Review Article

Review of the Wall Temperature Prediction Capability of Available Correlations for Heat Transfer at Supercritical Conditions of Water

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The validity of the wall temperature predictions by 18 correlations available in the literature for supercritical heat-transfer regimes of water was verified for 12 experimental datasets consisting of 355 data points available in the literature. The correlations were ranked based on criteria like % data with <5% error, % data with <10°C error and minimum error band in temperature prediction. Details of the best fitting correlations were tabulated. The analysis indicated that for normal heat-transfer conditions, most of the correlations give close predictions. However, at deteriorated heat transfer regimes, only very few prediction points are closer to experimental value. Also, in the ranking process, the first position keeps varying, and no one correlation shall be said as the best for all experiments. Evaluation of the applicability of heat flux to mass-flux-ratio-based prediction of heat-transfer deterioration indicated 75% agreement. The empirical formulae linking mass flux for the prediction of the starting heat flux for heat-transfer deterioration indicated 58.33% of agreement. This review indicated that continued precise experimentation covering wide range of parameter conditions near pseudocritical regime and development of correlations is felt necessary for the accurate prediction of supercritical fluid heat transfer.

1. Introduction

Many applications of supercritical fluids like power engineering, aerospace engineering, and refrigeration engineering have been mentioned in [1–15]. Water at supercritical conditions is largely used in fossil fuel fired boilers [5]. In order to increase the thermal efficiency of nuclear power plants, use of the supercritical water cooling for nuclear reactor is recommended by the Generation IV International Forum (GIF) [14]. Wide uses of supercritical water in power engineering have made the heat transfer of water at supercritical pressure very important and crucial because thorough understanding of the heat transfer is essential for the optimum design and safe operation of the equipment operating at supercritical fluid conditions.

Drastic changes in the properties of fluids at supercritical conditions have been discussed in [1, 3–5, 7, 8, 10–17]. Although supercritical water does not undergo phase change, it exhibits drastic changes in thermophysical properties that

influence heat transfer in a narrow band of temperature or enthalpy. This temperature or enthalpy at which the drastic change occurs is different for each pressure condition. The impact of these property variations on heat transfer has been discussed in [1–21]. As stated in [6], heat transfer to supercritical pressure water and steam was extensively investigated. Goldmann et al. found pseudoboiling phenomenon resembling nucleate boiling, while Shitsman et al. observed that the amount of deterioration depends on the inlet enthalpy and pressure. Ackerman et al. pointed out that a pseudofilm boiling phenomenon can occur in smooth-bore tubes when the pseudocritical temperature of the fluid is between the temperature of the bulk fluid and that of the heated surface. The investigation of Vikrev and Lokshin indicated that the deterioration in horizontal tubes is less than not so sharp as that occurring in vertical tubes for a comparable heat flux.

Shitsman [19] states that, with rising flow, independent of pressure and in proportion to the increase in the heat flux, the temperature distribution diverges more and more from

the respective theoretical curves which correspond with the usual formula given as follows for convective heat transfer:

$$\text{Nu} = 0.023\text{Re}^{0.8}\text{Pr}^{0.4}. \quad (1)$$

Many researchers have conducted experiments and published empirical correlations applicable for predicting the heat transfer at supercritical conditions of water. Each correlation is applicable for the specified range of operating parameters. The objective of the present study is to compare the prediction capability of various correlations for the experimental data available in the literature.

2. Thermophysical Properties of Fluids Near Pseudocritical Conditions

Heat transfer in convective heat transfer of fluids is influenced by their thermophysical properties for the given conditions. The drastic variations of thermophysical properties near pseudocritical temperatures make the prediction of heat transfer a difficult task. The thermophysical properties at any pressure and temperature or enthalpy condition for many fluids are well established and are provided by NIST/ASME steam property tables based on IAPWS 1997. This is especially important for the creation of generalized correlations in nondimensional form, which allows the experimental data for several working fluids to be combined into one set. The most significant thermophysical property variations occur near the critical and pseudocritical points [2, 7].

The thermophysical properties of water at different pressure and temperature, including the supercritical region, can be calculated using the NIST software (1996, 1997). Also, the latest NIST software (2002) calculates the thermophysical properties of different gases and refrigerants for wide ranges of pressure and temperature [7].

Figure 1 displays the trend of thermal conductivity, specific heat, density, and dynamic viscosity with increase in temperature for water at 230 bar taking the peak property in the temperature range as unity and the same at other temperatures as a ratio of the property at the given temperature to the peak value. It is seen that each property has a peak value at one particular temperature. This particular temperature above critical temperature at which the specific heat peaks is termed as pseudocritical temperature. For the selected 230 bar, the pseudocritical temperature is 377.63°C. The pseudocritical temperature keeps increasing with increase in pressure. With increase in pressure, the peaks in property variation come down. Near critical and pseudocritical temperatures, density and viscosity drop significantly, enthalpy and kinematic viscosity increases sharply, and specific heat, thermal conductivity, and Prandtl's number sharply peak and fall. Similar trends are observed in all other fluids.

3. Predictive Methods for Heat Transfer at Supercritical Pressures

Development of analytical models for predicting heat transfers in turbulent flow and at supercritical conditions was not successful due to the complex nature of flow and

the abrupt changes in fluid properties. Cheng et al. [8] have plotted the ratio of actual heat-transfer coefficient to heat-transfer coefficient calculated as per (1) with respect to fluid temperature. It is observed that the ratio peaks near pseudocritical temperature at low-heat fluxes, and the same is dipping near pseudocritical temperature at high-heat fluxes. If the Dittus and Boelter correlation is valid, the ratio would be constant at 1 throughout the temperature range. The peaks and dips indicate heat-transfer enhancement and deterioration and the heat-transfer behavior at supercritical condition is different. The wall temperature increase due to the deterioration in heat-transfer coefficient is smooth compared to abrupt increase that is taking place due to boiling crisis in subcritical pressures, and, hence, there is no unique definition for the onset of heat-transfer deterioration so far. For the prediction of heat transfer under such complex conditions, conducting experiments and developing empirical correlations of nondimensional numbers are followed.

Most of the empirical correlations have the general form of a modified Dittus and Boelter equation [8] as given in the following:

$$\text{Nu}_x = C\text{Re}_x^m\text{Pr}_x^n F. \quad (2)$$

The correction factor F takes into account the effect of property variation and the entrance effect; that is, F is a function of $\{(\rho_w/\rho_b), ((Cp)_{av}/Cp), (L/D)\}$.

A more detailed general form of correlations for calculating heat transfer at super-critical pressures in water and other fluids is given as follows [7]:

$$\begin{aligned} \text{Nu}_{t,x} = C_1 \text{Re}_{t,x}^{m_1} \text{Pr}_{t,x}^{m_2} \left(\frac{\rho_t}{\rho_x} \right)_x^{m_3} \left(\frac{\mu_t}{\mu_x} \right)_x^{m_4} \left(\frac{k_t}{k_x} \right)_x^{m_5} \\ \times \left(\frac{(Cp)_{av,t}}{Cp_t} \right)_x^{m_6} \left(1 + C_2 \left(\frac{D_{hy}}{L_h} \right)_x \right)^{m_7}. \end{aligned} \quad (3)$$

The subscript “ t ” in (3) refers to either wall temperature or bulk fluid temperatures or average of wall and bulk fluid temperature or their combinations. Around 18 such equations proposed by various authors as given in [1, 3–5, 7, 8, 11, 12, 15, 19, 20] are listed as (B.1) to (B.18) in Table 1.

4. Comparison of the Wall Temperature Predictions of Different Correlations

In order to evaluate the prediction capability of the various correlations listed in Table 1, the wall temperature data along with the operating conditions given in the literature [3, 7, 10, 12, 14, 15, 18] were used. Twelve experimental wall temperature datasets available in these literatures were considered. The test parameters and tube inner diameter applicable for each graph were collected. An excel macroprogram was developed for computing wall temperature as per different correlations. X steam excel version of IAPWS 1997 was used for steam properties. Wall temperatures for these experimental conditions containing 355 data points were calculated using 18 correlations. Absolute and percentage temperature deviations of prediction by each correlation for

TABLE 1: List of correlations used for comparing supercritical water heat transfer in vertical pipe.

Equation no.	Name of correlation	Correlation	Conditions
Equation (B.1)	Dittus and Boelter (1930)	$Nu_b = 0.023 Re_b^{0.8} Pr_b^{0.4}$ [8, 13, 19].	Valid for fully developed turbulent flow in smooth tubes for fluid with Prandtl numbers ranging from about 0.6 to 100 and with moderate temperature difference between wall and fluid conditions.
Equation (B.2)	Mc Adams (1942)	$Nu_b = 0.0243 Re_b^{0.8} Pr_b^{0.4}$ [5, 7, 13, 15].	Modified version of (B.1) used for supercritical condition.
Equation (B.3)	Bringer and Smith (1957)	$Nu_x = 0.0266 Re_x^{0.77} Pr_w^{0.55}$ [5, 7].	Nu_x and Re_x are evaluated at t_x . Temperature t_x is defined as t_b if $(t_{pc} - t_b)/(t_w - t_b) < 0$, as t_{pc} if $0 \leq (t_{pc} - t_b)/(t_w - t_b) \leq 1$, and as t_w if $(t_{pc} - t_b)/(t_w - t_b) > 1$ for supercritical water up to $p = 34.5$ MPa.
Equation (B.4)	Shitsman (1959, 1974)	$Nu_b = 0.023 Re_b^{0.8} Pr_{min}^{0.8}$ [5, 7, 19].	“min” means minimum Pr value, that is, either the Pr value is evaluated at the bulk fluid temperature or the Pr value is evaluated at the wall temperature, whichever is less. Assumption: thermal conductivity is a smoothly decreasing function of temperature near the critical and pseudo-critical points.
Equation (B.5)	Bishop et al. (1964)	$Nu_b = 0.0069 Re_b^{0.9} (Pr)_{av}^{0.66} (\rho_w/\rho_b)^{0.43} (1 + 2.4 (D/x))$ [5, 7, 8, 11, 13, 15].	x is the axial location along the heated length. Pressure = 22.8–27.6 MPa, and bulk fluid temperature = 282–527°C. Mass flux = 651–3662 kg/m ² s, and heat flux = 0.31–3.46 MW/m ² .
Equation (B.6)	Swenson et al. [1]	$Nu_w = 0.00459 Re_w^{0.923} (Pr_w)_{av}^{0.613} (\rho_w/\rho_b)^{0.231}$ $hD/k_w = 0.00459 (GD/\mu_w)^{0.923} [((H_w - H_b)(\mu_w))/((T_w - T_b)(k_w))]^{0.613} (\rho_w/\rho_b)^{0.231}$ [1, 5–8, 10, 15, 21]. $Nu = Nu_0 (\rho_w/\rho_b)^{0.3} [(Cp)_{av}/Cp_b]^n$, where, according to Petukhov and Kirillov (1958), $Nu_0 = [(\xi/8) Re_b (Pr)_{av}]/[12.7 \text{ Sqrt}(\xi/8) ((Pr)_{av}^{(2/3)} - 1) + 1.07]$ and $\xi = 1/(1.82 \log_{10} Re_b - 1.64)^2$.	Pressure = 22.8–41.4 MPa, and bulk fluid temperature = 75–576°C. Mass flux = 542–2150 kg/m ² s. Assumption: thermal conductivity is a smoothly decreasing function of temperature near the critical and pseudo-critical points.
Equation (B.7)	Krasnoshchekov et al. (1967)	Later, Krasnoshchekov et al. (1971) added a correction factor to the above equation for the tube entrance region in the form of $f(x/D) = 0.95 + 0.95(x/D)^{0.8}$. Also, this correction factor can be used for a heated tube abrupt inlet within $2 \leq x/D \leq 15$ [10].	Exponent $n = 0.4$ at $T_w/T_{pc} \leq 1$ or $T_b/T_{pc} > 1.2 \leq 1$, $n = n_1 + 0.18 T_w/T_{pc}$ at $1 \leq T_w/T_{pc} \leq 2.5$, and $n = n_1 + (5 \cdot n_1 - 2) \times (1 - T_b/T_{pc})$ at $1 \leq T_b/T_{pc} \leq 1.2$. Valid within the following range: $8 \times 10^4 < Re_b < 5 \times 10^5$, $0.85 < (Pr_b)_{av} < 65$, $0.90 < (\rho_w/\rho_b) < 1.0$, $0.02 < (Cp)_{av}/Cp_b < 4.0$, $0.9 < T_w/T_{pc} < 2.5$, $4.6 \times 10^4 < q < 2.6 \times 10^6$, where q is in W/m ² and $x/D \geq 15$ [5–8].
Equation (B.8)	Kondrat'ev [20]	$Nu_b = 0.020 Re_b^{0.8}$ [5, 7, 20].	Valid within the range of $10^4 < Re < 4 \times 10^5$ and $t_b = 130$ – 600°C . This equation is not valid within the pseudo-critical region.
Equation (B.9)	Ornatsky et al. (1970)	$Nu_b = 0.023 Re_b^{0.8} Pr_{min}^{0.8} (\rho_w/\rho_b)^{0.3}$ [5, 7].	Pr_{min} is in the minimum value of Pr_w or Pr_b .
Equation (B.10)	Yamagata et al. [3]	$Nu_b = 0.0135 Re_b^{0.85} Pr_b^{0.8} F_c$ [3, 5, 7, 8].	$F_c = 1$ for $E > 1$, $F_c = 0.67 Pr_{pc}^{-0.05} ((Cp)_{av}/Cp_b)^{n1}$ for $0 \leq E \leq 1$, $F_c = ((Cp)_{av}/Cp_b)^{n2}$ for $E < 0$, $E = (T_{pc} - T_b)/(T_w - T_b)$, $n1 = -0.77 (1 + (1/Pr_{pc})) + 1.49$, $n2 = -1.44 (1 + (1/Pr_{pc})) - 0.53$. Pressure = 226–294 bar, and bulk fluid temperature = 230–540°C. Mass flux = 310–1830 kg/m ² s, heat flux = 116–930 kW/m ² .

TABLE 1: Continued.

Equation no.	Name of correlation	Correlation	Conditions
Equation (B.11)	Watts and Chou et al. (1982)	$\text{For } (Gr_b)_{av}/(Re_b^{2.7}(Pr_b)_{av}^{0.5}) \leq 10^{-4},$ $Nu/Nu_{varp} = [1-3000(Gr_b)_{av}/(Re_b^{2.7}(Pr_b)_{av}^{0.5})]^{0.295}.$ $\text{For } (Gr_b)_{av}/(Re_b^{2.7}(Pr_b)_{av}^{0.5}) \geq 10^{-4},$ $Nu/Nu_{varp} = [7000(Gr_b)_{av}/(Re_b^{2.7}(Pr_b)_{av}^{0.5})]^{0.295}$ $[4, 11].$	$Nu = \alpha D/\lambda_b,$ $Nu_{varp} = 0.021 Re_b^{0.8} (Pr_b)_{av}^{0.55} (\rho_w/\rho_b)^{0.35},$ $(Gr_b)_{av} = [\rho_b(\rho_b - \rho_{av})gD^3]/\mu_b^2,$ $Re_b = GD/\mu,$ $(Pr_b)_{av} = Cp_{av} \mu_b/\lambda_b,$ $Cp_{av} = (H_w - H_b)/(T_w - T_b).$ $\rho_{av} = [\text{Integral } (\rho dT)] \text{ with limits } T_w \text{ and } T_b/[T_w - T_b]$
Equation (B.12)	Gorban et al. (1990)	$Nu_b = 0.0059 Re_b^{0.90} Pr_b^{-0.12}$ $[5, 7].$	
Equation (B.13)	Griem (1996)	$Nu_b = 0.0169 Re_b^{0.8356} Pr_b^{0.432}$ $[5, 7, 8].$	<p>It covers the entire enthalpy range due to a new method for determining a representative specific heat capacity. Heat capacities were computed with semiempirical equations at five reference temperatures.</p> $m = 0.69 - 81000/q_{dht} + f_c q.$ <p>The heat flux (q_{dht}) is that at which deterioration-rated heat transfer occurs (W/m^2).</p> <p>The heat flux is calculated according to $q_{dht} = 200 G^{1.2}$.</p> <p>The coefficient f_c is calculated according to</p> $f_c = 29 \times 10^{-8} + 0.11/q_{dht} \text{ for } 0 \leq H_b \leq 1500 \text{ kJ/kg},$ $f_c = -8.7 \times 10^{-8} - 0.65/q_{dht} \text{ for } 1500 \leq H_b \leq 3300 \text{ kJ/kg},$ $f_c = -9.7 \times 10^{-7} - 1.30/q_{dht} \text{ for } 3300 \leq H_b \leq 4000 \text{ kJ/kg}.$ <p>Valid for T_b from 20°C to 550°C (bulk fluid enthalpy from 100 to 3300 kJ/kg), G from 100 to 1750 kg/m²s, and q from 0 to 1.8 MW/m².</p> <p>Exponent</p> $n = 0.4 \text{ for } T_b < T_w < T_{pc} \text{ and for } 1.2 T_{pc} < T_b < T_w,$ $n = 0.4 + 0.2 ((T_w/T_{pc}) - 1) \text{ for } T_b < T_{pc} < T_w,$ $n = 0.4 + 0.2 ((T_w/T_{pc}) - 1) [1 - 5((T_b/T_{pc}) - 1)] \text{ for } T_{pc} < T_b < 1.2 T_{pc}, \text{ and } T_b < T_w.$ <p>T_b, T_{pc}, and T_w are in K.</p> <p>Valid for forced convection heat transfer in water and carbon dioxide at supercritical pressures.</p>
Equation (B.14)	Kitoh et al. (1999)	$Nu_b = 0.015 Re_b^{0.85} Pr_b^m$ $[5, 7, 10].$	
Equation (B.15)	Jackson (2002)	$Nu_b = 0.0183 Re_b^{0.82} (Pr_b)_{av}^{0.5} (\rho_w/\rho_b)^{0.3}$ $[(Cp)_{av}/Cp_b]^n$ $[5-7, 11, 15].$	<p>Fluidfreon, HFC134a.</p> <p>Pressure: 4.1 to 4.5 MPa, mass flux: 600 to 2000 kg/m²s, and heat flux: up to 160 kW/m².</p> <p>Pressure: 90–300 bar, mass flux: 600–1200 kg/m²s, and heat flux: 200–600 kW/m².</p> <p>Pressure: 24 MPa, inlet fluid temperature: 320–350°C, mass flux: 200–1500 kg/m²s, and heat flux $\leq$ 1250 kW/m².</p>
Equation (B.16)	Kang and Chang et al. [11]	$Nu_b = 0.0244 Re_b^{0.762} Pr_{av}^{0.552} (\rho_w/\rho_b)^{0.0293}$ $[11].$	
Equation (B.17)	Zhu et al. [12]	$Nu_b = 0.0068 Re_b^{0.90} (Pr_b)_{av}^{0.63}$ $(\rho_w/\rho_b)^{0.17} (k_w/k_b)^{0.29} [12].$	
Equation (B.18)	Mokry et al. [15]	$Nu_b = 0.0061 Re_b^{0.904} (Pr_b)_{av}^{0.684}$ $(\rho_w/\rho_b)^{0.564} [15].$	

each point in the graph were calculated with experimental wall temperature as base. The correlations were ranked based on criteria like % predictions with <5% error, % predictions with <10°C error, and minimum deviation in temperature prediction for the selected dataset. The trend of wall temperature predicted by the best fitting correlation was plotted along with experimental temperature. Details of the best fitting correlation were tabulated. The observations are given below.

4.1. Experiments of Vikhrev et al. (1967) [7, 18]. Figures 2 and 3 display the trends of inner wall temperatures calculated by the best fitting correlations along with reference experimental

wall temperatures for two different operating conditions given in [7, 18]. Table 2 details the parameter conditions and the comparative information on the predicted wall temperature of the best fitting correlation with reference to the experimental wall temperature.

The experimental wall temperature trend seen in Figure 2 indicates heat-transfer deteriorations at two locations: one near the entry and the other near the exit at locations where the fluid temperatures are well below the pseudocritical temperature. No deterioration phenomenon is predicted even by the best fitting correlation. Similarly, the smooth drop in wall temperature occurring well before pseudocritical temperature and the sudden peaking of wall temperature at a fluid temperature of 387.6°C just before pseudocritical

TABLE 2: Consolidated details of all experimental data and the best fitting correlations for the cases with deteriorated heat transfer.

Sl. no.	Parameter	Vikhrev et al. [18] Dataset 1 (Figure 2)	Vikhrev et al. [18] Dataset 2 (Figure 3)	Zhu et al. [12] Dataset 1 (Figure 8)	Zhu et al. [12] Dataset 2 (Figure 9)	Mokry et al. [15] Dataset 1 (Figure 10)	Wang et al. [14] Dataset 1 (Figure 12)	Wang et al. [14] Dataset 2 (Figure 13)
01	Tube ID (mm)	20.4	20.4	26	26	10	19.8	26
02	Pressure (bar (a))	265	265	260	300	241	250	260
03	Heat flux (kW/m^2)	570	1160	300	300	148	660	350
04	Mass flux ($\text{kg/m}^2\text{s}$)	495	1400	600	600	201	1200	600
05	Heat flux to mass flux ratio (kJ/kg) [5]	1.152	0.829	0.5	0.5	0.736	0.55	0.583
06	Limiting heat flux to avoid deterioration (kW/m^2) [3, 15]	342.4, 309.8	1192, 984	431.3, 388	431.3, 388	116, 90.7	990.9, 835	431.3, 388
07	Fluid temperature range ($^{\circ}\text{C}$)	60 to 340	147 to 403.8	336.8 to 440.6	336.8 to 408.1	321.94 to 397.93	244.21 to 385.29	335 to 437
08	Pseudocritical temperature at the given pressure ($^{\circ}\text{C}$)	390.53	390.53	388.8	402.3	381.83	385.17	388.77
09	Fluid temperature at which peak change in metal temperature is observed ($^{\circ}\text{C}$)	91.7 and 329.9	356.9, 387.6, 392.3, and 403.8	408.4	408.1	330.7 and 381.5	385.29	387.53
10	$(T_w - T_b)$ at normal wall temperature zone-Experimental	116.3 to 152	98.8 to 111.6	30.7 to 50.9	31.3 to 41.8	39.5 to 68.7	53.7 to 64.7	37.6 to 116.5
11	$(T_w - T_b)$ at peak wall temperature zone, experimental	282.2 and 278.4	179.9	191.8	192.2	60.5 and 70.3	119.1	264.8
12	Name of correlation the metal temperature prediction of which has the closest fit with experimental data	Xiaojiang Zhu	Watts and Chou	Xiaojiang Zhu	Watts and Chou	Gorban	Gorban	Mokry
13	$(T_w - T_b)$ at normal wall temperature zone, best correlation	92.2 to 143.1	86.9 to 111.6	25.41 to 59.85	32.93 to 45.53	52.35 to 79.6	50.1 to 55.7	42.9 to 99.7
14	$(T_w - T_b)$ at peak wall temperature zone, best correlation	149 and 123.8	97.1	36.94	127.62	52.68 and 48.86	50.1	42.8
15	Total number of data points	29	20	16	8	80	26	15
16	% data with <5% error in metal temperature prediction	48.28	70	68.75	75	98.75	88.46	40
17	% data with <10 $^{\circ}\text{C}$ error in metal temperature prediction	37.93	20	56.25	50	48.75	42.31	20
18	Minimum and maximum deviation from experimental metal temperature ($^{\circ}\text{C}$)	-154.6 to +9.9	-82.78 to +23.33	-155 to +10	-64.56 to +10.72	-21.39 to +24.41	-68.98 to +0.42	-222 to +10

FIGURE 1: Trends of the thermophysical properties of water at 230 bar.

FIGURE 2: Trends of experimental (Vikhrev et al. [18]) wall temperature and that calculated using the best fitting Xiaojing Zhu correlation for dataset 1 in Table 2.

temperature seen in Figure 3 are not predicted even by the best fitting correlation.

4.2. *Experiments of Yamagata et al. (1972) [3].* Figures 4 and 5 display the trends of inner wall temperatures calculated by the best fitting correlations along with reference experimental wall temperatures for two different operating conditions given in [3]. Table 3 details the parameter conditions and the comparative information on the predicted wall temperature of the best fitting correlation with reference to the experimental wall temperature.

Observations of Figure 4 and Table 3 for dataset 1 indicate very good agreement of the best fitting correlation even at pseudocritical temperature. Also, many correlations predict 100% agreement for the first two considerations of % data with <5% error and <10°C error in prediction. Though there is 100% agreement for the best fitting correlation as per

FIGURE 3: Trends of experimental (Vikhrev et al. [18]) wall temperature and that calculated using the best fitting Watts and Chou correlation for dataset 2 in Table 2.

FIGURE 4: Trends of experimental (Yamagata et al. [3]) wall temperature and that calculated using the best fitting Ornatsky correlation for dataset 1 in Table 3.

the selected criteria for dataset 2, the wall temperature deviation is comparatively larger as seen in Figure 5.

4.3. *Lookup Table Data of Loewenberg et al. (2008) [10].* Figures 6 and 7 display the trends of inner wall temperatures calculated by the best fitting correlations along with reference wall temperatures for two different operating conditions given in [10]. Table 3 details the parameter conditions and the comparative information on the predicted wall temperature of the best fitting correlation with reference to the experimental wall temperature.

Observation of Figure 6 and Table 3 for dataset 1 indicates very good agreement of the best fitting correlation even at pseudocritical temperature. Also, for this dataset, many correlations predict 100% agreement for the first two considerations of % data with <5% error and <10°C error in prediction. The observations of Figure 7 for dataset 2 indicate

TABLE 3: Consolidated details of all experimental data and the best fitting correlations for cases with normal heat transfer.

Sl. no.	Parameter	Yamagata et al. [3] Dataset 1 (Figure 4)	Yamagata et al. [3] Dataset 2 (Figure 5)	Loewenberg et al. [10] Dataset 1 (Figure 6)	Loewenberg et al. [10] Dataset 2 (Figure 7)	Mokry et al. [15] Dataset 2 (Figure 11)
01	Tube ID (mm)	7.5	7.5	20	20	38
02	Pressure (bar (a))	245	245	250	235	241
03	Heat flux (kW/m^2)	233	930	300	1200	252
04	Mass flux ($\text{kg}/\text{m}^2\text{s}$)	1260	1260	1000	2250	543
05	Heat flux to mass flux ratio (kJ/kg) [5]	0.185	0.738	0.300	0.533	0.464
06	Limiting heat flux to avoid deterioration (kW/m^2) [3, 15]	1050.7, 879.7	1050.7, 879.7	796.2, 686	2106.9, 1617.2	382.6, 345.5
07	Fluid temperature range ($^{\circ}\text{C}$)	334.01 to 391.86	341 to 381.9	273.78 to 406.41	273.78 to 406.41	266.33 to 380.1
08	Pseudocritical temperature at the given pressure ($^{\circ}\text{C}$)	383.33	383.33	385.17	379.56	381.83
09	Fluid temperature at which peak change in metal temperature is observed ($^{\circ}\text{C}$)	381.61	381.9	376.4	379.59	373.1
10	$(T_w - T_b)$ at normal wall temperature zone, experimental	8.6 to 14.6	37.1 to 51.5	18.2 to 36.6	47.95 to 71.59	38.7 to 57.6
11	$(T_w - T_b)$ at peak wall temperature zone, experimental	2.9	39.4	15.5	27.41	18.8
12	Name of correlation the metal temperature prediction of which has the closest fit with experimental data	Ornatsky	Shitsman	Watts and Chou	Jackson	Mokry
13	$(T_w - T_b)$ at normal wall temperature zone, best correlation	6.2 to 13.7	42.2 to 51.7	16.5 to 39	46.00 to 88.41	40.47 to 48.81
14	$(T_w - T_b)$ at peak wall temperature zone, best correlation	2.8	32.4	15	25.74	30
15	Total number of data points	35	17	15	15	79
16	% data with <5% error in metal temperature prediction	100	100	100	100	100
17	% data with <10 $^{\circ}\text{C}$ error in metal temperature prediction	100	100	100	80	96.2
18	Minimum and maximum deviation from experimental metal temperature ($^{\circ}\text{C}$)	-2.4 to +0.73	-7 to +8.1	-7.59 to +2.39	-3.98 to +16.82	-10.2 to +11.2

FIGURE 5: Trends of experimental (Yamagata et al. [3]) wall temperature and that calculated using the best fitting Shitsman correlation for dataset 2 in Table 3.

FIGURE 6: Trends of the lookup table (Loewenberg et al. [10]) wall temperature and that calculated using the best fitting Watts and Chou correlation for dataset 1 in Table 3.

comparatively higher deviation in wall temperature and lower % agreement for the selected criteria even for the best fitting correlation.

4.4. Experiments of Zhu et al. (2009) [12]. Figures 8 and 9 display the trends of inner wall temperatures calculated by the best fitting correlations along with experimental wall temperatures for two different operating conditions given in [12]. Table 2 details the parameter conditions and the comparative information on the predicted wall temperature of the best fitting correlation with reference to the experimental wall temperature.

As per Figure 8 and dataset 1 in Table 2, the experimental wall temperature indicates a sharp peak of 600.2°C at a fluid temperature of 408.4°C with $(T_w - T_b)$ of 191.8°C. None of the correlations indicate this peak. Even the best fitting correlation has only 68.5% of data with <5% error

FIGURE 7: Trends of the lookup table (Loewenberg et al. [10]) wall temperature and that calculated using the best fitting Jackson correlation for dataset 2 in Table 3.

in prediction, and the error band for the overall data range is -155 to +10°C. Figure 9 and dataset 2 in Table 2 also indicate sharp increase in wall temperature near the exit. Though many correlations do not predict this peak, the best fitting correlation indicates this and follows the trend of experimental wall temperature. However, only 75% of data are with <5% error in prediction, and the error band for the overall data range is -64.56 to +10.72°C.

4.5. Experiments of Mokry et al. (2011) [15]. Figures 10 and 11 display the trends of inner wall temperatures calculated by the best fitting correlations along with experimental wall temperatures for two different operating conditions given in [15]. Tables 2 and 3 detail the parameter conditions and the comparative information on the predicted wall temperature of the best fitting correlation with reference to the experimental wall temperature.

As per experimental dataset 1 in Table 2 and Figure 10, heat-transfer deterioration is observed at two locations: one near the entry where the fluid temperature is well below pseudocritical temperature and the other near exit at location where the fluid temperature is near the pseudocritical temperature. None of the correlations indicate the first peak, and all of them including the best correlation indicate a dip in wall temperature at the second location contrary to the experimental observation. Many correlations indicate parallel wall temperature trend for dataset 2 in Table 3. As seen in Figure 11, the best fitting correlation has minimum error band of -10.2 to +11.2°C for the overall dataset.

4.6. Experiments of Wang et al. (2011) [14]. Figures 12 and 13 display the trends of inner wall temperatures calculated by the best fitting correlations along with experimental wall temperatures for two different operating conditions given in [14]. Table 2 details the parameter conditions and the comparative information on the predicted wall temperature of

FIGURE 8: Trends of experimental (Zhu et al. [12]) wall temperature and that calculated using the best fitting Xiaojing Zhu correlation for dataset 1 in Table 2.

FIGURE 9: Trends of experimental (Zhu et al. [12]) wall temperature and that calculated using the best fitting Watts and Chou correlation for dataset 2 in Table 2.

FIGURE 10: Trends of experimental (Mokry et al. [15]) wall temperature and that calculated using the best fitting Gorbán correlation for dataset 1 in Table 2.

FIGURE 11: Trends of experimental (Mokry et al. [15]) wall temperature and that calculated using the best fitting Sarah Mokry correlation for dataset 2 in Table 3.

FIGURE 12: Trends of experimental (Wang et al. [14]) wall temperature and that calculated using the best fitting Gorbán correlation for dataset 1 in Table 2.

the best fitting correlation with reference to the experimental wall temperature.

Dataset 1 in Table 2 and Figure 12 indicate sharp increase in wall temperature near the exit where the fluid temperature is just above pseudocritical temperature. None of the correlations, including the best one, indicate this peak, and all of them show a dip in temperature near the exit contradicting the experimental observation. The prediction by Gorbán correlation has 88.46% of predictions with <5% error with the error band of -68.98 to $+0.42^{\circ}\text{C}$ for the overall dataset. As per Figure 13 and dataset 2 in Table 2, the experimental wall temperature indicates a sharp peak of 652.3°C at a fluid temperature of 387.53°C with $(T_w - T_b)$ of 264.8°C . None of the correlations indicate this peak. Even the best fitting correlation has only 40% of the data with <5% error in prediction, and the error band for the overall data range is -222 to $+10^{\circ}\text{C}$.

FIGURE 13: Trends of experimental (Wang et al. [14]) wall temperature and that calculated using the best fitting Sarah Mokry correlation for dataset 2 in Table 2.

The analysis of the above wall temperature figures and the values in the tables indicate that even the best fitting correlations agree well only in the normal heat-transfer zones and not in the deteriorated heat-transfer zones.

5. Results and Discussion

5.1. Wall Temperature Prediction Capability of Heat-Transfer Correlations. Analyses of the 12 experimental datasets indicate that there are 7 deteriorated and 5 normal heat-transfer conditions in the group. The consolidated information of the selected experimental works and the data on the prediction level of the best fitting correlation for each dataset are listed in Table 2 for the deteriorated and in Table 3 for the normal heat-transfer conditions. As seen in the tables, the Watts and Chou correlation is the best for 2 deteriorated and 1 normal heat-transfer cases, the Gorban and Xiaojing Zhu correlations are the best for each 2 deteriorated heat-transfer cases, the Mokry correlation is the best for 1 deteriorated and 1 normal heat-transfer cases, and the Ornatsky, Shitsman and Jackson correlations are the best for each 1 normal heat-transfer case.

It is observed that the agreement of the predictions of the best fitting correlations for 5 normal heat transfer cases indicates almost 100% of the prediction satisfying the <5% and <10°C error criteria with the maximum error band at -10.2 to +16.82°C. However, the agreement of the predictions of the best fitting correlations for 7 deteriorated heat-transfer cases shows lower % of the prediction satisfying the <5% and <10°C error criteria. Also, the error band is as high as -222 to +24.41°C. It is also observed that the best fitting correlation position keeps varying from case to case under the selected criteria. In few cases, many correlations have the same % of agreement with respect to the <5% and <10°C error criteria, and the best is selected based on the difference in the error band.

Zahalan et al. [22, 23] conducted an extensive literature survey, analyzed the capability of 14 correlations for wall temperature prediction, and opined that the correlation by

Mokry et al. showed quite good predictions for subcritical liquid and superheated steam compared to other correlations. Based on the overall weighted average and root mean square (RMS) errors, Zahalan et al. [22, 23] determined that, within the supercritical region, the latest correlation by Mokry et al. showed the best for data within all three subregions investigated.

Similar analysis was made in the current work for all of the selected 355 data points. The details of average and RMS errors of metal temperature predictions for different correlations are listed in Table 4. As seen in the table, the Mokry et al. correlation was the best as per weighted average error. The weighted average error of the Krasnoschekov correlation is lesser than that of Mokry et al. However, it is not considered since it was only for 9 applicable data points out of the selected 355 data points. The Xiaojing Zhu correlation was the best as per RMS errors. Though the RMS errors of Krasnoschekov, Kondrat'ev, and Bishop correlations are lower than that of Xiaojing Zhu, they were not considered since they were applicable only for 9, 282, and 66 data points, respectively, out of the selected 355 datasets.

5.2. Applicability of Heat Flux to Mass Flux Ratio for Predicting Deteriorated Heat Transfer. Articles [5, 7, 18] report that heat-transfer deterioration occurs for operating conditions with the ratio of heat flux to mass flux (q/G) greater than 0.4. Analysis of the 12 experiments and the details in Tables 2 and 3 indicate that q/G ratios for two experiments are less than 0.4 and the metal temperatures for these two cases are normal. For ten cases, the q/G ratio is greater than 0.4. Seven out of these ten exhibit deteriorated wall temperature conditions. Though the q/G ratios for the remaining three (Table 3) are greater than 0.4, the experimental wall temperatures are normal. The overall agreement of the q/G -ratio-based prediction is 75% for the 12 experiments selected in this paper.

5.3. Applicability of the Empirical Formulae for Predicting Limiting Heat Flux. Articles [7, 8] report (4), and article [3] reports (5) given below for predicting the starting heat flux for deteriorated heat transfer as a function of mass flux:

$$q_{dht} \text{ in W/m}^2 = 200G^{1.2} \quad (4)$$

(see [7, 8]),

$$q_{dht} \text{ in kW/m}^2 = 0.2G^{1.2} \quad (5)$$

(see [3]).

Analysis of the 12 experiments and the details in Tables 2 and 3 indicate that there are two experiments in which the heat flux is higher than the heat flux calculated by (4) and (5) and the wall temperatures for these two cases indicate deterioration. Though the experimental heat flux is less than those calculated by (4) and (5), the experimental wall temperatures indicate deteriorated condition for five more cases. The overall agreement of the prediction of the deteriorated heat transfer by (4) and (5) is 58.33% for the 12 experiments selected in this paper.

TABLE 4: Average and RMS errors of wall temperature prediction by various correlations for the selected data points.

Equation no.	Correlation	Average error (%)	RMS error (%)	No. of applicable data points
Equation (B.1)	Dittus and Boelter (1930)	-5.2500	9.4837	All 355
Equation (B.2)	Mc Adams (1942)	-5.7839	9.8609	All 355
Equation (B.3)	Bringer and Smith (1957)	-5.1090	9.6819	All 355
Equation (B.4)	Shitsman (1959, 1974)	-3.7453	8.5276	All 355
Equation (B.5)	Bishop et al. (1964)	-3.8194	6.5453	66
Equation (B.6)	Swenson et al. [1]	6.5411	14.4906	90
Equation (B.7)	Krasnoshchekov et al. (1967)	0.0237	0.1560	9
Equation (B.8)	Kondrat'ev [20]	-1.2354	6.4086	282
Equation (B.9)	Ornatsky et al. (1970)	-1.2940	8.9133	All 355
Equation (B.10)	Yamagata et al. [3]	-7.0392	11.0684	All 355
Equation (B.11)	Watts and Chou et al. (1982)	-3.6744	8.3295	All 355
Equation (B.12)	Gorban et al. (1990)	-1.0198	7.9306	169
Equation (B.13)	Griem (1996)	-6.4152	10.2791	All 355
Equation (B.14)	Kitoh et al. (1999)	-6.5683	10.5762	340
Equation (B.15)	Jackson (2002)	-4.4797	8.6144	All 355
Equation (B.16)	Kang and Chang et al. [11]	-1.6150	7.8109	All 355
Equation (B.17)	Zhu et al. [12]	-3.7481	7.7072*	All 355
Equation (B.18)	Mokry et al. [15]	-0.0489*	8.8816	All 355

*The lowest of the correlations applied to all 355 data points.

Article [15] reports (6) given below for predicting the starting heat flux for deteriorated heat transfer as a function of mass flux:

$$q_{dht} \text{ in kW/m}^2 = -58.97 + 0.745G \quad (6)$$

(see [15]).

For the same mass flux conditions, the starting heat flux for deteriorated heat transfer predicted by (6) is lower than that calculated by (4) and (5). Analysis of the 12 experiments and the details in Tables 2 and 3 indicate that there are four experiments in which the heat flux is higher than that calculated by (6). The wall temperatures for three of these four cases indicate deterioration, whereas no deterioration is observed for one case. Though the experimental heat flux is less than that calculated by (6), the experimental wall temperatures indicate deteriorated condition for four more cases. The overall agreement of the prediction of the deteriorated heat transfer by (6) is 58.33% for the 12 experiments selected in this paper.

6. Conclusion

The validity of the wall temperature predictions by 18 correlations for 12 supercritical experimental datasets consisting of 355 data points available in the literature was verified. The correlations were ranked based on criteria like % data with <5% error, % data with <10°C error, and minimum error band in temperature prediction for the overall dataset. The trends of closely fitting predicted wall temperatures were plotted along with experimental wall temperature. Details of the best fitting correlations were tabulated.

The analysis indicated that, for normal heat-transfer conditions, most of the correlations give close predictions.

However, at deteriorated heat-transfer regimes near pseudocritical temperature, only very few predictions are closer with lower percentage of data falling close to experimental value. Also, in the ranking process, the first position keeps varying from case to case under the selected criteria. That is, no one correlation shall be said as the best for all experiments.

Analysis of the entire 355 datasets together, based on average and RMS errors, indicated that the Mokry et al. correlation was the best as per weighted average error and the Xiaojing Zhu correlation was the best as per RMS error for the selected experimental cases.

Evaluation of the applicability of heat flux to mass flux ratio- (q/G -) based prediction of heat-transfer deterioration given in [5, 7, 18] indicated 75% agreement for the selected 12 experimental cases. Evaluation of the empirical formulae linking mass flux for the prediction of the starting heat flux for heat-transfer deterioration given in [3, 7, 8, 15] indicated 58.33% of agreement for the selected 12 experimental cases.

This review indicated that continued precise experimentation covering wide range of parameter conditions near pseudocritical temperature regime and development of correlations is felt necessary for the accurate prediction of supercritical fluid heat transfer.

Nomenclature

- C: Constant
- Cp: Specific heat, J/kg K
- Cp_{av}: Average specific heat = $(H_w - H_b)/(T_w - T_b)$ J/kg K
- D: Inner diameter of tube, m
- E: Ratio $(T_{pc} - T_b)/(T_w - T_b)$
- F: Factor

G : Mass flux, $\text{kg/m}^2\text{s}$
 g : Acceleration due to gravity, m/s^2
 H : Enthalpy, J/kg
 h : Convection heat-transfer coefficient, $\text{W/m}^2\text{K}$
 k : Thermal conductivity, W/mK
 L : Length, m
 p : Pressure, MPa , bar
 q : Heat flux, kW/m^2
 T, t : Temperature, $^\circ\text{C}$
 Nu : Nusselt number
 Re : Reynolds number
 Pr : Prandtl number
 Pr_{av} : Average Prandtl number = $\text{Cp}_{\text{av}}\mu_b/k_b$.

Greek Letters

μ : Dynamic viscosity, Pa s
 ρ : Density, kg/m^3
 ξ : Friction coefficient
 α : Heat-transfer coefficient
 λ : Thermal conductivity, W/mK .

Subscript

av : Average
 b : Bulk
 dht : Deteriorated heat transfer
 w : Wall
 iw : Inner wall
 pc : Pseudocritical
 t : Temperature
 x : Axial location
 hy : Hydraulic
 min : Minimum.

Superscript

m : Constant
 n : Constant.

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