) similar to those of subcritical convective heat transfer (usually, this regime occurs outside critical or pseudocritical regions); (2) Deteriorated Heat-Transfer (DHT) regime with lower values of the HTC and hence, higher values of wall temperature within some part of a flow channel compared to those of the NHT regime; and (3) Improved Heat-Transfer (IHT) regime with higher values of the HTC and hence, lower values of wall temperature within some part of a flow channel compared to those of the NHT regime.

Most of the existing heat-transfer correlations are capable of predicting HTCs only at the NHT and IHT regimes, but fail to predict HTCs at the DHT regime. Figure 1 shows several heat-transfer correlations for vertical bare tubes with upward flow of supercritical water at lower value of mass flux.

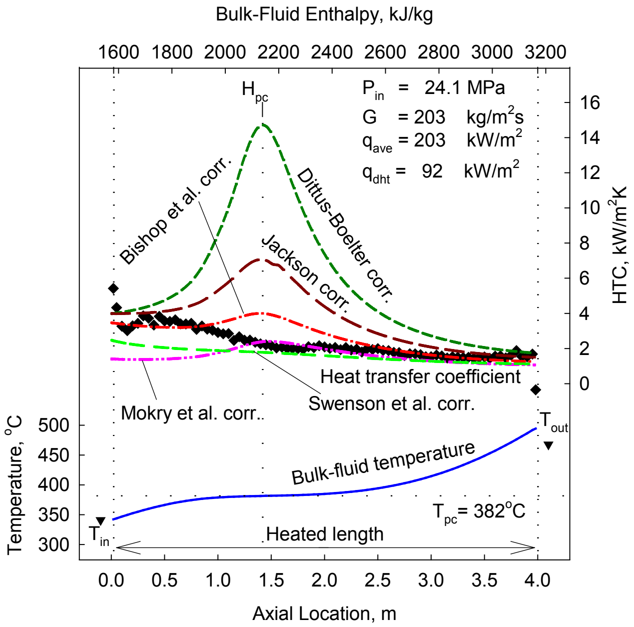


Figure 1: Temperature and HTC variations along vertical tube (4-m heated length and 10-mm ID): P_{in} = 24.1 MPa, G = 203 kg/m^{2}s, q_{avg} = 203 kW/m^2, q_{dht} = 92 kW/m^2 [6].

1.2. SC fluids

Supercritical fluids have unique properties [7, 8]. It is well established that thermophysical properties of any fluid, including water, experience significant changes within critical and pseudocritical regions. Figure 2 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). The National Standards Institute of Technology (NIST) Reference Fluid Properties (REFPROP) software was used to calculate these thermophysical properties [9].

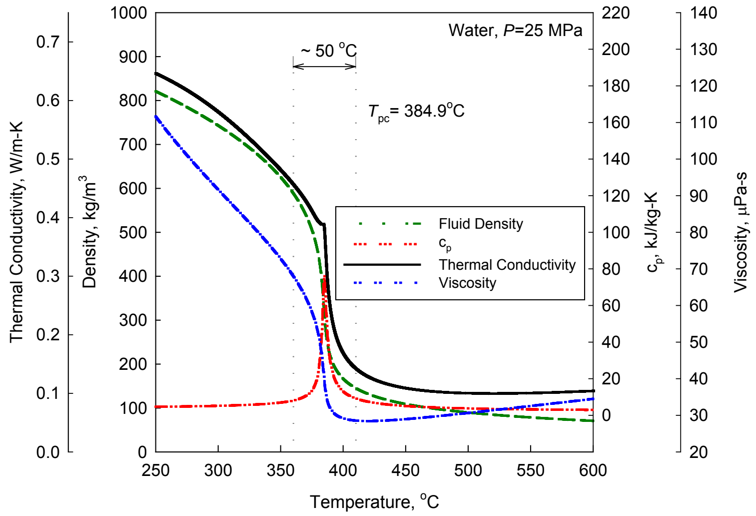


Figure 2. Selected properties of supercritical water at pseudocritical point.

Beyond the critical point, the fluid becomes a dense gas. Crossing from high-density fluid to low-density fluid does not involve a distinct phase change. Phenomena such as a dry-out (critical heat flux) are therefore not applicable. However, at supercritical conditions, a DHT regime may exist [3].

Table 1 lists parameters of current Pressure-Tube (PT) SCWR concepts being developed by AECL (Canada) and RDIPE (Russia).

Table 1. Major parameters of SCW CANDU® and KP-SKD nuclear-reactor concepts [3].

Parameters	SCW CANDU	KP-SKD
Reactor type	PT	PT
Reactor spectrum	Thermal	Thermal
Thermal power, MW	2540	1960
Electric power, MW	1220	850
Thermal efficiency, %	48	42
Pressure, MPa	25	25
Inlet temperature, °C	350	270
Outlet temperature, °C	625	545
Flowrate, kg/s	1300	922
Number of fuel channels	300	653
Number of fuel elements in bundle	43	18
Length of bundle string, m	6	–
Maximum cladding temperature, °C	850	700

This paper presents selected results on heat transfer to supercritical water flowing upward in vertical bare tubes of various lengths and diameters within a wide range of operating conditions.

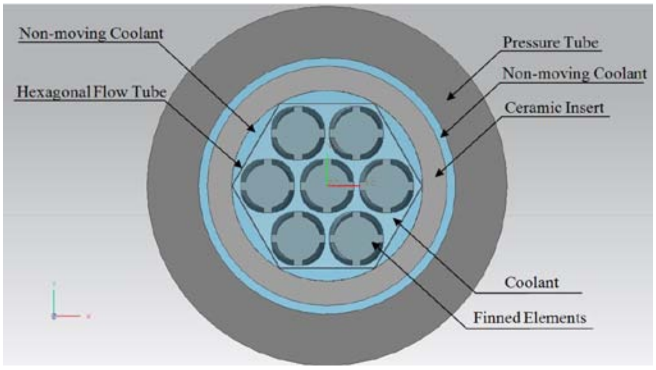
The main objective of this paper was to select the best supercritical-water bare-tube correlation for HTC calculations in: 1) fuel bundles of SCWRs as a preliminary and conservative approach; 2) heat exchangers in case of indirect-cycle SCW NPPs; and 3) heat exchangers in case of hydrogen co-generation at SCW NPPs from SCW side.

2. Background

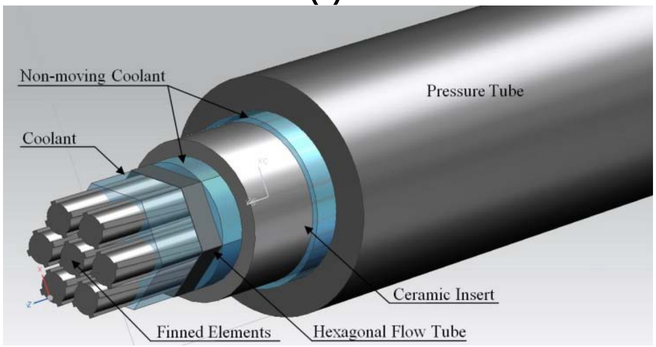
Currently, there is just only one supercritical-water heat-transfer correlation for fuel bundles. This correlation was obtained in a 7-helically-finned-element bundle developed by Dyadyakin and Popov (for details, see Figure 3) [3]. It seems that this test bundle was intended for application in a transport (mobile) nuclear reactor, not in a power reactor (for example, see Figure 4). Moreover, heat-transfer correlations for bundles are usually very sensitive to a particular bundle design. Therefore, this correlation cannot be used for 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. The conservative approach is based on a 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, 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 correlations are available in various literature sources, however, differences in HTC values can be up to several hundred percent [3].



(a)



(b)

Figure 3. Cross-section (a) and 3-D image (b) of the Dyadyakin and Popov test bundle installed inside pressure tube [3].

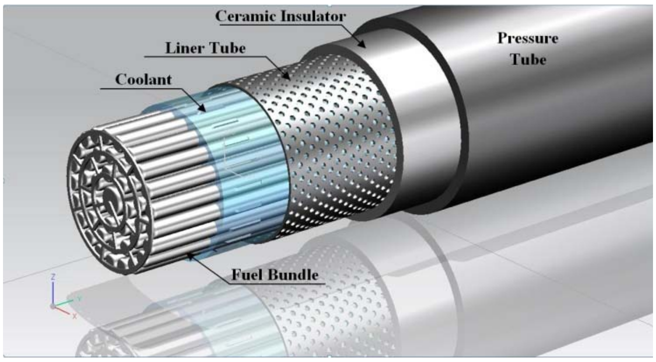


Figure 4. 3-D image of SCW CANDU-reactor fuel channel with bundle inside.

2.1 Existing correlations

Many heat-transfer correlations have been proposed to calculate HTCs in forced convection of various fluids including water at supercritical pressures [3]. However, these correlations show very different results within the same operating conditions. An analysis performed by Pioro and Duffey [3] showed that the Bishop et al. correlation was obtained within the same range of operating conditions as those of SCWRs.

One of the most widely used correlations for supercritical water and two of the latest ones were chosen for this comparison: 1) Bishop et al. correlation [9, 10], 2) Mokry et al. (modified Bishop et al.) correlation [11] and 3) Gupta et al. (modified Swenson et al.) correlation. All these three correlations were obtained within the same range of operating conditions as those in SCWRs.

Bishop et al. [9, 10] conducted experiments in supercritical water 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 vertical circular bare tubes were generalized using the following correlation with a fit of ±15%:

$$\mathbf{Nu_b} = 0.0069\,\mathbf{Re_b}^{0.9}\,\overline{\mathbf{Pr}}_\mathbf{b}^{0.66}\left(\frac{\rho_w}{\rho_b}\right)^{0.43}\left(1+2.4\frac{D}{x}\right) \quad (1)$$

Equation (1) uses the cross-sectional averaged Prandtl number. The last term in the correlation accounts for the entrance-region effect.

In the present verification, the Bishop et al. correlation was used without the entrance-region term, because this term depends significantly on a particular design of the inlet of the bare test section:

$$\mathbf{Nu_b} = 0.0069\ \mathbf{Re_b^{0.9}}\ \overline{\mathbf{Pr}}_\mathbf{b}^{0.66} \left(\frac{\rho_w}{\rho_b}\right)^{0.43} \tag{2}$$

This empirical correlation was proposed in the early nineteen-sixties, when experimental techniques were not at the same level as they are today. Also, the 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 [3]). Therefore, it was necessary to develop a new or an updated version of the Bishop et al. correlation based on a new set of heat-transfer data and the latest thermophysical properties of water [12] within the SCWRs operating range.

Recently, the Bishop et al. correlation was modified by Mokry et al. using experimental dataset obtained in Russia by P. Kirillov with co-workers [6]:

$$\mathbf{Nu_b} = 0.0061\ \mathbf{Re_b^{0.904}}\ \overline{\mathbf{Pr}}_\mathbf{b}^{0.684} \left(\frac{\rho_w}{\rho_b}\right)^{0.564} \tag{3}$$

Swenson et al. [3] found that conventional correlations (for example, Bishop et al.), i.e., correlations in which the majority of thermophysical properties based on a bulk-fluid temperature, did not work well; and suggested using the wall temperature for thermophysical properties calculations instead. However, the correlation they suggested was developed about half a century ago and, like the Bishop et al. correlation, might be outdated as well. A modified correlation was then developed by Gupta et al. based on the same dataset by Kirillov et al.:

$$\mathbf{Nu_w} = 0.004\ \mathbf{Re_w^{0.923}}\ \overline{\mathbf{Pr}}_\mathbf{w}^{0.773} \left(\frac{\mu_w}{\mu_b}\right)^{0.366} \left(\frac{\rho_w}{\rho_b}\right)^{0.186} \tag{4}$$

Since the last two correlations were obtained within the same ranges using the same dataset, the current comparison will be more representing of how the correlations will predict HTC experimental data within other operating conditions.

However, all these correlations are intended only for use at NHT and IHT regimes. For DHT regime, an empirical correlation was proposed for deteriorated heat-flux calculations at which the DHT appears (for details, see [13]):

$$q_{dht} = -58.97 + 0.745\ G\ \ , \mathrm{kW/m^2} \tag{5}$$

A more thorough discussion and comparison of various heat-transfer correlations can be found in Pioro and Duffey [3].

3. Correlations comparison

For comparison of these correlations, experimental datasets were retrieved from graphs published in the open literature. The following figures show selected datasets and curves calculated with these three correlations. The graphs were put in the ascending order of a pressure first, and then mass and heat fluxes, respectively. A range of pressures used in this comparison is within 23.5 − 31 MPa, mass fluxes within 249 − 1260 kg/m^{2}s and heat fluxes within 101 − 698 kW/m^2. Tube heated lengths and internal diameters vary widely also. A heat-flux value at which the DHT regime starts according to Equation (5) is shown in each graph for reference purposes.

Twenty five graphs in total were collected from Pis'menny et al. experiments. However, in this paper only several selected graphs are shown with various mass and heat fluxes (Figures 5−11). In all these figures, the Bishop et al. correlation overpredicts slightly experimental HTC values and those values calculated with other two correlations within a wide range of flow conditions. Therefore, this correlation predicts the lowest wall-temperature values, which is actually an optimistic approach not used in nuclear engineering.

On the opposite, the Gupta et al. correlation predicts the lowest values of HTC and corresponding to that the highest wall-temperature values, which is the conservative approach, which is used in nuclear engineering.

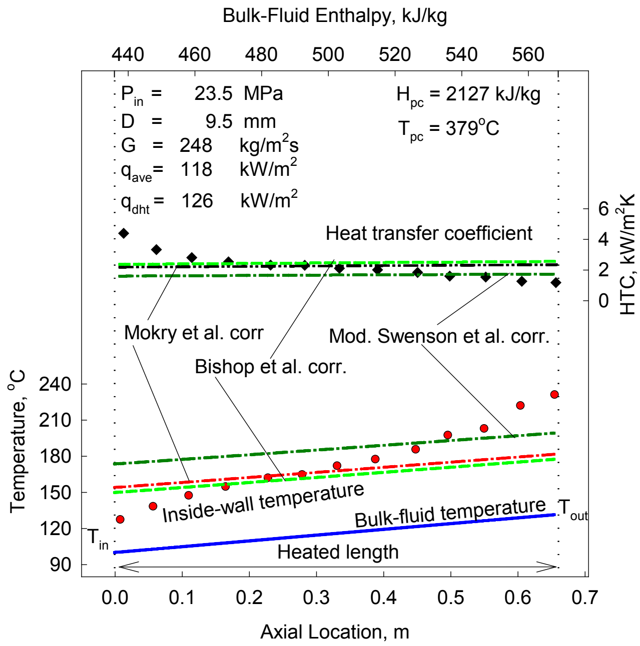


Figure 5: Temperature and HTC variations along vertical tube (0.6-m heated length and 9.5-mm ID): P_{in} = 23.5 MPa, G = 248 kg/m^{2}s, and q_{avg} = 118 kW/m^2 [14].

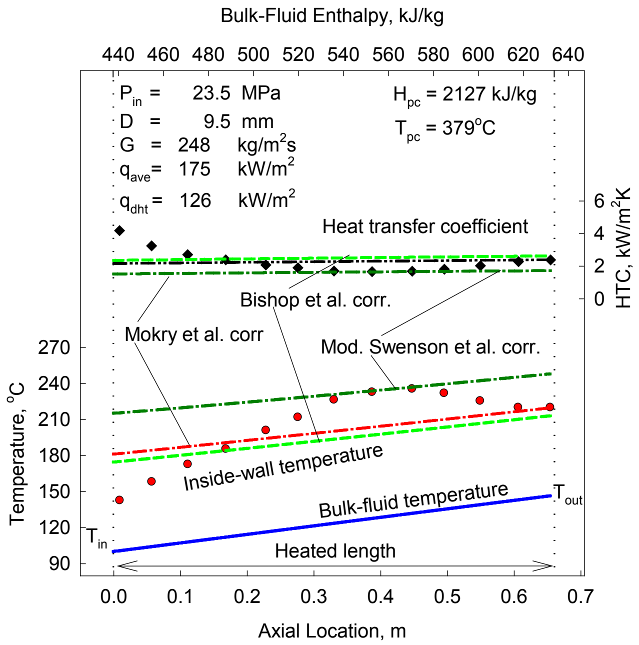


Figure 7: Temperature and HTC variations along vertical tube (0.6-m heated length and 9.5-mm ID): P_{in} = 23.5 MPa, G = 248 kg/m^{2}s, and q_{avg} = 175 kW/m^2 [14].

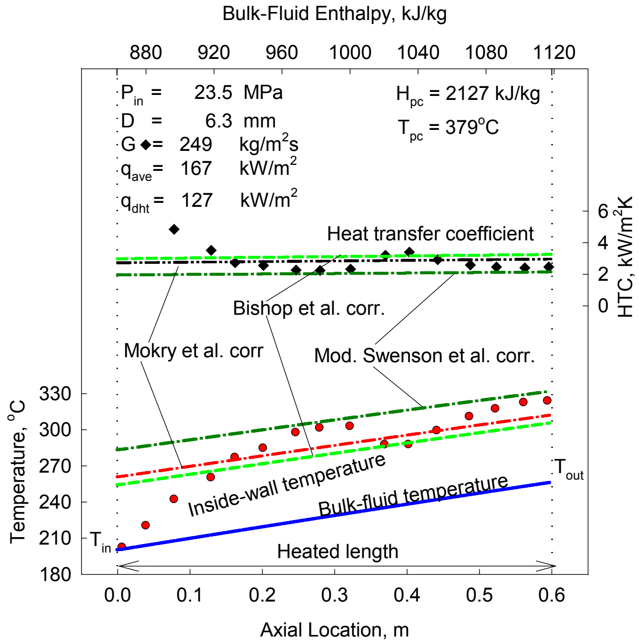


Figure 6: Temperature and HTC variations along vertical tube (0.6-m heated length and 6.3-mm ID): P_{in} = 23.5 MPa, G = 249 kg/m^{2}s, and q_{avg} = 167 kW/m^2 [14].

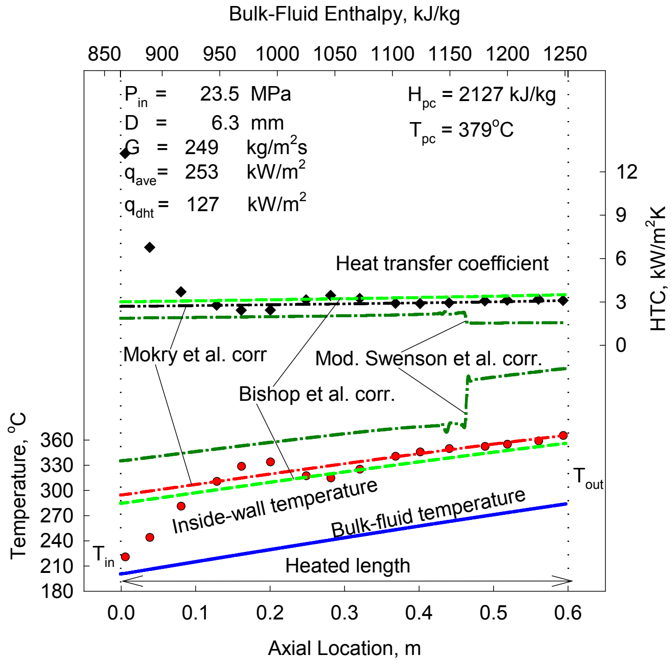


Figure 8: Temperature and HTC variations along vertical tube (0.6-m heated length and 6.3-mm ID): P_{in} = 23.5 MPa, G = 249 kg/m^{2}s, and q_{avg} = 253 kW/m^2 [14].

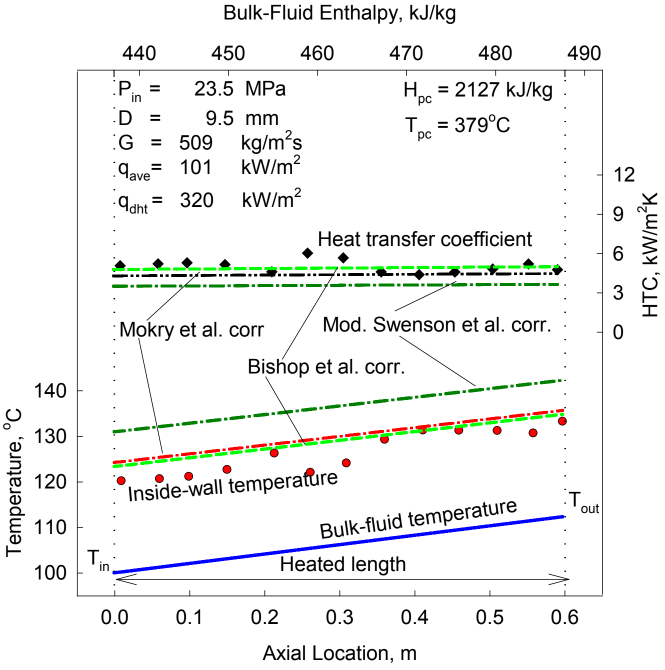


Figure 9: Temperature and HTC variations along vertical tube (0.6-m heated length and 9.5-mm ID): P_{in} = 23.5 MPa, G = 509 kg/m^{2}s, and q_{avg} = 101 kW/m^2 [14].

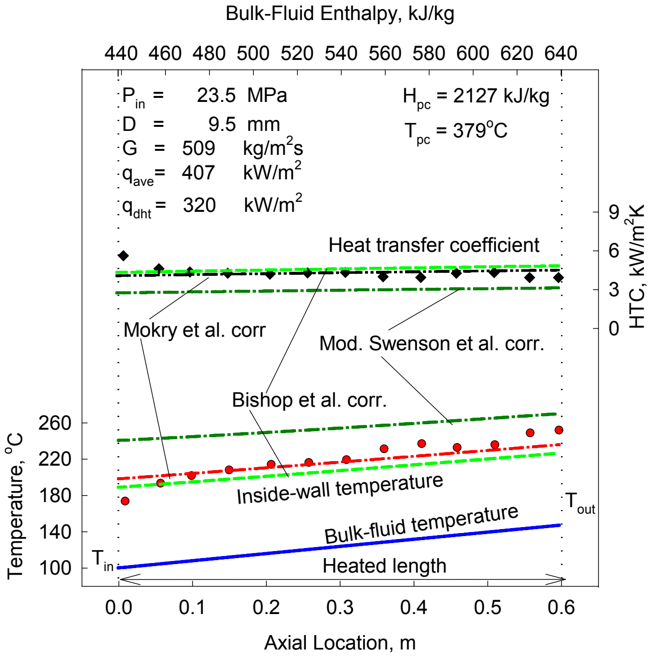


Figure 11: Temperature and HTC variations along vertical tube (0.6-m heated length and 9.5-mm ID): P_{in} = 23.5 MPa, G = 509 kg/m^{2}s, and q_{avg} = 407 kW/m^2 [14].

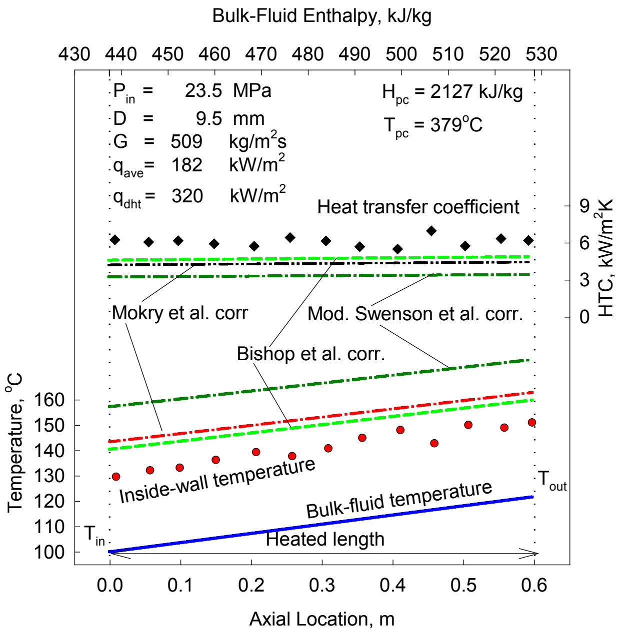


Figure 10: Temperature and HTC variations along vertical tube (0.6-m heated length and 9.5-mm ID): P_{in} = 23.5 MPa, G = 509 kg/m^{2}s, and q_{avg} = 182 kW/m^2 [14].

The next group of graphs is collected from multiple literature sources/authors to show how the correlations behave within a wider range of flow conditions as it is indicated in the captions.

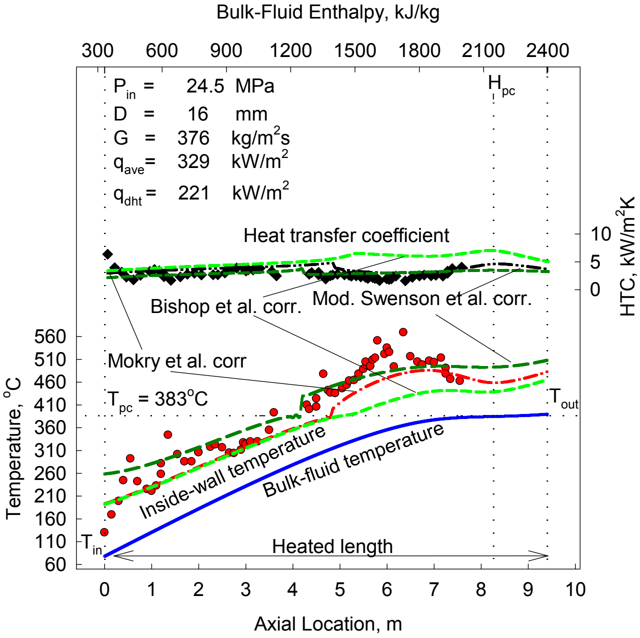


Figure 12: Temperature and HTC variations along vertical tube (9-m heated length and 16-mm ID): P_{in} = 24.5 MPa, G = 376 kg/m^{2}s, and q_{avg} = 329 kW/m^2 [15].

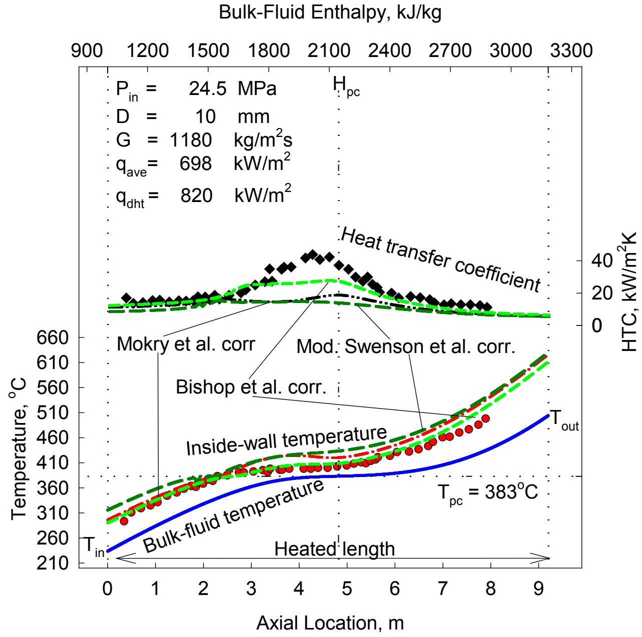


Figure 14: Temperature and HTC variations along vertical tube (9-m heated length and 10-mm ID): P_{in} = 24.5 MPa, G = 1180 kg/m^{2}s, and q_{avg} = 698 kW/m^2 [15].

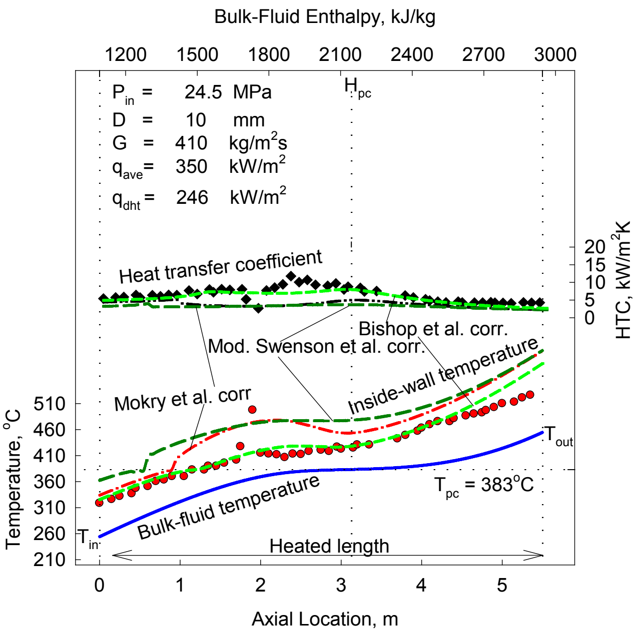


Figure 13: Temperature and HTC variations along vertical tube (5-m heated length and 10-mm ID): P_{in} = 24.5 MPa, G = 410 kg/m^{2}s, and q_{avg} = 350 kW/m^2 [15].

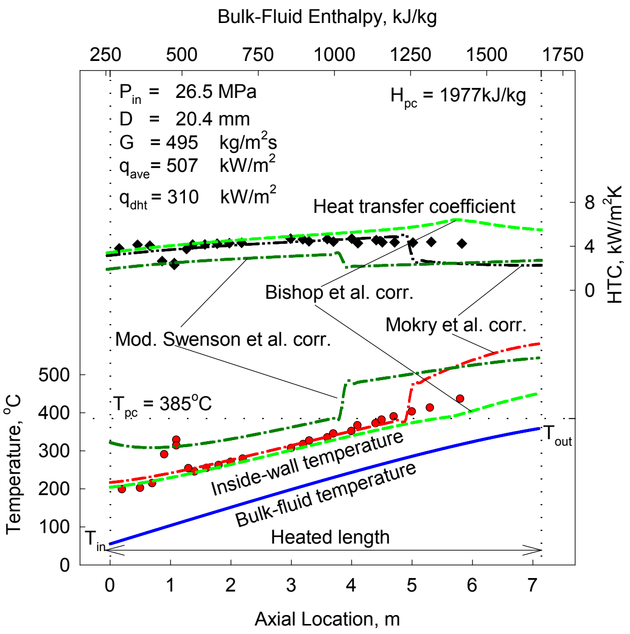


Figure 15: Temperature and HTC variations along vertical tube (7-m heated length and 20.4-mm ID): P_{in} = 26.5 MPa, G = 495 kg/m^{2}s, and q_{avg} = 507 kW/m^2 [16].

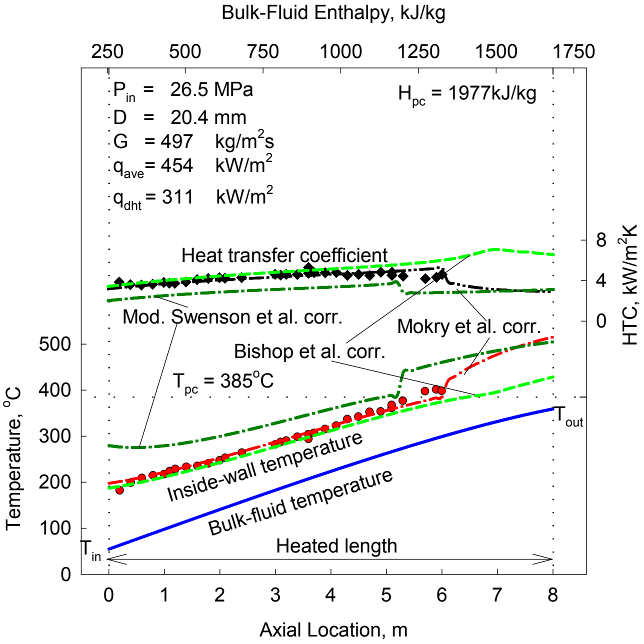


Figure 16: Temperature and HTC variations along vertical tube (8-m heated length and 20.4-mm ID): P_{in} = 26.5 MPa, G = 497 kg/m^{2}s, and q_{avg} = 454 kW/m^2 [16].

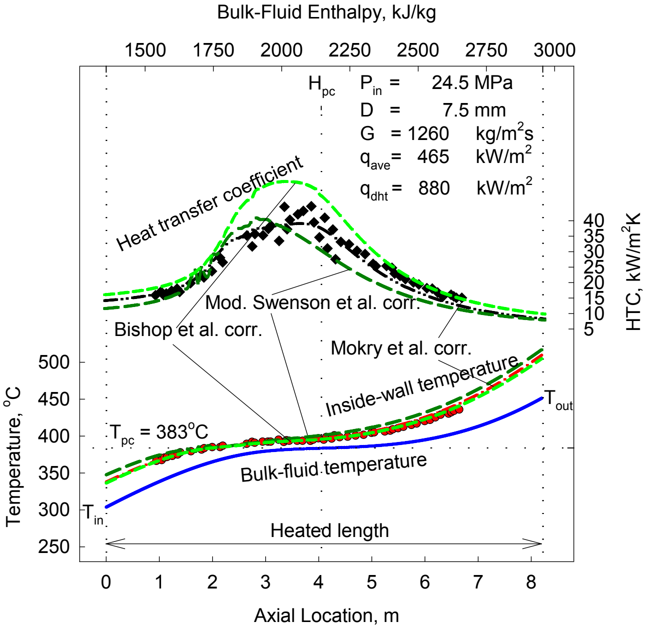


Figure 18: Temperature and HTC variations along vertical tube (8-m heated length and 7.5-mm ID): P_{in} = 24.5 MPa, G = 1260 kg/m^{2}s, and q_{avg} = 465 kW/m^2 [17].

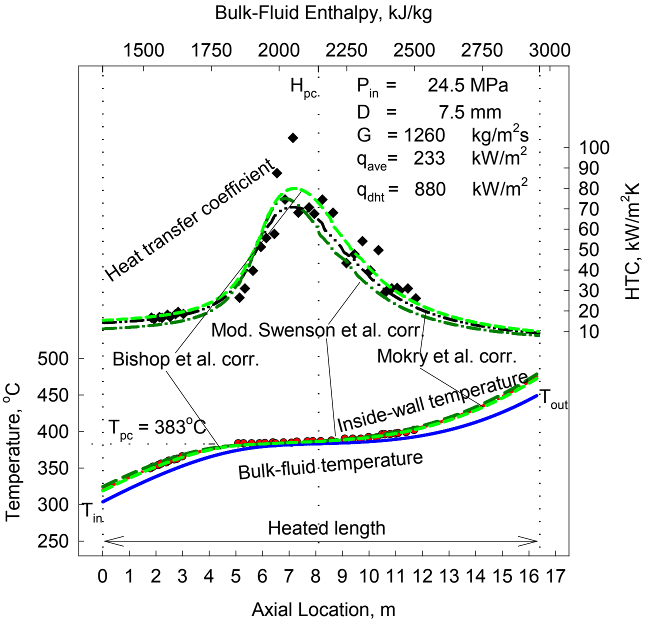


Figure 17: Temperature and HTC variations along vertical tube (16-m heated length and 7.5-mm ID): P_{in} = 24.5 MPa, G = 1260 kg/m^{2}s, and q_{avg} = 233 kW/m^2 [17].

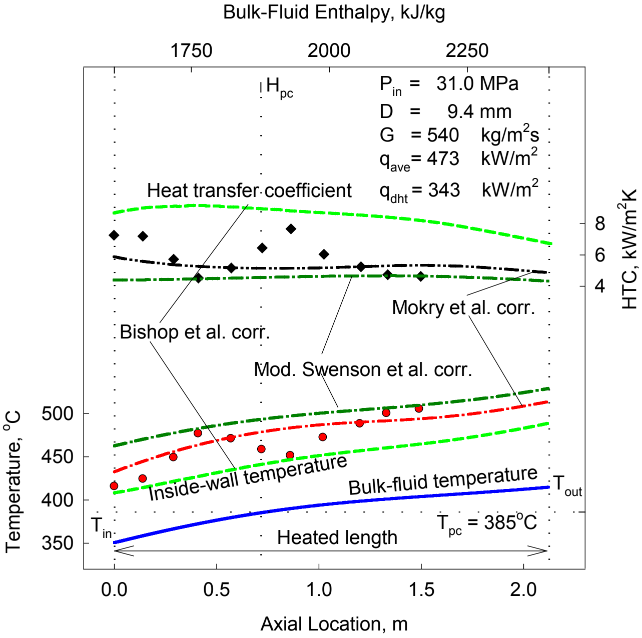


Figure 19: Temperature and HTC variations along vertical tube (2-m heated length and 9.4-mm ID): P_{in} = 31 MPa, G = 540 kg/m^{2}s, and q_{avg} = 473 kW/m^2 [18].

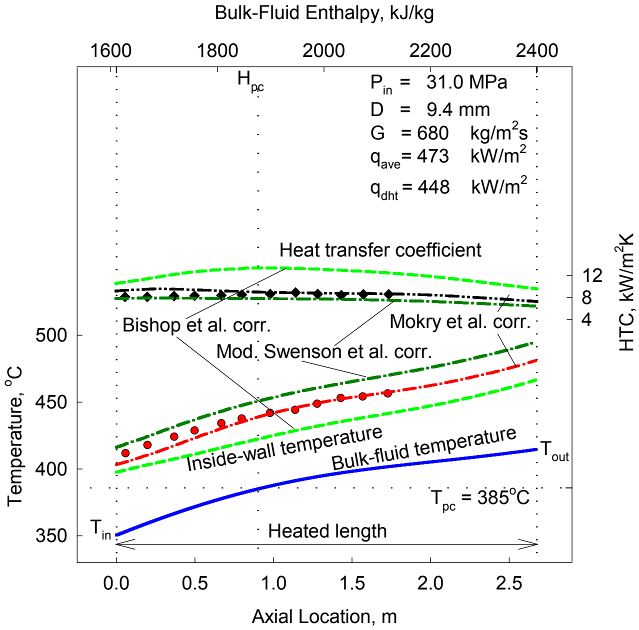


Figure 20: Temperature and HTC variations along vertical tube (2.5-m heated length and 9.4-mm ID): P_{in} = 31 MPa, G = 680 kg/m²s, and q_{avg} = 473 kW/m² [18].

3.3 Results

In general, the following trends were observed within the current comparison:

1) The Gupta et al. correlation is always more conservative in predicting wall-temperature values. The Mokry et al. correlation proved to be less conservative compared to the Gupta correlation, but usually provides a better fit for experimental data within the most operating conditions. The Bishop et al. correlation proved to be the least conservative with almost all predictions for wall temperature below the actual experimental values.
2) At a certain heat flux, i.e., usually at about a double value of the deteriorated heat flux, the Gupta et al. correlation deviates significantly from the experimental data, and some unexplained jumps in the calculated values were observed. The same phenomenon happens and for the Mokry et al. correlation, but at higher heat-flux values. As for the Bishop et al. correlation, no jumps occurred, but the deviation from experimental data increases with increasing heat-flux values.
3) It was found that the longer the tube is, the more accurate each correlation fits the experimental data.

4. Conclusions

In this paper, a comprehensive study of selected three heat-transfer correlations applicable for supercritical water flowing upward in vertical bare tubes has been conducted. A large dataset was collected from 33 papers by 27 authors including more than 125 graphs within wide-range experimental data. This dataset was investigated and analyzed. Heat transfer coefficients and wall temperatures were calculated using these three empirical correlations and compared to the experimental data.

These three empirical correlations used in the comparison are: 1) the Bishop et al. correlation, 2) the Mokry et al. correlation (modified Bishop et al.) and 3) the Gupta et al. (modified Swenson et al.) correlation.

The main objective of this paper was to select the best supercritical-water bare-tube correlation for HTC calculations in: 1) fuel bundles of SCWRs as a preliminary and conservative approach; 2) heat exchangers in case of indirect-cycle SCW NPPs; and 3) heat exchangers in case of hydrogen co-generation at SCW NPPs from SCW side.

The comparison shows that all three correlations predict the experimental data within a reasonable uncertainty at the normal and improved heat-transfer regimes and at lower heat and mass fluxes. However, within the pseudocritical region the Bishop et al. correlation deviates significantly from the experimental data. On the other hand, the Mokry et al. and Gupta et al. correlations show a significantly better fit within the most operating conditions. In the most cases studied, the Gupta et al. correlation showed more conservative approach than the Mokry et al. correlation by predicting lower heat transfer coefficients and corresponding to that higher temperature values.

Due to this, the modified Swenson et al. correlation could be the best candidate for development of heat-transfer correlations for bundles, since the HTC's in bundles are usually higher than those in tubes, because of heat-transfer enhancements due to appendages in bundles.

Future work on this topic includes correlating larger supercritical-water datasets with the proposed correlation, developing correlation(s) for modeling fluids (supercritical carbon dioxide and refrigerants), developing a correlation for supercritical-water bundle data, and developing a correlation for deteriorated heat-transfer regimes.

6. ACKNOWLEDGMENTS

Financial supports from the NSERC Discovery Grant and NSERC/NRCan/AECL Generation IV Energy Technologies Program (NNAPJ) are gratefully acknowledged.

7. NOMENCLATURE

$\bar{c}_p$	average specific heat, J/kg·K, $\left(\frac{H_w - H_b}{T_w - T_b}\right)$
D	diameter, m
G	mass flux, kg/m^{2}s
h	heat transfer coefficient, W/m^{2}K
H	enthalpy, J/kg
k	thermal conductivity, W/m·K
L	length, m
P	pressure, Pa
Q	heat transfer rate, W
q	heat flux, W/m^2
T	temperature, ^{o}C
x	axial location, m

<u>Greek letters</u>

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

<u>Dimensionless numbers</u>

Nu	Nusselt number $\left(\frac{h \cdot D}{k}\right)$
Pr	Prandtl number $\left(\frac{\mu \cdot c_p}{k}\right)$
$\overline{\mathbf{Pr}}$	averaged Prandtl number $\left(\frac{\mu_b\,\bar{c}_p}{k_b}\right)$
Re	Reynolds number $\left(\frac{G \cdot D}{\mu}\right)$

<u>Subscripts</u>

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

Abbreviations:

AECL	Atomic Energy Canada Limited
CANDU	CANada Deuterium Uranium (reactor)
DHT	Deteriorated Heat Transfer (regime)
GIF	Generation IV International Forum
HTC	Heat Transfer Coefficient
IHT	Improved Heat Transfer (regime)
KP-SKD	Pressure-tube nuclear reactor at supercritical pressure (in Russian abbreviations)
NIST	National Institute of Standards and Technology
NPP	Nuclear Power Plant
PT	Pressure Tube (reactor)
PV	Pressure Vessel (reactor)
PWR	Pressurized Water Reactor
RDIPE	Research & Development Institute of Power Engineering (Moscow)
SCW	SuperCritical Water
SCWR	SuperCritical Water Reactor

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