# COMPARISON OF SELECTED HEAT-TRANSFER CORRELATIONS FOR SUPERCRITICAL WATER FLOWING UPWARD IN VERTICAL BARE TUBES

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## Abstract

This paper presents an extensive study of selected heat-transfer correlations applicable to supercritical water flowing upward in vertical bare tubes. A comprehensive combined dataset was collected from 33 papers by 27 authors including more than 125 graphs within a wide range of parameters. These ranges are: pressures 22.5 – 34.5 MPa, inlet temperatures 85 – 350°C, mass fluxes 250 – 3400 kg/m$^2$s, heat fluxes 75 – 5400 kW/m$^2$ and tube lengths 0.6 – 27.4 m. This combined dataset was investigated and analyzed. Heat Transfer Coefficients (HTCs) and wall temperatures were calculated using several selected correlations and compared to the experimental data.

Two of the most widely used correlations and a more recently developed one were chosen for this comparison: modified Bishop et al. correlation (1964), Swenson et al. correlation (1965) and Mokry et al. correlation (2009). The main objective of the study was to find the best correlation for supercritical water heat transfer in bare tubes, which might also be used for preliminary calculations of fuel bundles as a conservative approach. The examined correlations are intended for normal and improved heat-transfer regimes.

The comparison shows that the Bishop et al. correlation deviates quite significantly from the experimental data within some flow conditions. On the other hand, the Swenson et al. and Mokry et al. correlations show a significantly better fit within most of the examined operating conditions.

## 1. Introduction

New Nuclear Power Plants (NPPs) with Generation-IV pressure-channel 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 [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 (374ºC and 22 MPa).

SuperCritical Water-cooled nuclear Reactors (SCWRs) are intended to increase the coolant pressure from the existing 10 – 16 MPa to about 25 MPa, the inlet temperature to about 350°C and the outlet temperature to 625°C. The coolant would pass through its pseudocritical point before reaching the channel outlet, and this may result in 3 regimes for forced-convective heat transfer to water: (1) Normal Heat-Transfer (NHT) regime characterized in general with Heat Transfer Coefficient (HTC) values similar to those of subcritical convective heat transfer far from 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 test section 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 test section compared to those of the NHT regime.

It should be noted that in general, most 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 values of mass flux.

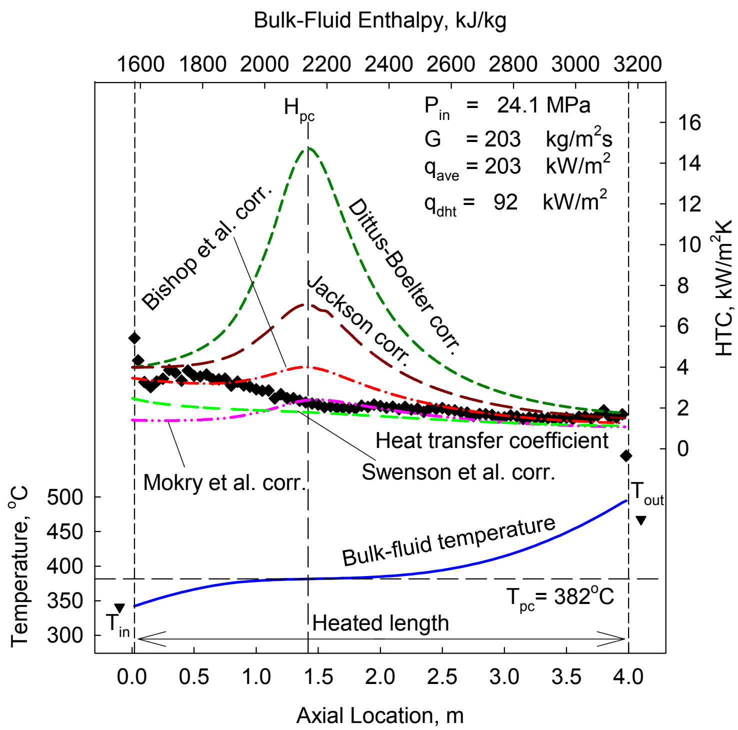


**Figure 1** Temperature and HTC variations along vertical tube (4-m heated length and 10-mm ID): $P_{in}$ = 24.1 MPa, $G$ = 203 kg/m$^2$s, $q_{ave}$ = 203 kW/m$^2$, and $q_{dht}$ = 92 kW/m$^2$ [6].

## 2. Existing correlations

Two of the most widely used correlations and the latest one were chosen for this comparison: 1) Bishop et al. correlation [14], 2) Swenson et al. correlation [15] and 3) Mokry et al. correlation [17]. All three of these correlations were obtained within the same range of operating conditions as those in SCWRs.

Bishop et al. [3], [14] 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 tubes were generalized using the following correlation with a fit of ±15%:

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

This correlation was proposed in the early nineteen-sixties when experimental techniques were not at the same (advanced) level as they are 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 – 25 MPa was not officially recognized until the nineties [3]).

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

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

Swenson et al. [3], [15] found that conventional correlations, i.e., correlations in which the majority of thermophysical properties are based on a bulk-fluid temperature, did not work well and they suggested the following correlation:

$$\mathrm{Nu_w} = 0.00459\,\mathrm{Re_w^{0.923}}\,\overline{\mathrm{Pr}}_\mathrm{w}^{0.613}\left(\frac{\rho_w}{\rho_b}\right)^{0.231} \quad (3)$$

Equation (3) was obtained within the following range: $P$ = 22.8 − 41.4 MPa, $G$ = 542 − 2150 kg/m$^2$s, $T_w$ = 93 − 649°C and $T_b$ = 75 − 576°C; and predicted experimental data within ±15%. Equation (3) provided a better fit for some experimental data than Equation (2). However, both of these correlations were obtained more than 45 years ago. Therefore, it was necessary to develop a new correlation, which would be based on latest experimental datasets.

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

$$\mathbf{Nu_b} = 0.0061\,\mathbf{Re_b^{0.904}}\,\overline{\mathbf{Pr}}_\mathbf{b}^{0.684}\left(\frac{\rho_w}{\rho_b}\right)^{0.564} \quad (4)$$

It should be noted again that these three correlations are used for predicting HTCs only at the NHT and IHT regimes and don't work at the DHT regime. For the DHT regime, an empirical correlation was proposed for heat-flux calculations at which the DHT regime appears (for details, see [7]):

$$q_{dht} = -58.97 + 0.745 \cdot G \text{, kW/m}^2 \quad (5)$$

## 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 ascending order with pressure first, and then mass and heat fluxes, respectively. The range of pressures used in this comparison was 24.1 – 26.5 MPa, mass fluxes 376 – 1260 kg/m$^2$s and heat fluxes 233 – 698 kW/m$^2$. Tube heated lengths and internal diameters varied widely also. A heat-flux value at which the DHT regime starts is shown in each graph for reference purposes.

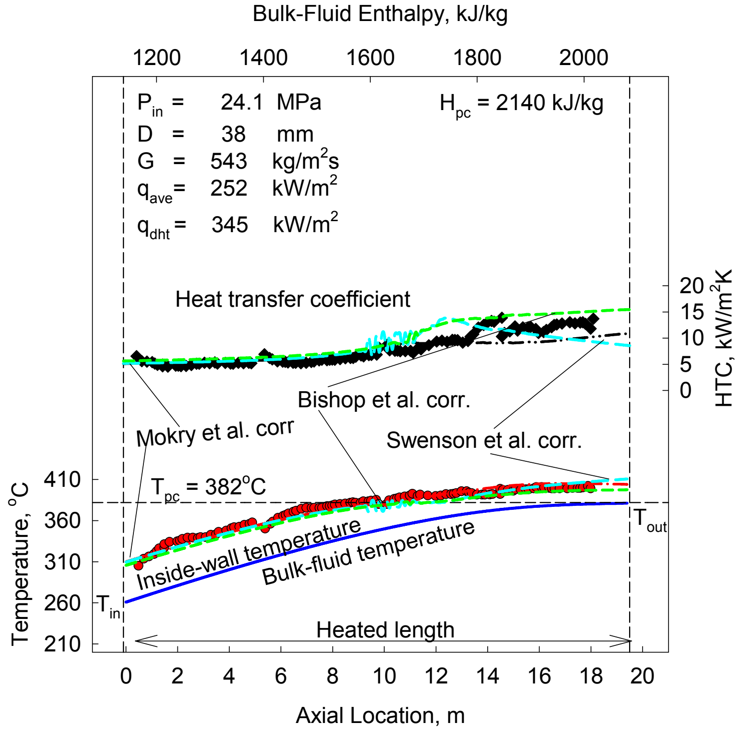


**Figure 2** Temperature and HTC variations along vertical tube (19-m heated length and 38-mm ID): $P_{in}$ = 24.1 MPa, $G$ = 543 kg/m$^2$s, and $q_{ave}$ = 252 kW/m$^2$ [8].

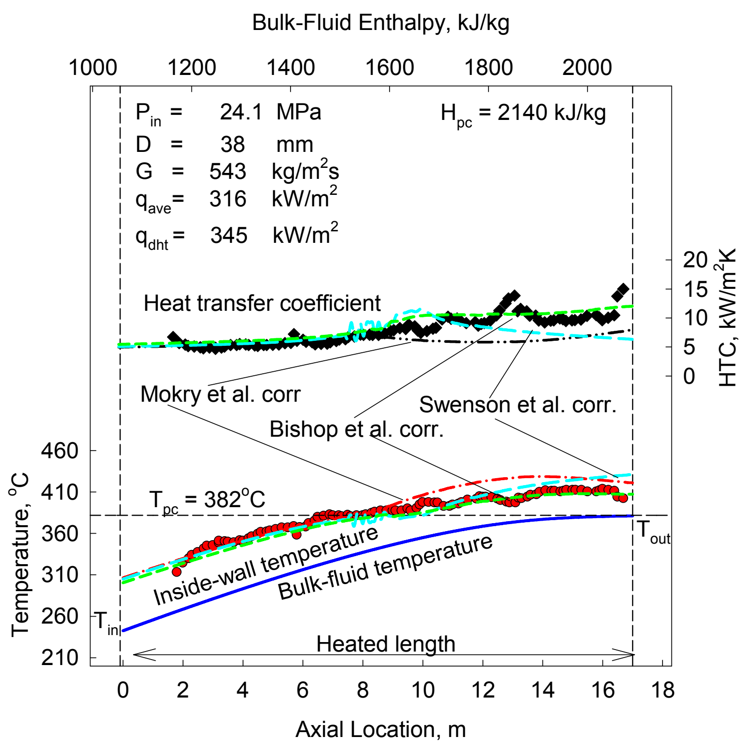


**Figure 3** Temperature and HTC variations along vertical tube (16-m heated length and 38-mm ID): $P_{in}$ = 24.1 MPa, $G$ = 543 kg/m$^2$s, $q_{ave}$ = 316 kW/m$^2$ [8].

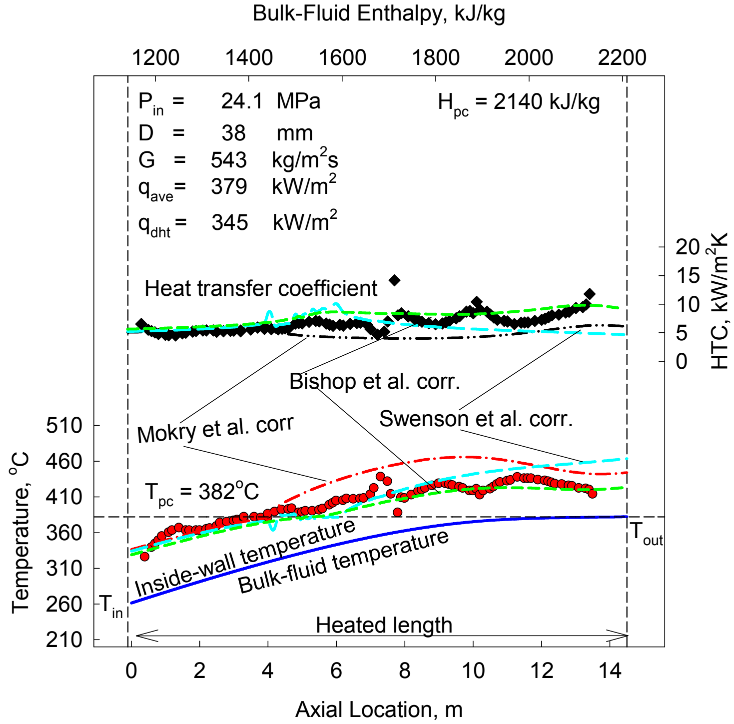


**Figure 4** Temperature and HTC variations along vertical tube (14-m heated length and 38-mm ID): $P_{in}$ = 24.1 MPa, $G$ = 543 kg/m$^2$s, and $q_{ave}$ = 379 kW/m$^2$ [8].

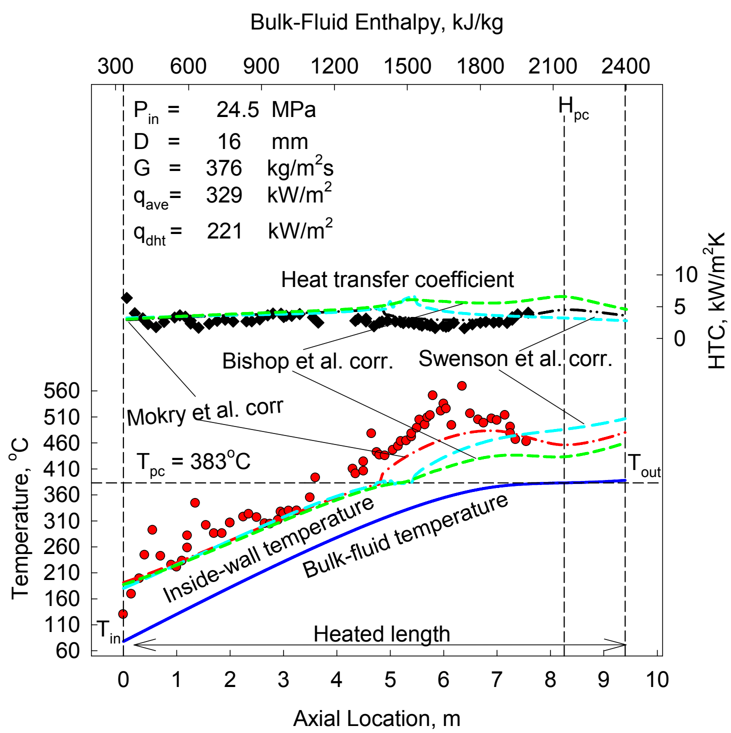


**Figure 5** Temperature and HTC variations along vertical tube (9-m heated length and 16-mm ID): $P_{in}$ = 24.5 MPa, $G$ = 376 kg/m$^2$s, and $q_{ave}$ = 329 kW/m$^2$ [9].

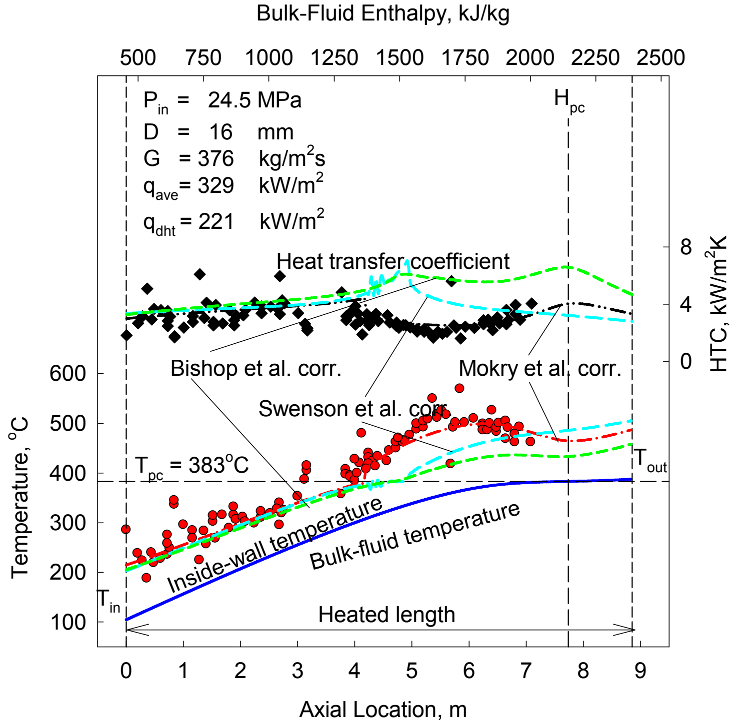


**Figure 6** Temperature and HTC variations along vertical tube (9-m heated length and 16-mm ID): $P_{in}$ = 24.5 MPa, $G$ = 376 kg/m$^2$s, and $q_{ave}$ = 329 kW/m$^2$ [9].

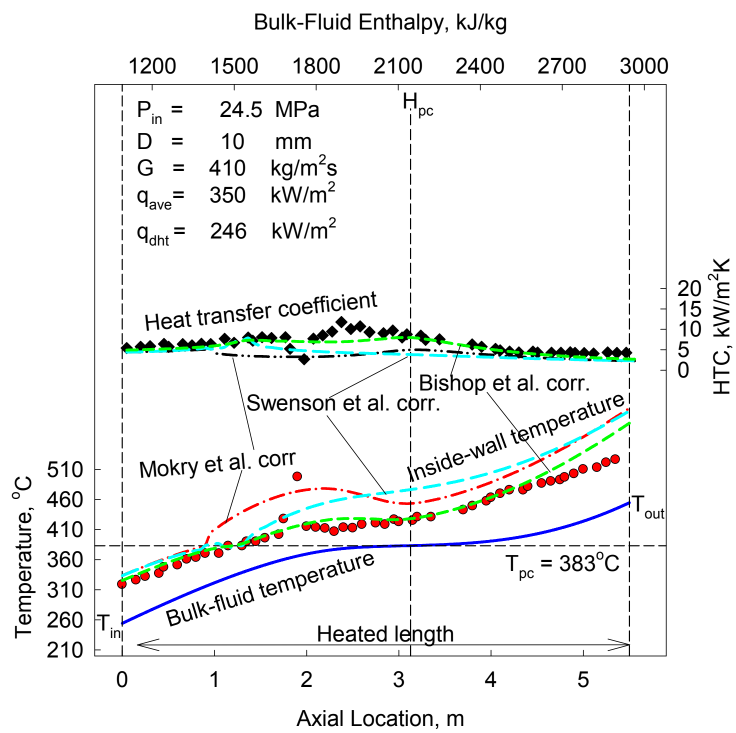


**Figure 7** Temperature and HTC variations along vertical tube (5-m heated length and 10-mm ID): $P_{in}$ = 24.5 MPa, $G$ = 410 kg/m$^2$s, and $q_{ave}$ = 350 kW/m$^2$ [9].

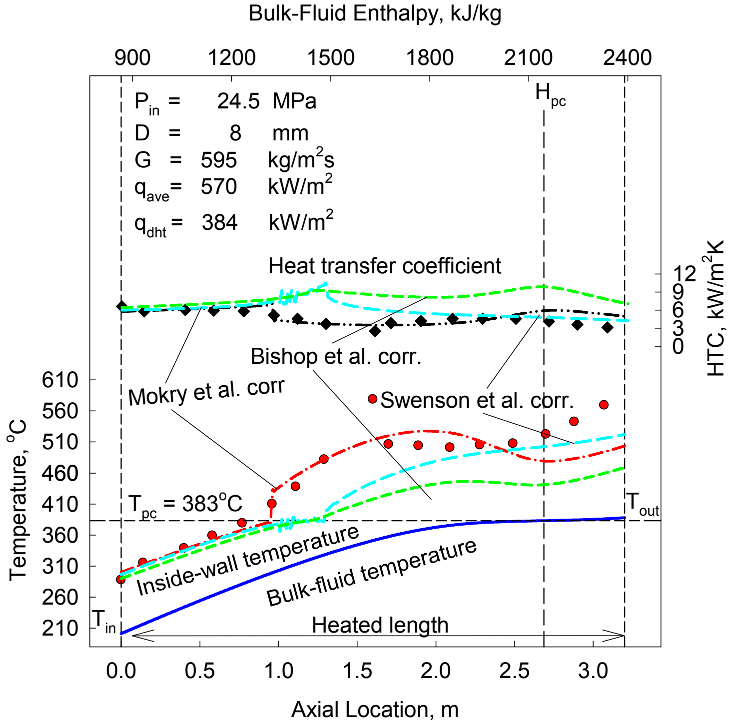


**Figure 8** Temperature and HTC variations along vertical tube (3-m heated length and 8-mm ID): $P_{in}$ = 24.5 MPa, $G$ = 595 kg/m$^2$s, and $q_{ave}$ = 570 kW/m$^2$ [10].

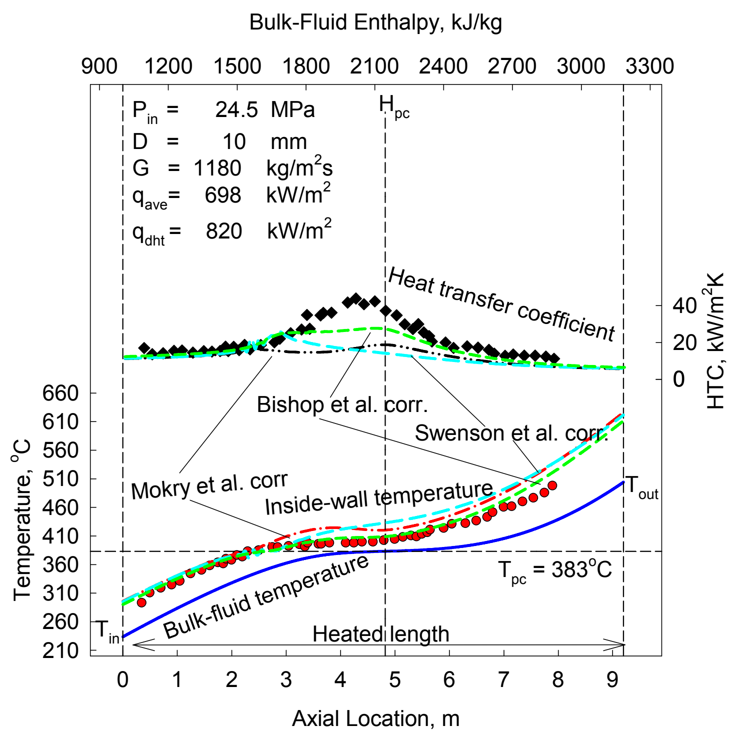


**Figure 9** Temperature and HTC variations along vertical tube (9-m heated length and 10-mm ID): $P_{in}$ = 24.5 MPa, $G$ = 1180 kg/m$^2$s, and $q_{ave}$ = 698 kW/m$^2$ [9].

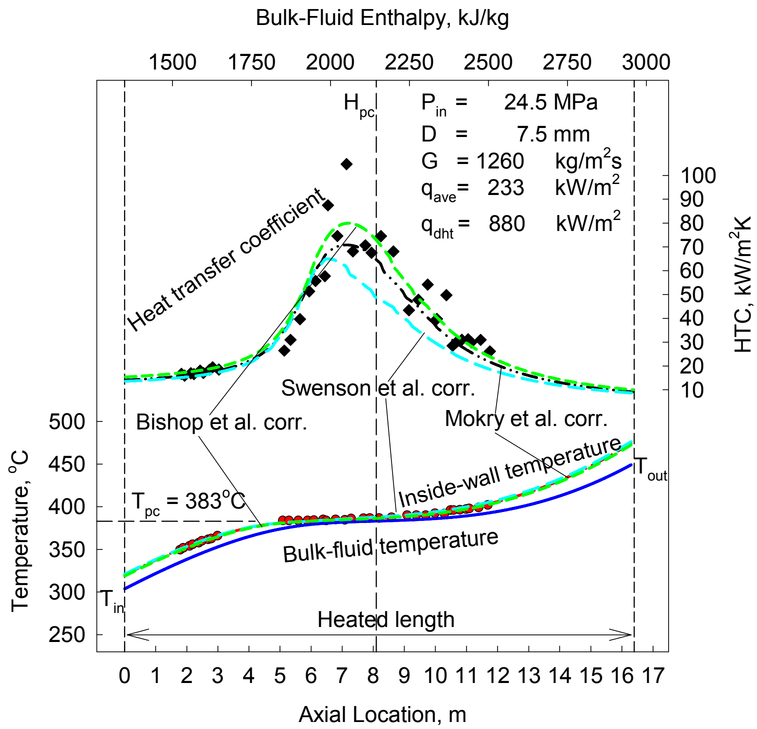


**Figure 10** Temperature and HTC variations along vertical tube (16-m heated length and 7.5-mm ID): $P_{in}$ = 24.5 MPa, $G$ = 1260 kg/m$^2$s, and $q_{ave}$ = 233 kW/m$^2$ [11].

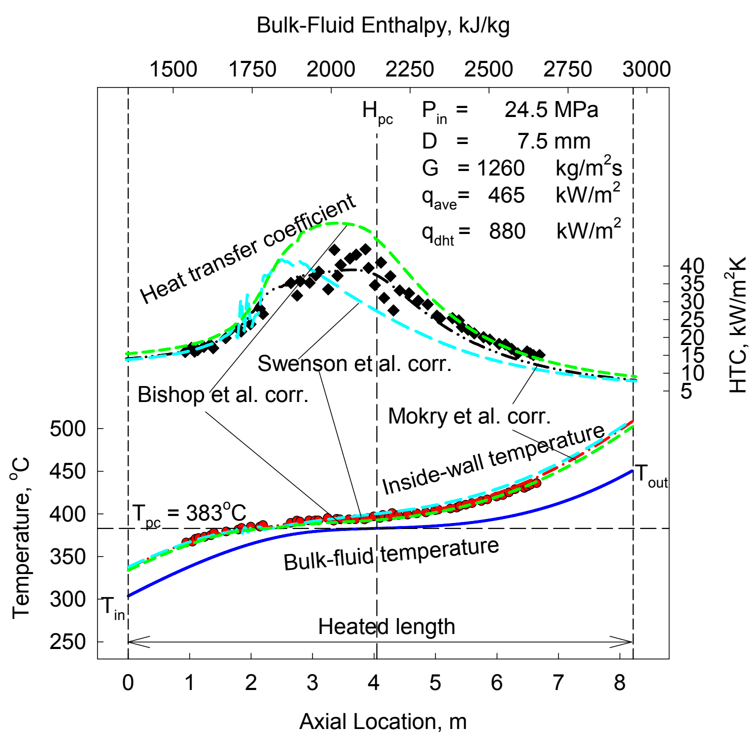


**Figure 11** Temperature and HTC variations along vertical tube (8-m heated length and 7.5-mm ID): $P_{in}$ = 24.5 MPa, $G$ = 1260 kg/m$^2$s, and $q_{ave}$ = 465 kW/m$^2$ [11].

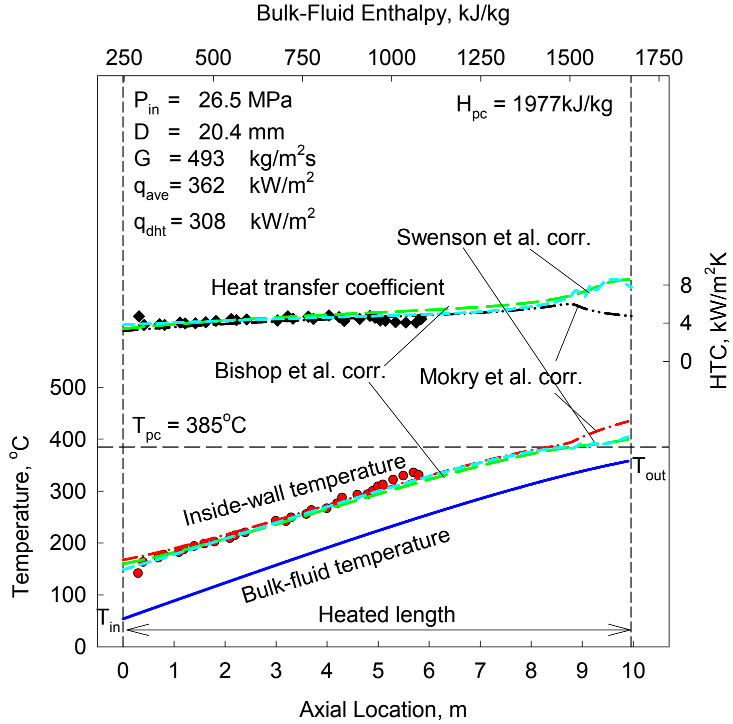


**Figure 12** Temperature and HTC variations along vertical tube (10-m heated length and 20-mm ID): $P_{in}$ = 26.5 MPa, $G$ = 493 kg/m$^2$s, and $q_{ave}$ = 362 kW/m$^2$ [12].

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

## 4. Conclusions

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

Three correlations were used in the comparison: 1) modified Bishop et al. correlation (1964), 2) Swenson et al. correlation (1965) and 3) Mokry et al. correlation (2009). The main objective of the study was to find the best correlation for supercritical-water heat transfer in bare tubes, which might also be used for preliminary calculations of fuel bundles, as a conservative approach.

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

## 5. Acknowledgements

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## 6. 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$^2$ |
| $R_a$ | surface roughness, µm |
| $T$ | temperature, $^o$C |
| $V$ | volume, m$^3$ |
| $x$ | axial location, m |

Greek letters

| | |
|---|---|
| $\mu$ | dynamic viscosity, Pa·s |
| $\rho$ | density, kg/m$^3$ |
| $\delta$ | thickness, mm |

Dimensionless numbers

| | |
|---|---|
| **Nu** | Nusselt number $\left(\frac{h \cdot D}{k}\right)$ |
| **Pr** | Prandtl number $\left(\frac{\mu \cdot c_p}{k}\right)$ |
| $\overline{\mathbf{Pr}}$ | Average 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 |
| calc | calculated |
| cr | critical |
| dht | deteriorated heat-transfer |
| exp | experimental |
| h | heated |
| hy | hydraulic |
| in | inlet |
| out | outlet |
| pc | pseudocritical |

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