Heat-Transfer Characteristics of SuperCritical Water Flowing Upward in Bare-Tubes

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Abstract

There has been many correlations developed for Supercritical Water (SCW) flowing in bare-tubes. These correlations, generally, have limits based on the experimental trials. However, this does not indicate the true range to which these correlations can be applied. Furthermore, increases in heat flux and decreases in mass flux have been known to lead to Deteriorated Heat-Transfer (DHT). One way to classify fluids in the supercritical region is to use the *Eckert Number* to differentiate between two different *sub-states*[1]; when $T < T_{pc}$, SCW is considered to be liquid-like, whereas at $T > T_{pc}$, SCW is considered to be gas-like. There is a significant decrease in RMS error for calculated HTC in trials where there is a single *sub-state* across the cross-section. Trials where there is a combination of *sub-states* have drastically higher RMS error for HTC. Furthermore, some trials indicate a decrease in HTC at the interphase between the two *sub-states*.

1. Introduction

One of the aims of SuperCritical Water Reactor (SCWR) designs is to increase thermal efficiency by operating primary side coolant at supercritical conditions (T_{cr} = 373.9°C; P_{cr} = 22.06 MPa) [1] [2] [3]. Proposed primary side operating parameters of current SCWR designs are [1] [3] [4]:

- P = 25 MPa
- T_{in} = 300 − 350°C
- T_{out} = 550 − 625°C

Unfortunately, drastic changes occur to SuperCritical Water's (SCW's) thermophysical properties as it crosses the pseudocritical point: $T_{pc@25\text{MPa}}$ = 384.9°C, which is located within the operating range [1] [2]. The pseudocritical point is a point at a $P > P_{cr}$, and at a temperature ($T > T_{cr}$) corresponding to the maximum value of specific heat at that particular pressure; i.e. a discontinuity region in the thermophysical properties [1]. SCW at $T < T_{pc}$ is considered to be in a liquid-like *sub-state*[1] whereas SCW at $T > T_{pc}$ is considered to be in a gas-like *sub-state*[1]. Due to the differences in the thermophysical properties of the two *sub-states*, there must be a change in the heat-transfer mechanism of the fluid.

At a given cross-section when the fluid is near the pseudocritical region, wall and bulk-fluid properties can diverge to two different *sub-states*. The *Eckert number* is a ratio that is used to determine the *sub-state* of the supercritical fluid.

[1] The term *sub-state* will be used to differentiate the supercritical state into liquid-like and vapor-like regions.

$$\boldsymbol{E} = \frac{T_{pc}-T_b}{T_w-T_b} \tag{1}$$

- If **E** > 1, then the supercritical fluid is assumed to be liquid-like over the cross section [6]. The specific heat is monotonic within the cross-section [7].
- If **E** < 0, then the supercritical fluid is assumed to be gas-like over the cross section [6]. The specific heat is monotonic within the cross-section [7].
- For 0 ≥ **E** ≥ 1, the fluid is assumed to be gas-like near the heated wall and liquid-like farther from the heated wall [6]. Here, there is a peak in the specific heat within the cross-section [7].

2. Determination of Experimental HTC

By applying heat balance to the test section, the axial step increase (dx set to 1 mm) in the coolant's bulk-fluid specific enthalpy can be determined [8].

$$h_{b(i+1)} = h_{b(i)} + \frac{q_{(i)} \cdot dx \cdot p_h}{A_{fl} \cdot G} \tag{2}$$

Given the bulk-fluid enthalpy profile across the test section, the bulk-fluid temperature profile can also be obtained. Since the coolant temperature at the wall is measured at about 80 points across the heated length, the experimental HTC at these axial positions can be determined.

$$\mathrm{HTC}_{exp} = \frac{q}{T_{w_o} - T_{b_{calc}}} \tag{3}$$

Thermophysical properties of water at each axial position were calculated according to inlet pressure and local bulk-fluid temperature using NIST REFPROP [2]. Pressure losses were considered to be negligible across the heat length.

3. Determination of Calculated HTC

Many studies in the last decade focused on heat-transfer to SCW in bare-tubes with diameters close to the hydraulic-equivalent diameter of proposed SCWR bundles [9]. Correlations such as Mokry et al. (2011) and Jackson (2002) are based on these data sets and are shown in Table 1 [9] [10].

Table 1. Summary of some HTC correlations.

	Correlation	Range
Jackson (2002) [10]	$\mathbf{Nu}_b = 0.0183 \cdot \mathbf{Re}_b^{0.82} \cdot \mathbf{Pr}_b^{0.5} \left(\frac{\rho_w}{\rho_b}\right)^{0.3} \left(\frac{\overline{c_p}}{c_{pb}}\right)^n$ $n = 0.4$; for $T_b < T_w < T_{pc}$; & $1.2 \cdot T_{pc} < T_b < T_w$ $n = 0.4 + 0.2\left(\frac{T_w}{T_{pc}} + 1\right)$; for $T_b < T_{pc} < T_w$ $n = 0.4 + 0.2\left(\frac{T_w}{T_{pc}} + 1\right)\left[1 - 5\left(\frac{T_b}{T_{pc}} - 1\right)\right]$; for $T_{pc} < T_b < 1.2 \cdot T_{pc}$; & $T_b < T_w$	Supercritical pressures
Mokry et al. (2011) [9]	$\mathbf{Nu}_b = 0.061 \cdot \mathbf{Re}_b^{0.904} \cdot \overline{\mathbf{Pr}}_b^{0.684} \left(\frac{\rho_w}{\rho_b}\right)^{0.564}$	P = 22.8 – 29.4 MPa G = 200 – 1500 kg/m^{2}s q = 70 – 1250 kW/m^2 D = 3 – 38 mm

4. Comparison of Calculated and Experimental HTC

By plotting the experimental HTC versus the HTC calculated using correlations shown in Table 1, the accuracy of the correlation can be illustrated. The *Eckert number* is used to categorize the HTC distribution, and to illustrate regions of weakness in for each correlations. Figure 1 & 2 show trials of low mass and heat flux from Kirillov et al. (2005) [11].

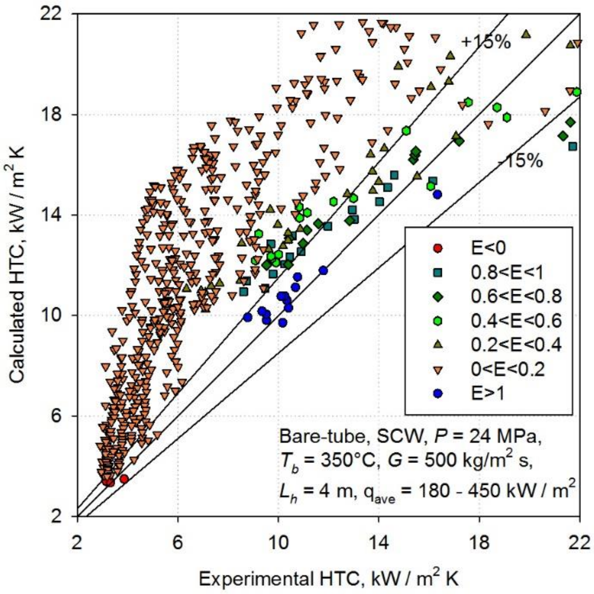

Figure 1. The experimental HTC versus the HTC calculated using Jackson (2002) separated for different *Eckert number* ranges

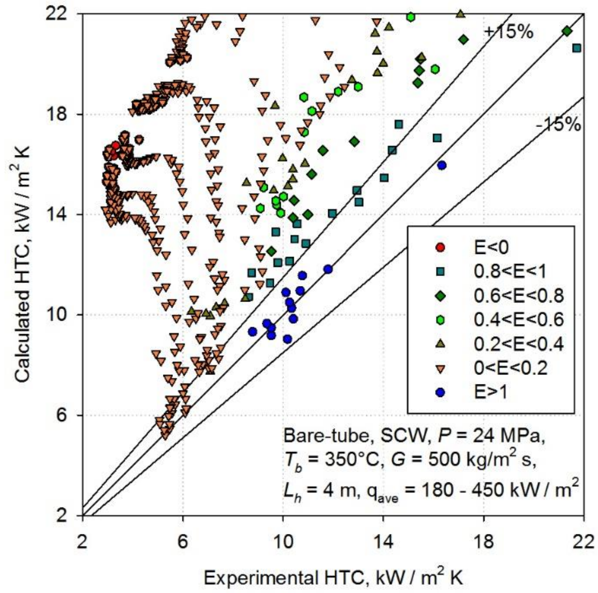

Figure 2. The experimental HTC versus the HTC calculated using Mokry et al. (2011) separated for different *Eckert number* ranges

The accuracy of the correlations illustrated in Figure 1 & 2 were directly dependent on the *Eckert number*. For $\mathbf{E} > 1$, the calculated HTC was within ±15% of the experimental HTC for both correlations, whereas for $\mathbf{E} < 0$, only Jackson (2002) was able to accurately predict HTC (within ±15%), as shown in Figure 1 & 2. It should be noted that Jackson (2002) uses three unique exponents for the specific heat ratio depending on the bulk-fluid, wall, and pseudocritical temperatures of the fluid, as shown in Table 1.

For $0 < \mathbf{E} < 1$, both correlations had difficulty in accurately predicting the HTC, especially as $\mathbf{E} \rightarrow 0$. Since Mokry et al. (2011) did not take into account the abrupt variations in the thermophysical properties around the pseudocritical point (by having unique exponents depending on the *sub-state* of the fluid), its ability to predict HTC diminished significantly as $\mathbf{E} \rightarrow 0$, as shown in Figure 2. However, since Jackson (2002) accounts for these variations, it was able to better predict HTC in the $0 < \mathbf{E} < 1$ region. Nevertheless, the accuracy of Jackson (2002) steadily decreased as $E \rightarrow 0$, as shown in Figure 1. It should be noted that no correlation was successful in predicating HTC at $0 < E < 0.2$.

Figure 3 & 4 show trials of high mass and heat flux from Kirillov et al. (2005) [11].

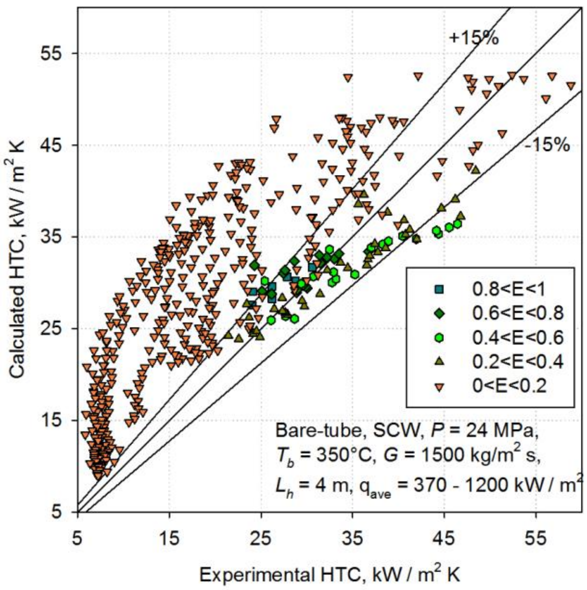

Figure 3. The experimental HTC versus the HTC calculated using Jackson (2002) separated for different *Eckert number* ranges

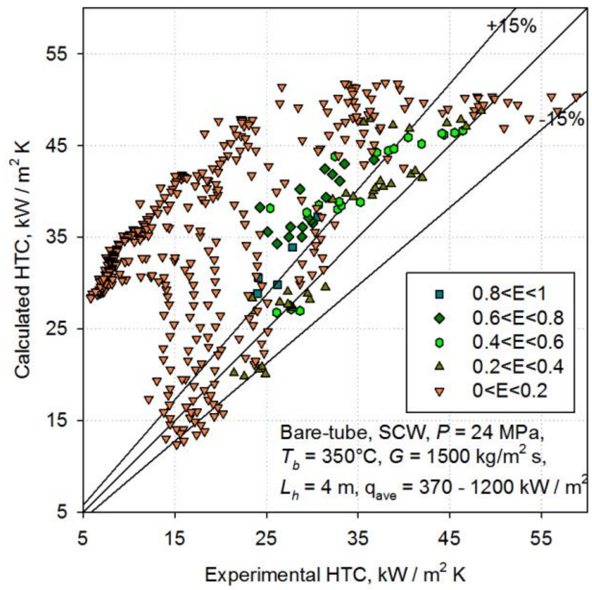

Figure 4. The experimental HTC versus the HTC calculated using Mokry et al. (2011) separated for different *Eckert number* ranges

Trials illustrated in Figure 3 & 4 did not have SCW at **E** < 0 and **E** > 1. Similar to Figure 1 & 2, both correlations had difficulty in accurately predicting HTC when 0 < **E** < 1, especially as **E** → 0. Again since Jackson (2002) accounts for variations of thermophysical properties at the critical point, it was more accurate in predicting HTC for 0.2 < **E** < 1 than Mokry et al. (2011), as shown in Figure 3 & 4. It should be noted that the accuracy of both correlations steadily decreased as **E** → 0 and that no correlation was successful in predicating HTC at 0 < E < 0.2.

5. Conclusion

Due to the abrupt changes in the thermophysical properties at the pseudocritical point, a single static correlation cannot be used predict HTC of a fluid for the entirety of the supercritical region. Rather adjustments should be made depending on the *sub-state* of the fluid in the cross-section, as indicated by the *Eckert number*, because heat-transfer to the fluid is characteristic of its *sub-state* in the supercritical region.

While Mokry et al. (2011) shows good results when predicting HTC for a simple and easy to use equation, a correction factor or different unique exponents should be introduced to better predict the HTC based on the *sub-state* of the fluid. That being said, even though Jackson (2002) uses differing exponents based on the *sub-state* of the coolant, as shown in Table 1, it still lacks the ability to accurately predict HTC when 0 < **E** < 0.2.

Since E → 0^+ means that $T_b \approx T_{pc}$, and since thermophysical properties vary significantly around that the pseudocritical point, this paper proposes to introduce another case (in addition to **E** > 0, **E** < 1, 0 < **E** < 1), where 0 < **E** < 0.2, to increase the accuracy of predicting HTC for a supercritical fluid.

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