Chapter

Heat Transfer Correlations for Supercritical Water in Vertically Upward Tubes

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Abstract

Supercritical pressure water (SCW) has been widely used in many engineering fields and industries, such as fossil fuel-fired power plants, newly developed Gen-IV nuclear power plants and so forth. Heat transfer characteristics of SCW are of great importance for both design and safe operation of the related systems. Many heat transfer correlations have been developed in the history for predicting the heat transfer characteristics of SCW. However, the prediction accuracy of the existing correlations is less than satisfactory, especially in the cases with deteriorated heat transfer (DHT) because of the severe and quick variation in thermal physical properties of SCW in the vicinity of the fluids' pseudo critical point. It is very necessary to develop new correlations for the heat transfer of SCW to meet the engineering requirements for satisfactory prediction of the heat transfer behavior of SCW. In this chapter, experimental data on heat transfer of SCW are extensively collected from published literatures, and the performance of the existing heat transfer correlations for SCW are reviewed and quantitatively evaluated against the collected experimental data, and then a new heat transfer correlation for SCW with high prediction accuracy is proposed.

Keywords: supercritical water, enhanced heat transfer, deteriorated heat transfer, correlation, smooth tube

1. Introduction

Supercritical pressure fluids (SCFs) have been widely used in many engineering fields and industries, such as fossil fuel-fired power plants, newly developed Gen-IV nuclear power plants, chemical processes, and so forth. Heat transfer characteristics of SCFs are of great importance for both design and safe operation of the related systems. As one of the most popular SCFs, supercritical pressure water (SCW) has been selected as the ideal working fluid in nuclear power plants and fossil-fired power stations, and the heat transfer behavior of SCW has attracted more and more attention from both scholars and engineers in these fields [1, 2].

As well known, most of the newly designed thermal power plants are operated at supercritical pressures, and the operating parameters of future fossil-fired power plants have been suggested to raise to even higher levels to gain higher thermal efficiency, and at the same time, to obtain effective gains in reduction of the pollution products emission. For example, the U.S. Department of Energy has ever proposed a research program (AD 760), in which the operating parameters of the future fossil-fired power plants are suggested to raise to 37.9 MPa/732°C/760°C with an efficiency of up to 47%. A program similar to AD 760, i.e., the AD 700 thermal program, has also been proposed in Europe, and planned to build the ultra-supercritical steam condition at 720°C and 35 MPa in the future thermal power plants so as to obtain a cycle efficiency up to 50% [2]. There is no doubt that the heat transfer characteristics of SCW is an important issue for the thermal power plants with high level parameters. The higher the operating parameters, the higher the thermal efficiency, and as well, accordingly, the more important is the precise prediction of heat transfer characteristics of SCW. It should be noted that deteriorated heat transfer (DHT) is one kind of special heat transfer phenomena of SCW that might happen in the heat transfer tube and even lead to the burst of heat transfer tube or other failure accidents in the plants. On the other hand, the supercritical water-cooled reactors (SCWRs) has been selected as one of the six most promising reactors concepts presented at the Generation IV International Forum due to its high thermal efficiency and other features [3]. Similar to the situation in supercritical pressure thermal power plants, the heat transfer of SCW is an important issue for SCWRs as well. Furthermore, due to the possible risks in release of radioactive medium under conditions with tube or vessel failures, the heat transfer of SCW is of much more concern for the safe operation of SCWRs than that of thermal power stations, and as a result, precise knowledge about the heat transfer characteristics of SCW is one of the major tasks for the design and operation of SCWRs [3, 4]. Besides, heat transfer of SCW is of significance for other applications with SCW as the working fluid, such as SCW gasification system [5].

Two methods have been proposed by different scholars to predict the heat transfer characteristics of SCW: the look-up Table [6, 7] and the heat transfer correlations [8]. The look-up table for heat transfer of SCW is based on real experimental data. The prediction accuracy of such look-up table is pretty high; however, the applicable ranges of the operation parameters (e.g., pressures, mass fluxes, and heat fluxes) of the look-up table are limited by the experimental conditions. In the development of ultra-supercritical pressure boilers or other heat exchangers with high operation parameters, the applicability of the look-up table seems to be limited. Unlike the look-up table, heat transfer correlations have been developed on the basis on experimental data, dimensionless analysis, and theoretical analysis of the heat transfer phenomena. The applicability of heat transfer correlations are much flexible than that of look-up tables, and as a result, heat transfer correlations for SCW have found wide applications in related industries and engineering.

In the last few decades, many heat transfer correlations for SCW were proposed (see **Table 3** in the later section of this chapter). Generally, the existing heat transfer correlations could be divided into three categories [9], as listed in **Table 1**. The first type heat transfer correlation for SCW was built on the basis of the

Types	Forms	Remarks
I	$Nu = C_0 \times Re^{C_1} \times Pr^{C_2}$	C_0, C_1, C_2, C_3, C_4 are constants; F represents thermophysical properties correction terms; $\mathbf{Gr^*}$ represents the buoyancy correction terms; q^+ represents the thermal acceleration correlation terms
II	$Nu = C_0 \times Re^{C_1} \times Pr^{C_2} \times F$	
III	$Nu = C_0 \times Re^{C_1} \times Pr^{C_2} \times F \times (Gr^*)^{C_3} \times (q^+)^{C_4}$	

Table 1.
Three types of heat transfer correlations for SCW.

Dittus-Boelter et al.'s correlation [10]. Under supercritical pressure conditions, there exists no phase change of the fluid, but the thermophysical properties of the SCW experience dramatic change in the vicinity of pseudocritical point which might have great impact on the heat transfer behavior of the SCW. In view of this fact, a few correction terms consisting of the fluid thermophysical properties, such as ρ_w/ρ_b, μ_w/μ_b, λ_w/λ_b among the others, were introduced to the first type correlations, resulting in the emerge of second type heat transfer correlations for SCW. With the deepening research on heat transfer phenomena of SCW, buoyancy effect and thermal acceleration were considered to be the main reasons for DHT of SCW and then two special correction terms, i.e., $\mathbf{Gr}^*$ and q^+ proposed by Jackson [11] and were added to the second type correlations, yielding the third type heat transfer correlations for SCW.

Pioro et al. [8, 12] have conducted a comprehensive review of the existing heat transfer correlations for SCW and argued that none of the existing correlations could predict the heat transfer of SCW accurately under all heat transfer regimes. Lei et al. [2] ever put emphasis on the deterioration heat transfer of SCW by analyzing the physical mechanism of special heat transfer behavior of the SCW and tried to build new correlation for SCW, and found that most of the existing correlations for heat transfer of SCW focused mainly on the enhanced heat transfer (EHT) regimes of SCW, and these correlations were not capable of providing satisfactory prediction accuracy when it was applied to the DHT regime of SCW, and he thus suggested that excluding DHT data in the development of heat correlations should be responsible for the distinct deviations between the calculated heat transfer values and the experimental data of SCW in the DHT regimes. Another reason for the unsatisfied prediction accuracies of the existing correlations for heat transfer of SCW might be, to some extent, attributed to old thermophysical properties data adopted in the development of some of the existing heat transfer correlations [13]. Therefore, a new and accurate correlation for heat transfer of SCW is expected to be effectively accurate under both the DHT and EHT regimes of SCW, and special emphasis should be directed onto the DHT phenomena, which is the most dangerous situation to not only thermal power plants but also to the Gen-IV SCWRs and other heat transfer equipment with SCW as the working fluid.

In this chapter, experimental data on heat transfer of SCW are collected, including both the EHT regimes and the DHT regimes. Existing heat transfer correlations for SCW are well reviewed. Detailed assessments of prediction accuracy of the existing correlations are also conducted against the collected experimental data. On the basis of the evaluation of the prediction behavior of the existing heat transfer correlations for SCW, a new correlation is proposed for the heat transfer of SCW to cover both the EHT regime and the DHT regime. The prediction capability of the new correlation is also assessed against the collected experimental data.

2. Experimental data and existing heat transfer correlations

Since 1960s, a series of experimental investigations on heat transfer of SCW have been conducted, and a large amount of experimental data have been accumulated. A comprehensive survey of experimental investigations on heat transfer correlations of SCW has been provided by Pioro et al. [4, 8, 14] and showed that most of previous experimental data for heat transfer of SCW focused primarily on the flow of SCW in vertical circular tubes [2]. In the present study, approximately 12,704 data points and 250 experimental cases about the flow and heat transfer of SCW in vertical circular tubes are retrieved and collected from the published literatures.

Table 2 outlines the main information about the experimental data collected in this study on the heat transfer of SCW flowing in vertically upward smooth tubes. It is seen that the experimental data used in the present study covers the parameters of pressures from 2.25×10^7 to 3.103×10^7 Pa, mass fluxes from 200 kg/(m^2·s) to 2500 kg/(m^2·s), heat fluxes from 1.48×10^5 to 2×10^6 W/m^2, and the tube

Author	Year	$P \times 10^6$ [Pa]	G [kg/(m^2·s)]	$q \times 10^3$ [W/m^2]	$d \times 10^{-3}$ [m]
Shitsman et al. [15]	1963	23.3/25.3	430/449	210–386	8
Bishop et al. [16]	1964	24.1/24.2	543/678	252/606	5/38
Swenson et al. [17]	1965	23/31	2150	789	9.42
Vikrev et al. [18, 19]	1964 1967	26.5	495–1400	507–1160	20.4
Styrikovich et al. [20]	1967	24	700	348–872	22
Herkenrath et al. [21]	1967	22.5/24/25	700/1000/1500	300–1410	10/20
Kondratev et al. [22]	1969	25.3	700	581	18
Ackerman et al. [23]	1970	22.75/31.03	542.52–1220	472.9–1261	9.42
Ornatsky et al. [24]	1970	25.5	1500	1810	3
Yamagata et al. [25]	1972	22.6/24.5/29.4	1120–1260	233–930	7.5/10
Lee et al. [26]	1974	24.1/24.5	376/543	252–379	16/38
Polyakov et al. [27]	1991	24.5/29.4	595/675	500/570	8
Griem et al. [28]	1996	25	500/1000	300	14
Koshizuka et al. [29]	2000	31	540/680	473	9.4
Yoshida et al. [30]	2000	24.5	376/410/1180	329/350/698	10/16
Hu et al. [31]	2001	23/26/30	600/900/1200	200–500	26
Xu et al. [32]	2004	23/25/27/30	800/1000/1200	200–600	12
Kirillov et al. [33]	2005	24–24.9	200/1500	227–884	10
Zhu et al. [34]	2009	30	600	250	26
Wang et al. [35, 36]	2010 2011	25–29	600/1200	350/660	17/19.8/26
Mokry et al. [3, 37]	2010 2011	24.0/24.1/24.2	201–500	148–335	10/38
Pan et al. [38]	2011	22.5/27/28/30	1009–1626	216–649	17
Li et al. [39, 40]	2011 2018	23/25/26	459.8–1497.5	192–1326.5	7.6
Wang et al. [41]	2012	23/25/26	449–1520.6	192–1154.3	7.6/10
Wang et al. [42]	2013	23/24/25/26	450–1500	450–1250	10
Huang et al. [43]	2013	23–25.01	631–1263	420–1102	6
Li et al. [44]	2013	23/24/25	607.5–1263	466–1102	6
Zhao et al. [45]	2014	25	1000	570/760	7.6
Gu et al. [46]	2015	23/25/26	780/1000	700/900	10
Shen et al. [47, 48]	2016	28.5	1536	468	19
Qu et al. [49]	2018	24/24.8/30	404/407/420/690	205/250/284/315	19

Table 2.
Experimental data of heat transfer of SCW collected from literatures.

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diameters from 3 to 38 mm. Detailed analysis of the experimental data shows that among the 250 experimental cases collected, including both in this study, 134 cases are in the EHT regimes, while 116 cases of them are in the DHT regimes.

As well known, many heat transfer correlations have been proposed for predicting the heat transfer characteristics of SCW, and **Table 3** listed 34 of them as examples, for SCW in vertically upward tubes. It is seen from **Table 3** that many of the correlations were proposed 40 years ago and old thermophysical property data

Author	Year	Correlation
Dittus-Boelter et al. [10]	1985	$Nu = 0.023\,Re_b^{0.8}Pr_b^{1/3}$
Shitsman et al. [50]	1957	$Nu = 0.023\,Re_b^{0.8}Pr_{min}^{0.8}$ $Pr_{min} = Pr_b$ for $Pr_b < Pr_w$, $Pr_{min} = Pr_w$ for $Pr_w < Pr_b$
Petukhov et al. [8]	1963	$Nu = \dfrac{\left[f\,Re_b Pr_b \left(\frac{\mu}{\mu_w}\right)^{0.11}\left(\frac{\lambda_w}{\lambda_b}\right)^{0.33}\left(\frac{\overline{C_p}}{C_{p,b}}\right)^{0.35}/8\right]}{\left[12.7\sqrt{\frac{f}{8}}\left(Pr_b^{2/3}-1\right)+1.07\right]}$ $f = \left[1.82\log_{10}(Re_b)-1.64\right]^{-2}$
Domin et al. [51]	1963	$Nu = \begin{cases} 0.1\,Re_b^{0.66}\overline{Pr}_b^{1.2}, T_w \geq 623.15K \\ 0.036\,Re_b^{0.8}\overline{Pr}_b^{0.4}\left(\frac{\mu_w}{\mu_b}\right), 523.15K < T_w < 623.15K \end{cases}$
Swenson et al. [17]	1965	$Nu = 0.00459\,Re_w^{0.923}\overline{Pr}_w^{0.613}(\rho_w/\rho_b)^{0.231}$
Krasnoschekov et al. [52]	1967	$Nu = Nu_0\left(\frac{\rho_w}{\rho_b}\right)^{0.3}\left(\frac{\overline{C_p}}{C_{p,b}}\right)^{n}$ $Nu_0 = \dfrac{(\xi/8)\,Re_b\overline{Pr}}{12.7\sqrt{\xi/8}\left(\overline{Pr}^{2/3}-1\right)+1.07}$ $n = \begin{cases} 0.4 & T_b < T_w < T_{pc} \text{ or } 1.2T_{pc} < T_b < T_w \\ n_1 = 0.22 + 0.18(T_w/T_{pc}) & 1 \leq (T_w/T_{pc}) \leq 2.5 \\ n_1 + (5n_1 - 2)(1-(T_b/T_{pc})) & T_b < T_w \text{ and } 1 \leq (T_b/T_{pc}) \leq 1.2 \end{cases}$
Kondratev et al. [22]	1969	$Nu = 0.02\,Re_b^{0.8}$
Ornatsky et al. [24]	1970	$Nu = 0.023\,Re_b^{0.8}Pr_{min}^{0.8}\left(\frac{\rho_w}{\rho_b}\right)^{0.3}$ $Pr_{min} = Pr_b$ for $Pr_b < Pr_w$, $Pr_{min} = Pr_w$ for $Pr_w < Pr_b$
Grass et al. [53]	1971	$Nu = \dfrac{(f/8)\,Re_b Pr_b}{1.07 + 12.7\sqrt{f/8}\left(Pr_G^{2/3}C_{p,b}/C_{p,w}-1\right)}$ $f = \left[1.82\log_{10}(Re_b)-1.64\right]^{-2}$ $Pr_G = Pr_b$ for $Pr_b < 0.5Pr_w$, $Pr_G = Pr_w$ for $Pr_b > 0.5Pr_w$
Yamagata et al. [25]	1972	$Nu = 0.0135\,Re_b^{0.85}\overline{Pr}_b^{0.8}F_C$ $F_C = \begin{cases} 1.0 & (T_{pc}-T_b)/(T_w-T_b) \geq 1 \\ 0.67Pr_{pc}^{-0.05}(\overline{C_p}/C_{p,b})^{n_1} & 0 \leq (T_{pc}-T_b)/(T_w-T_b) \leq 1 \\ (\overline{C_p}/C_{p,b})^{n_1} & (T_{pc}-T_b)/(T_w-T_b) \leq 0 \end{cases}$ $n_1 = -0.77\left(1+\frac{1}{Pr_{pc}}\right)+1.49,\ n_2 = 1.44\left(1+\frac{1}{Pr_{pc}}\right)-0.53$
Yeroshenko et al. [54]	1981	$Nu = 0.023\,Re_b^{0.8}Pr_b^{0.4}\left[\frac{2}{(0.8\psi+0.2)^{0.5}+1}\right]^2 F$ $\psi = 1 + \beta(T_w - T_b)$ $F = \begin{cases} \left(\frac{\overline{C_p}}{C_{p,b}}\right)^{0.28} & \text{for } \overline{C_p} > C_{p,b} \\ 1 & \text{for } \overline{C_p} \leq C_{p,b} \end{cases}$

Author	Year	Correlation
Watts-Chou et al. [55]	1982	$Nu = 0.021\,Re_b^{0.8}\overline{Pr_b}^{0.55}\left(\frac{\rho_w}{\rho_b}\right)^{0.35}\phi$ $\phi = \begin{cases} 1 & \text{for } Bu \le 10^{-5} \\ (1-3000Bu)^{0.295} & \text{for } 10^{-5} < Bu \le 10^{-4} \\ (7000Bu)^{0.295} & \text{for } Bu \ge 10^{-4} \end{cases}$ $Bu = \frac{\overline{Gr}}{Re^{2.7}\overline{Pr}^{0.5}}$
Petukhov et al. [56]	1983	$Nu = Re_b\overline{Pr_b}(f/8)/\left[1 + 900/Re_b + 12.7(f/8)^{0.5}\left(Pr^{2/3} - 1\right)\right]$ $f = f_0(\rho_w/\rho_b)^{0.4}(\mu_w/\mu_b)^{0.2}$ $f_0 = \left[1.82\log_{10}(Re_b/8)\right]^{-2}(\rho_w/\rho_b)^{0.4}$
Kirillov et al. [41]	1990	$Nu = Nu_0\left(\frac{\rho_w}{\rho_b}\right)^{0.4}\left(\frac{\overline{C_p}}{C_{p,b}}\right)^{n}\varphi(k^*)$ $Nu_0 = Re_b\overline{Pr_b}(f/8)/\left(1 + 900/Re_b + 12.7(f/8)^{0.5}\left(\overline{Pr_b^{2/3}} - 1\right)\right)$ $f = (1.82\log_{10}Re_b)^{-2}, k^* = \left(1 - \frac{\rho_w}{\rho_b}\right)\frac{Gr_b}{Re_b^2}, Gr_b = \frac{g(1-\rho_w/\rho_b)D^3}{\nu_b^2}$ $n = \begin{cases} 0.4 \text{ for } \frac{T_w}{T_{pc}} < 1.0 \text{ and } \frac{T_b}{T_{pc}} > 1.2 \\ 0.22 + 0.18\frac{T_w}{T_{pc}} \text{ for } \frac{T_w}{T_{pc}} < 1.0 \text{ and } \frac{T_b}{T_{pc}} < 1.0 \\ 0.9\frac{T_b}{T_{pc}}\left(1 - \frac{T_w}{T_{pc}}\right) + 1.08\frac{T_w}{T_{pc}} - 0.68 \text{ for } \frac{T_w}{T_{pc}} < 1.0 \text{ and } \frac{T_b}{T_{pc}} < 1.2 \\ 0.7 \text{ for } \overline{C_p}/C_{p,b} \ge 1.0 \quad \text{other conditions} \end{cases}$ $\varphi(k^*) = \begin{cases} 0.8 - 1.65\ln k^* - 2.75(\ln k^*)^2 - 1.74(\ln k^*)^3 \\ \quad -0.55(\ln k^*)^4 - 0.09(\ln k^*)^5 - 0.0056(\ln k^*)^6 \\ \qquad \text{for } k^* \le 0.4 \\ 1.4(k^*)^{0.37} \text{ for } k^* > 0.4 \end{cases}$
Gorban et al. [8]	1990	$Nu = 0.0059\,Re_b^{0.9}Pr_b^{-0.12}$
Razumovskiy et al. [41]	1990	$Nu = Re_b Pr_b(f/8)\left(\frac{\overline{C_p}}{C_{p,b}}\right)^{0.65}/\left[1.07 + 12.7 \times \left(\frac{f}{8}\right)^{0.5} \times \left(Pr_b^{2/3} - 1\right)\right]$ $f = \left[1.82 \times \log_{10}(Re_b/8)\right]^{-2}((\rho_w/\rho_b) \times (\mu_w/\mu_b))^{0.18}$
Griem et al. [28]	1996	$Nu = 0.0169\,Re_b^{0.84}Pr_{sel}^{0.432}\omega$ $Pr_{sel} = \mu_b C_{p,sel}/\lambda_m, \ \lambda_m = 0.5(\lambda_w + \lambda_b)$ $\omega = \begin{cases} 0.82 & \text{for } h_b < 1540 kJ/kg \\ 1 & \text{for } h_b > 1740 kJ/kg \\ 0.82 + 9 \times 10^{-4} & \text{for } 1540 kJ/kg \le h_b \le 1740 kJ/kg \end{cases}$ For detailed of $C_{p,sel}$, please see [64]
Hu et al. [31]	2001	$Nu = 0.0068 \times Re_b^{0.9} \times \overline{Pr_b}^{0.63} \times (\rho_w/\rho_b)^{0.17} \times (\lambda_w/\lambda_b)^{0.29}$
Kitoh et al. [57]	2001	$Nu = 0.015\,Re_b^{0.85}Pr_b^{m}, m = 0.69 - 81000/200G^{1.2} + f_c q$ $f_c = 2.9 \times 10^{-8} + 0.11/200G^{1.2}$ for $0 \le h_b \le 1.5 \times 10^6 J/kg$ $f_c = -8.7 \times 10^{-8} - 0.65/200G^{1.2}$ for $1.5 \times 10^6 J/kg \le h_b \le 3.3 \times 10^6 J/kg$ $f_c = -9.7 \times 10^{-7} - 1.3/200G^{1.2}$ for $3.3 \times 10^6 J/kg \le h_b \le 4 \times 10^6 J/kg$

Author	Year	Correlation
Xu et al. [32]	2001	$Nu = 0.02269\,\mathrm{Re}_b^{0.8079}\overline{Pr}_b^{0.9213}\left(\frac{\mu_w}{\mu_b}\right)^{0.8687}\left(\frac{\rho_w}{\rho_b}\right)^{0.6638}$
Jackson [58]	2002	$\mathrm{Nu} = 0.0183\,\mathrm{Re}_b^{0.82}\mathrm{Pr}_b^{0.5}\left(\frac{\rho_w}{\rho_b}\right)^{0.3}\left(\frac{\overline{C_p}}{C_{p,b}}\right)^{n}$ $n = 0.4$ for $T_b < T_w < T_{pc}, 1.2T_{pc} < T_b < T_w$ $n = 0.4 + 0.2(T_w/T_{pc} - 1)$ for $T_b < T_{pc} < T_w$ $n = 0.4 + 0.2(T_w/T_{pc} - 1)[1 - 5(T_b/T_{pc} - 1)]$ for $T_{pc} < T_b < 1.2T_{pc}$ and $T_b < T_w$
Fewster et al. [59]	2004	$\mathrm{Nu} = 0.0183\,\mathrm{Re}_b^{0.82}\overline{\mathrm{Pr}}_b^{0.5}\left(\frac{\rho_w}{\rho_b}\right)^{0.3}$
Kuang et al. [60]	2008	$\mathrm{Nu} = 0.0239\,\mathrm{Re}_b^{0.759}\mathrm{Pr}_b^{0.833}\left(\frac{\lambda_w}{\lambda_b}\right)^{0.0863}\left(\frac{\rho_w}{\rho_b}\right)^{0.31}\left(\frac{\mu_w}{\mu_b}\right)^{0.1}$ $\cdot(\mathrm{Gr}^*)^{0.014}(q^*)^{-0.021}$ $\mathrm{Gr}^* = g\beta d^4 q/\lambda\nu^2,\ q^* = \frac{q\beta}{G\overline{C_p}}$
Cheng et al. [61]	2009	$\mathrm{Nu} = 0.023\,\mathrm{Re}_b^{0.8}\mathrm{Pr}_b^{1/3}F,\ F = \min(F_1, F_2)$ $F_1 = 0.85 + 0.776(\pi_A \cdot 10^3)^{2.4}$ $F_2 = \frac{0.48}{(\pi_{A,pc} \cdot 10^3)^{1.55}} + 1.21(1 - \pi_A/\pi_{A,pc})$ $\pi_A = \frac{\beta_b q_w}{GC_p}$
Yu et al. [62]	2009	$\mathrm{Nu} = 0.01378\,\mathrm{Re}_b^{0.9078}\overline{\mathrm{Pr}}_b^{0.6171}\left(\frac{\rho_w}{\rho_b}\right)^{0.4356}(\mathrm{Gr}^*)^{-0.012}(q^*)^{0.0605}$ $\mathrm{Gr}^* = g\beta d^4 q/\lambda\nu^2,\ q^* = \frac{q\beta}{G\overline{C_p}}$
Bringer et al. [63]	2010	$\mathrm{Nu} = 0.0266\,\mathrm{Re}_X^{0.77}\mathrm{Pr}_W^{0.55}$ $T_X = T_b$ *for* $(T_{pc} - T_b)/(T_w - T_b) < 0$ $T_X = T_{pc}$ *for* $0 \le (T_{pc} - T_b)/(T_w - T_b) \le 1$ $T_X = T_w$ *for* $(T_{pc} - T_b)/(T_w - T_b) > 1$
Gupta et al. [64]	2010	$\mathrm{Nu} = 0.004\,\mathrm{Re}_w^{0.923}\overline{\mathrm{Pr}}_w^{0.773}\left(\frac{\rho_w}{\rho_b}\right)^{0.186}\left(\frac{\mu_w}{\mu_b}\right)^{0.366}$
Mokry et al. [3]	2010	$\mathrm{Nu} = 0.0061\,\mathrm{Re}_b^{0.904}\overline{\mathrm{Pr}}_b^{0.684}\left(\frac{\rho_w}{\rho_b}\right)^{0.564}$
Wang et al. [65]	2012	$\mathrm{Nu} = 0.0122\,\mathrm{Re}_b^{0.752}\overline{\mathrm{Pr}}_b^{0.8775}\left(\frac{\lambda_w}{\lambda_b}\right)^{0.0746}\left(\frac{\rho_w}{\rho_b}\right)^{0.0402}$ $\cdot(\mathrm{Gr}^*)^{0.0157}K_V^{-0.031}$ $\mathrm{Gr}^* = g\beta d^4 q/\lambda\nu^2, K_V = 4q_w D\beta/(\mathrm{Re}^2\mu C_p)$
Liu et al. [66]	2012	$\mathrm{Nu} = 0.01\,\mathrm{Re}_b^{0.889}\overline{\mathrm{Pr}}_b^{0.73}\left(\frac{\lambda_w}{\lambda_b}\right)^{0.24}\left(\frac{\mu_w}{\mu_b}\right)^{0.153}\left(\frac{\rho_w}{\rho_b}\right)^{0.401}\left(\frac{\overline{C_p}}{C_{p,b}}\right)^{0.014}$ $\cdot(\mathrm{Gr}^*)^{0.007}(q^*)^{0.041}$ $\mathrm{Gr}^* = g\beta d^4 q/\lambda\nu^2,\ q^* = \frac{q\beta}{G\overline{C_p}}$
Wang et al. [42]	2013	$\mathrm{Nu} = 0.0182\,\mathrm{Re}_b^{0.8}\mathrm{Pr}_b^{0.38}\left(\frac{\lambda_w}{\lambda_b}\right)^{0.39}\left(\frac{\mu_w}{\mu_b}\right)^{1.47}\left(\frac{\rho_w}{\rho_b}\right)^{0.54}$
Liao et al. [9]	2014	$\mathrm{Nu} = 0.032089\,\mathrm{Re}_b^{0.88832}\overline{\mathrm{Pr}}_b^{0.71399}\left(\frac{\lambda_w}{\lambda_b}\right)^{0.03339}\left(\frac{\rho_w}{\rho_b}\right)^{0.68707}$ $\cdot(\mathrm{Gr}^*)^{0.00417}(q^*)^{0.18212}$ $\mathrm{Gr}^* = g\beta d^4 q/\lambda\nu^2,\ q^* = \frac{q\beta}{G\overline{C_p}}$
Wang and Li et al. [67]	2014	$\mathrm{Nu} = 0.00684\,\mathrm{Re}_b^{0.9}\overline{\mathrm{Pr}}_b^{0.69}\left(\frac{\lambda_w}{\lambda_b}\right)^{0.26}\left(\frac{\rho_w}{\rho_b}\right)^{0.31}$

Author	Year	Correlation
Zhao et al. [45]	2014	$\mathrm{Nu} = 0.023\,\mathrm{Re}_\mathrm{b}^{0.8}\mathrm{Pr}_\mathrm{b}^{1/3}F, F = \min(F_1, F_2)$ $F_1 = 0.62 + 0.06\ln(\pi_B)$ $F_2 = 11.46\ln(\pi_B)^{-1.04}$ $\pi_B = \frac{\beta_\mathrm{b} q_w D}{\lambda_b}$

Table 3.
Existing heat transfer correlations for SCW in vertical upward tubes.

might have been adopted in the development of those correlations. Kurganov et al. [13] have pointed out that some correlations developed on the basis of the old thermophysical property standard for SCW have become quite impractical when the thermophysical property shifts to IAPWS-97 Standard. From this point of view, accurate correlations for heat transfer of SCW must be developed by using the updated properties database.

3. Assessment of the prediction performance of the existing heat transfer correlations

3.1 Assessment method

As seen in **Table 3**, the heat transfer correlations for SCW have been proposed in different years and might be developed on different basis of experimental data. As a result, the applicability of each correlation might be different. As reported by Pioro et al. [8] and Lei et al. [2], there exist distinct discrepancies between the results predicted by different correlations. It is necessary to quantitatively evaluate the prediction performance of the existing correlations.

In this part, the prediction performance of the existing heat transfer correlations are quantitatively estimated by introducing four parameters, i.e., σ_1 (mean relative deviation, MRD), σ_2 (mean absolute deviation, MAD), σ_3 (standard deviation, SD), and ρ_{xy} (correlation coefficient between the predicted values and experimental values), as defined by Eq. (1) through Eq. (5).

$$\sigma_1 = \sum_{i=1}^{n} e_i / N \tag{1}$$

$$\sigma_2 = \sum_{i=1}^{n} |e_i| / N \tag{2}$$

$$\sigma_3 = \sqrt{\sum\nolimits_{i=1}^{n} (e_i - \sigma_1)/(N-1)} \tag{3}$$

where e_i is

$$e_i = \left[\mathrm{Nu}_{\mathrm{cal}}\text{-}\mathrm{Nu}_{\mathrm{exp}}\right]/\mathrm{Nu}_{\mathrm{exp}} \tag{4}$$

$$\rho_{xy} = \frac{Cov(X, Y)}{\sqrt{D(X)}\sqrt{D(Y)}} \tag{5}$$

where $D(X)$ refers to the variance of the experimental data X, $D(Y)$ refers to the variance of the calculated results Y, and $Cov(X, Y)$ is the covariation of X and Y [9]. The closer the ρ_{xy} is to 1.0, the better the correlation is [9].

3.2 Comparison of the predicted values by using existing correlations to the experimental data

As described in the preceding section, the existing heat transfer correlations listed in **Table 3** could generally be divided into three categories (see **Table 1**). For simplicity, two representative correlations are selected from each category of the correlations.

Figure 1(a) shows the comparison of the results calculated by the first type of correlations for heat transfer of SCW to the experimental data. This type of correlations is represented by the Dittus-Boelter et al.'s correlation [10] and Gorban

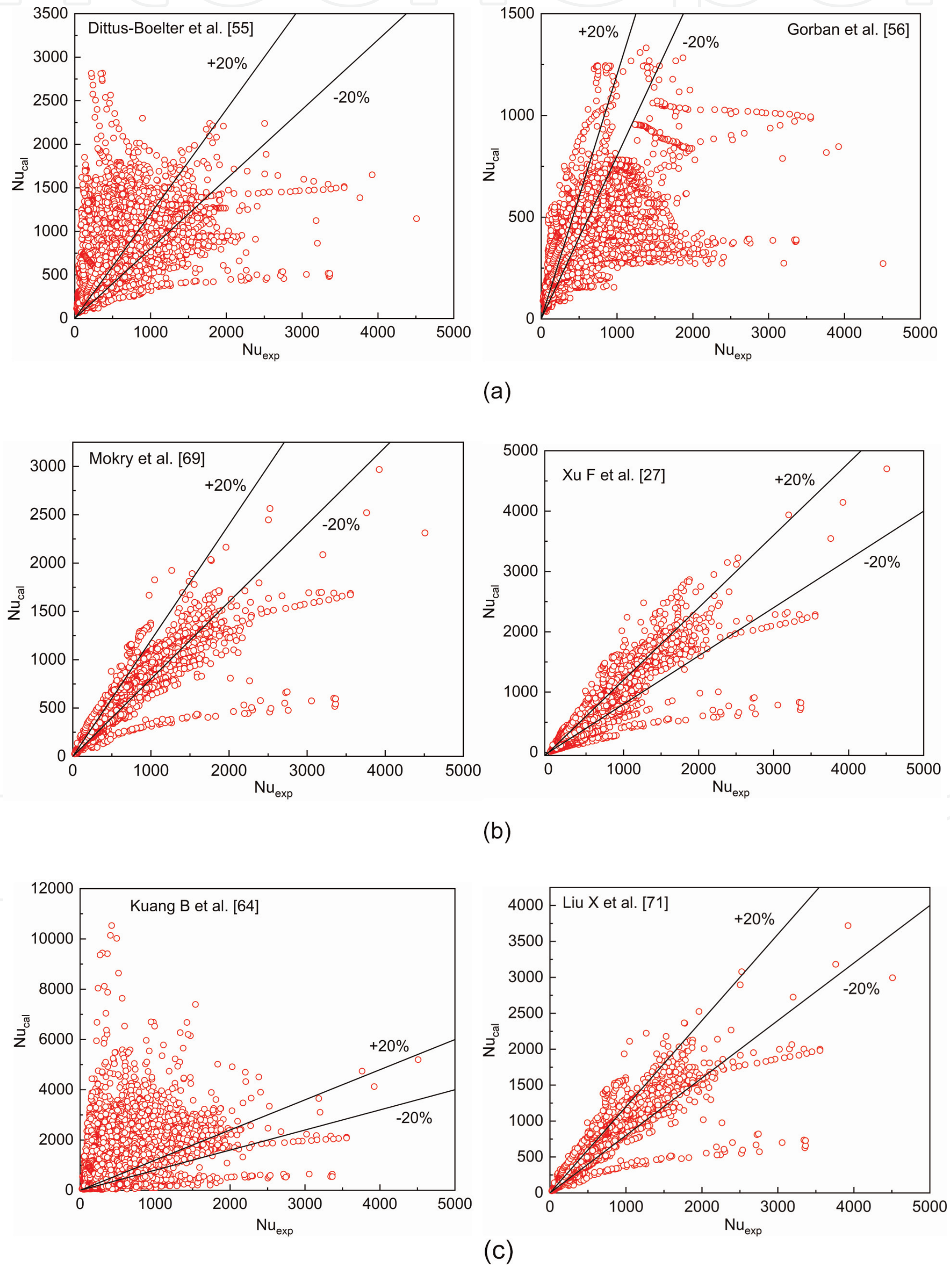

Figure 1.
Comparison of predicted values of correlations with all experimental data. (a) First type of correlations, (b) second type of correlations, (c) third type of correlations.

et al.'s correlation [8] here. It is seen from **Figure 1(a)** that most of the **Nu** values predicted by the correlations are out of ±20% error band, indicating a generally low prediction accuracy of this type of correlations. As explained in the preceding sections, no consideration in these correlations of the dramatic change of thermophysical properties of SCW in the vicinity of its pseudocritical point might be responsible for the low prediction accuracy of the correlations.

Figure 1(b) gives the representative comparison of the results calculated by the second type of correlations for SCW to the experimental data. This type of correlations is represented by the Mokry et al. [3] and Xu [32] correlations here. It can be seen from **Figure 1(b)** that most of predicted results by the correlations concentrate around the line of $\mathbf{Nu_{cal}} = \mathbf{Nu_{exp}}$, suggesting a remarkable improvement in the prediction accuracy of the correlations in comparison to that of the first type of the correlations. This improvement in the prediction accuracy might due to introducing thermophysical properties correction terms into the correlations.

Comparison of the results calculated by the third type correlations to the experimental data are illustrated in **Figure 1(c)**. Here, the third type correlations are represented by the Kuang et al.'s correlation [60] and Liu's correlation [66].

It is seen in **Figure 1(b)**, (c) that the prediction accuracy of the Mokry et al.'s correlation [3], Xu's correlation [32], and Liu's correlation [66] are in roughly the same level. It is surprising that although other two more correction factors (i.e., $\mathbf{Gr}^*$ and q^+) are introduced into the correlations, the prediction accuracy of Kuang et al.'s correlation [60] is unexpectedly worse than that of the Mokry et al.'s correlation [3] and Xu's correlation [32] in the present study. Another two correlations, i.e., Yu et al.'s correlation [62] and Liao's correlation [9], which are of forms similar to that of Kuang et al.'s correlation [60], provide similar prediction performance to that of Kuang et al.'s correlation [60] in this study. This result indicates that adding more correction factors in the correlations does not always produce better accuracy, and the correction terms added to the correlations should be selected carefully.

Figures 2, **3** depict the prediction performance of the 34 existing correlations listed in **Table 3**, under the EHT condition (experimental data from Yamagata et al. [25] is used) and the DHT condition (experimental data from Herkenrath et al. [21] is used), respectively.

It is seen from **Figure 2** that under the EHT conditions, most of existing correlations could provide relatively good prediction accuracy in the enthalpy region lower than 1600 kJ/kg and the region higher than 2800 kJ/kg of SCW (i.e., in the regions far away from the pseudocritical point). However, in the enthalpy region of 1600–2300 kJ/kg (a region around the pseudocritical point, named in lots of papers as the large specific heat region, and is hereafter abbreviated as LSHR), the predicated values of many heat transfer correlations, such as Yamagata et al.'s correlation [25], Domin et al. correlation [51] and Swenson et al. correlation [17], are much higher than the corresponding experimental values, implying low prediction capability of these correlations in the LSHR. Careful analysis of the forms of Yamagata et al. correlation [25], Domin's correlation [51], and Swenson et al.'s correlation [17] shows that only one thermophysical correction property factor is employed in the abovementioned three correlations. None of the 34 correlations could give good prediction accuracy in the whole enthalpy region of SCW. It is well known that the thermophysical properties of SCW experience dramatic change in the vicinity of pseudocritical point (i.e., in the LSHR), and with this view in mind, it is suggested that one thermophysical property correction factor might not be sufficient, and, however, proper and enough correction factors should be used in the corrections in order to capture the effect of the dramatic variation in thermophysical properties on the heat transfer of SCW in LSHR.

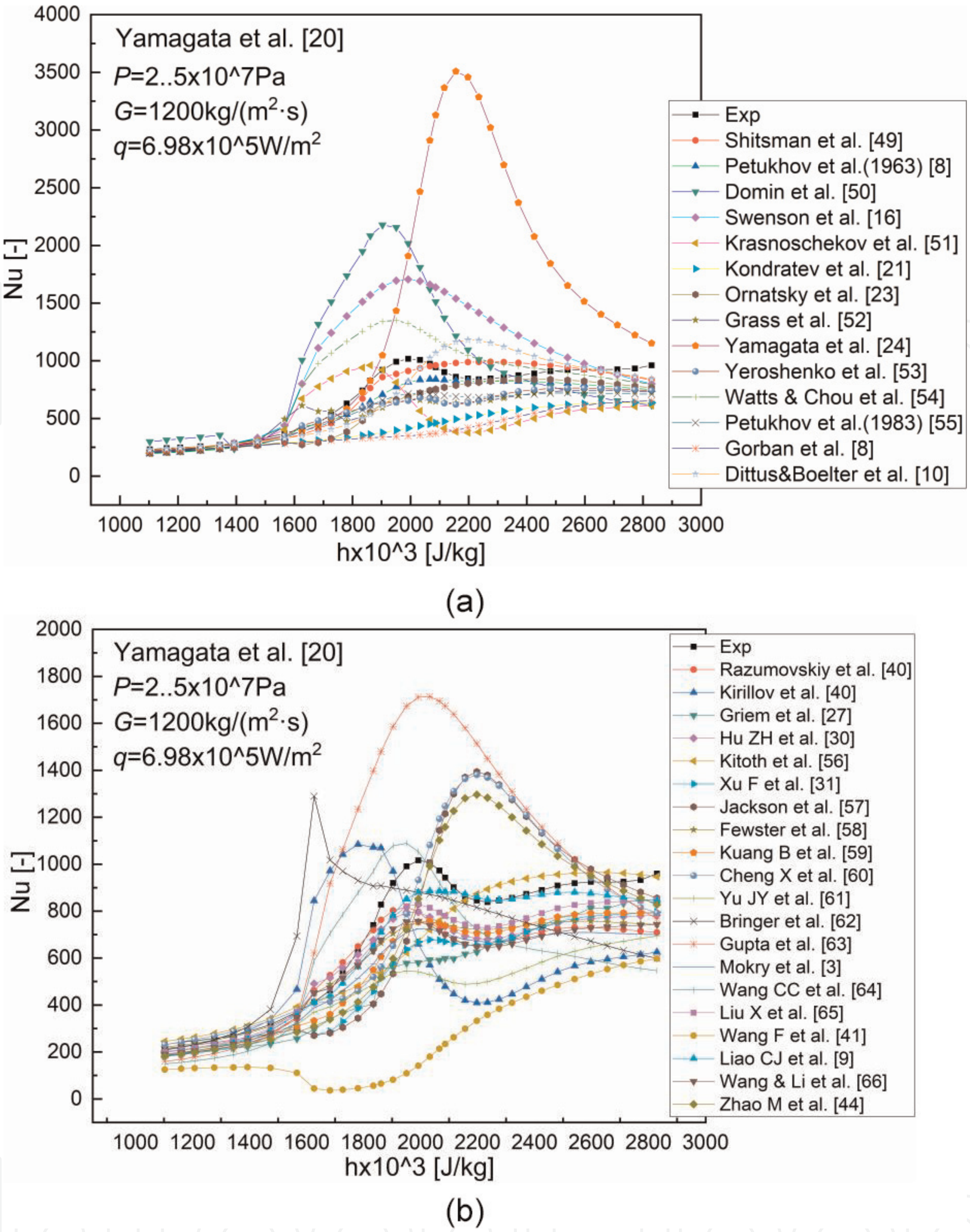

Figure 2.
*Comparison of the calculated values to the corresponding experimental data (Yamagata et al. [25], EHT case). (a) Prediction results of the first 14 correlations in **Table 3** (b)Prediction results of the last 20 correlations in **Table 3**.*

Figure 3 shows that most of the 34 heat transfer correlations for SCW could not provide high prediction accuracy under DHT conditions, except for Grass et al.'s correlation [53] and Petukhov et al.'s correlation [56]. It is seen from **Figure 3** that the predicted results of Grass et al.'s correlation [53] and Petukhov et al.'s correlation [56] agree pretty well with the corresponding experimental data under DHT conditions through the whole enthalpy region of SCW studied here. Unfortunately, as seen in **Figure 2**, the prediction results of the above two correlations do not agree satisfactorily with the corresponding experimental data under the EHT conditions, especially in the vicinity of pseudocritical point (in the LSHR). The reason for this result might be attributed to that most of the experimental data adopted in the development Petukhov et al.'s correlation [56] were under DHT regimes. Little

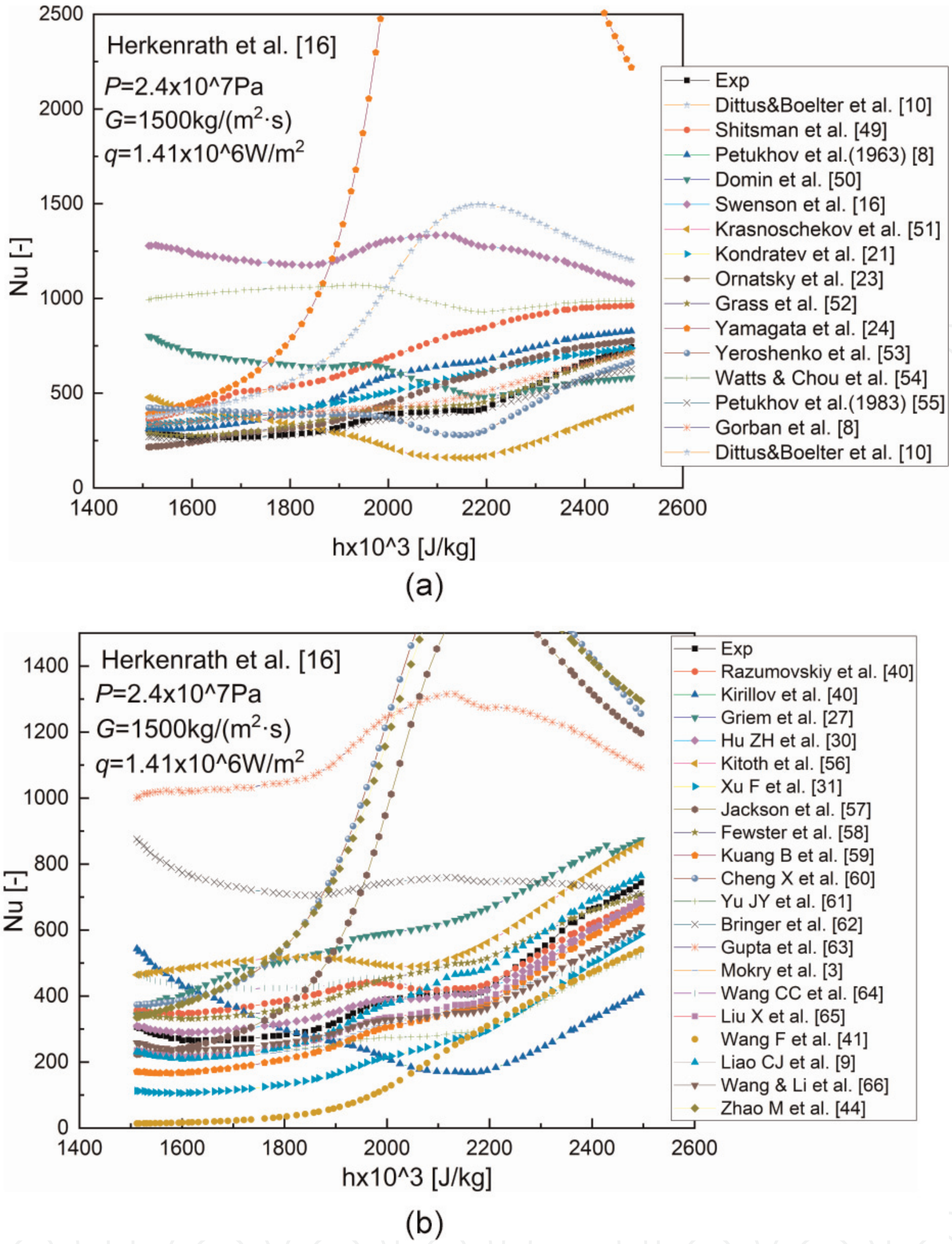

Figure 3.
Comparison of the calculated values to the corresponding experimental data (Herkenrath et al. [21], DHT case). (a) Prediction results of the first 14 correlations in ***Table 3*** *(b) Prediction results of the last 20 correlations in* ***Table 3***

information can be found about the experimental data used for developing Grass et al.'s correlation [53].

It is confusing that under EHT regimes, the prediction results of Miropolskii and Shitsman correlation [50] and Yu et al.'s correlation [62] agree relatively well with the corresponding experimental (see **Figure 2**) data, however, under DHT regimes, the prediction results of these two correlations are in quite different trend from that of the experimental data, indicating that these two correlations could not capture the variation characteristics of the experimental data under the DHT regimes (see **Figure 3**). As reported early by Pioro et al. [8] and Lei et al. [2], experiment data under DHT regime were excluded in the development of many of the heat transfer correlations, and this exclusion of the data under DHT regimes results in the low prediction accuracy under DHT regimes. It is seen again from

Author	σ_1 (%)	σ_2 (%)	σ_3 (%)	ρ_{xy}	% of data within the error bands		
					±10%	±20%	±30%
Dittus-Boelter et al. [10]	63.65	73.22	130.58	0.63	24.09	44.18	56.42
Shitsman et al. [50]	41.26	46.01	62.73	0.87	27.86	47.54	58.34
Petukhov et al. [56]	21.87	30.45	43.89	0.88	33.00	56.49	69.16
Domin et al. [51]	104.07	108.80	103.59	0.66	10.47	20.58	27.29
Swenson et al. [17]	124.64	127.80	122.01	0.67	14.40	24.35	30.17
Krasnoschekov et al. [52]	8.38	38.51	48.32	0.73	15.51	31.10	47.13
Kondratev et al. [22]	3.05	36.60	55.67	0.71	22.39	41.17	57.53
Ornatsky et al. [24]	8.51	25.29	38.31	0.90	35.26	59.41	73.23
Grass et al. [53]	12.90	25.84	35.85	0.87	33.96	58.78	71.51
Yamagata et al. [25]	224.43	226.89	461.56	0.42	15.67	28.81	37.73
Yeroshenko et al. [54]	9.98	21.85	30.41	0.90	34.45	59.81	76.28
Watts-Chou et al. [55]	101.98	106.21	113.46	0.69	14.95	26.94	33.73
Petukhov et al. [56]	2.66	15.03	20.42	0.92	46.26	74.20	87.30
Bringer et al. [63]	−8.17	33.42	45.33	0.70	20.84	39.92	56.12
Gorban et al. [8]	13.86	23.62	29.23	0.89	32.34	55.74	71.14
Razumovskiy et al. [41]	9.37	39.78	51.68	0.70	14.83	29.87	47.67
Kirillov et al. [41]	14.23	37.20	58.65	0.77	26.07	47.14	63.61
Griem et al. [28]	9.44	17.16	22.19	0.91	42.71	70.55	82.98
Hu et al. [31]	29.98	40.05	56.33	0.83	21.21	40.03	57.30
Kitoh et al. [57]	−14.18	20.45	22.89	0.93	39.15	58.84	72.20
Xu et al. [32]	52.14	69.88	133.56	0.65	22.48	41.18	56.38
Jackson [58]	16.39	24.13	29.53	0.90	31.54	55.12	73.00
Fewster et al. [59]	−0.42	16.41	22.62	0.93	45.37	68.69	83.67
Kuang et al. [60]	78.42	85.38	153.65	0.61	21.99	39.65	53.28
Cheng et al. [61]	−11.99	17.94	18.53	0.90	30.75	61.90	84.39
Yu et al. [62]	78.11	87.44	103.32	0.59	12.91	25.36	35.84
Gupta et al. [64]	104.79	111.99	111.23	0.70	13.59	25.09	33.42
Mokry et al. [3]	−5.03	13.26	16.58	0.93	46.04	78.81	93.30
Wang et al. [65]	22.92	39.26	44.58	0.80	14.26	30.07	49.74
Liu et al. [66]	6.10	14.81	19.29	0.93	45.46	75.86	88.79
Liao et al. [9]	−54.71	60.61	37.7	0.69	3.41	7.38	14.33
Wang et al. [42]	6.19	16.14	20.47	0.94	40.22	71.62	86.90
Wang and Li [67]	0.39	13.33	18.45	0.92	50.56	79.01	90.48
Zhao et al. [45]	60.03	76.49	146.38	0.59	23.65	44.20	57.80

Table 4.
Quantitative analysis of the existing heat transfer correlations.

the above results that the applicable scope of each heat transfer correlation is limited by the scope of the experimental database employed. Thus, it is of great importance to develop a new heat transfer correlation with high prediction accuracy over a wide range of experimental parameters covering the NHT regime, the EHT regime, and the DHT regime [4].

In order to gain comprehensive understanding of prediction performance of the existing correlations, quantitative analyses are conducted by employing four parameters, i.e., σ_1, σ_2, σ_3, and ρ_{xy} as defined in the previous section of this chapter, and the results of σ_1, σ_2, σ_3, and ρ_{xy} for each correlation are listed in **Table 4**.

It is seen from **Table 4** that the predicted values of most of the existing correlations falling into the ±10% error band are lower than 50%, and that falling into the ±30% error band are lower than 90%, indicating that no of these heat transfer correlations could give satisfactory predict accuracy under both DHT and EHT regimes. Generally, the prediction performance of Mokry et al.'s correlation [3]and Wang and Li's correlation [67] are compareatively the best among the 34 correlations. More than 90% of the calculated values of these two correlations fall into the ±30% error band. However, it should be noted that only about 50% of the calculated values of these two correlations fall into the ±10% error band, and the prediction accuracy the correlations needs to be improved further.

The Domin's correlation [51] and the Swenson et al.'s correlation [17] exhibit special prediction features, as seen in **Figure 2**. It is seen from **Table 4** that the predicted values of Domin's correlation [51] and Swenson et al.'s correlation [17] falling into ±30% error band are lower than 50%. This result is in accordance with that in **Figure 2**, that is, under EHT conditions, the prediction accuracy of these correlations are quite low in the LSHR of SCW although relatively good prediction performance is observed in the enthalpy region lower than 1600 kJ/kg and higher than 2800 kJ/kg of SCW. As seen in **Figure 3**, the Domin's correlation [51] and Swenson et al.'s correlation [17] could not provide prediction accuracy either under DHT conditions.

4. Development of the new heat transfer correlation

As we discussed earlier, insufficient description of the severe variation of thermophysical properties of SCW in the LSHR is one of the main reasons for the low prediction accuracy of the existing heat transfer correlations. Proper correction terms should be selected carefully to reflect the impact of thermophysical properties of SCW in LSHR on the heat transfer.

Based on the analysis of the existing heat transfer correlations, a general form of heat transfer correlations for SCW is suggested as follows:

$$\mathrm{Nu} = C_0\,\mathrm{Re}_b^{C_1}\mathrm{Pr}_b^{C_2}F_1^{k_1}\cdots F_n^{k_n} \tag{6}$$

where $F_1 \cdots F_n$ are correction terms, defined as one of the parameters such as ρ_w/ρ_b, μ_w/μ_b, λ_w/λ_b, C_p, and $\mathbf{Gr^*}$, and so on, and C_0, C_1, C_2, k_1, $\cdots$ k_2 are constant indices for the corresponding correction terms. As mentioned in the previous section, one thermophysical correction factor might not be sufficient to capture the effect of the severe variation of thermophysical properties of SCW on the heat transfer in LSHR. On the other hand, introducing too many correction terms into the correlation does not always mean a high prediction accuracy. It was shown that strong linear correlations existed among the correction terms, and such linear correlation might limit, even reduce, the prediction performance of the correlations [68]. Based on the multicollinearity analysis as conducted in

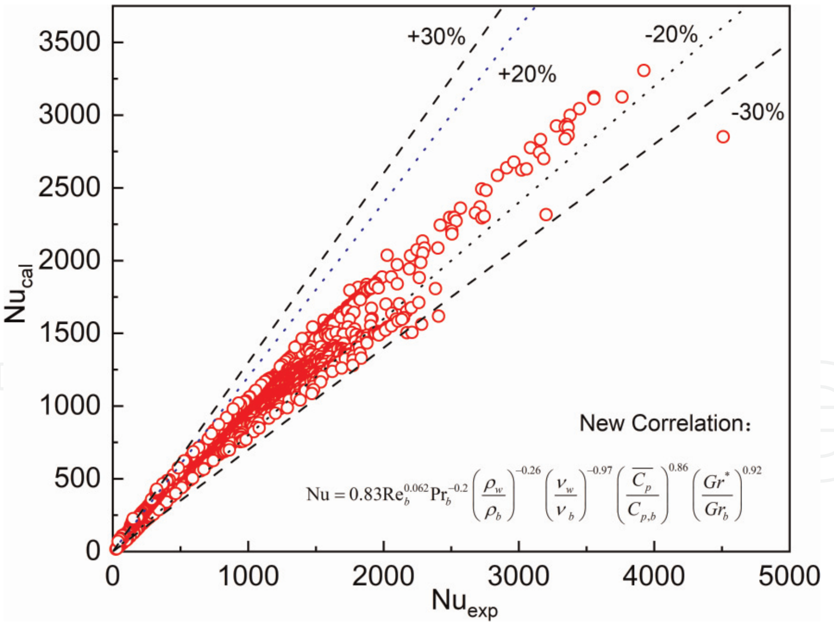

Figure 4.
Comparison between experimental and calculated ***Nu*** *using new heat transfer correlation.*

Correlation	σ_1(%)	σ_2(%)	σ_3(%)	ρ_{xy}	% of data within the error bands		
					±10%	±20%	±30%
New Correlation	0.77	6.71	9.23	0.991	78.57	95.18	99.39

Table 5.
Quantitative analysis of the new heat transfer correlation.

[68], four correction terms are finally adopted in the new heat transfer correlation, i.e.,

$$\mathrm{Nu} = C_0\,\mathrm{Re}_\mathrm{b}^{C_1}\mathrm{Pr}_\mathrm{b}^{C_2}\left(\frac{\rho_w}{\rho_b}\right)_1^{k_1}\left(\frac{\nu_w}{\nu_b}\right)^{k_2}\left(\frac{\overline{C_p}}{C_{p,b}}\right)^{k_3}\left(\frac{\mathrm{Gr}^*}{\mathrm{Gr}_\mathrm{b}}\right)^{k_4} \tag{7}$$

Experimental data including both the DHT regimes and the EHT regimes (as listed in **Table 2**) are adopted simultaneously in this study to develop the new heat transfer correlation, in hope to get high prediction accuracy under both the DHT and the EHT regimes. Based on the experimental database (**Table 2**), the constant indices in Eq. (7) are determined via the Levenberg–Marquardt method [69]. The final new heat transfer correlation for SCW is obtained as Eq. (8):

$$\mathrm{Nu} = 0.83\,\mathrm{Re}_\mathrm{b}^{0.062}\mathrm{Pr}_\mathrm{b}^{-0.2}\left(\frac{\rho_w}{\rho_b}\right)^{-0.26}\left(\frac{\nu_w}{\nu_b}\right)^{-0.97}\left(\frac{\overline{C_p}}{C_{p,b}}\right)^{0.86}\left(\frac{\mathrm{Gr}^*}{\mathrm{Gr}_\mathrm{b}}\right)^{0.92} \tag{8}$$

Figure 4 displays the comparison of the calculated **Nu** by using the new heat transfer correlation to the corresponding experimental results. It is seen from **Figure 4** that the relative errors of most of the calculated values are much lower than ±20%. **Table 5** gives the quantitative evaluation of the prediction performance of the new heat transfer correlation. It is clearly seen from **Table 5** that the new correlation has a mean absolute deviation of 9.23%, and 78.57% of the predicted results fall into the 10% error band, and 95.18% of the predicted results fall into the 20% error band, and 99.39% of the predicted results fall into the 30% error band, indicating that the prediction accuracy of the new correlation is better than that of the existing heat transfer correlations.

5. Conclusions

1. Comprehensive reviews of experimental data of heat transfer of SCW and heat transfer correlations for SCW are conducted in this study. Totally, 250 experimental cases and 12,704 data points about heat transfer of SCW are collected.

2. About 34 heat transfer correlations for SCW are evaluated. It is found that remarkable discrepancies exist among the results predicted by different correlations, and there is no correlation which could give satisfactory prediction accuracy under different heat transfer conditions.

3. A new heat transfer correlation is proposed for heat transfer of SCW flowing in vertically upward tubes under both DHT and EHT regimes, and the prediction performance of the new correlation is better than that of other correlations when both the DHT and EHT regimes are considered at the same time.

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Conflict of interest

The authors declared that there is on conflict of interest.

Appendices and Nomenclature

Bu	buoyance correction factor, $\mathrm{Bu} = \mathrm{Gr}/\left(\mathrm{Re}^{2.7}\overline{\mathrm{Pr}}^{0.5}\right)$
C	constant indices
C_p	specific heat at constant pressure, J/(kg·K)
$\overline{C_\mathrm{p}}$	average specific heat, $(h_w - h_b)/(T_w - T_b)$, J/(kg·K)
d	inner tube diameter, m
f	friction coefficient
g	acceleration due to gravity, m/s^2
Gr	Grashof number
Gr*	acceleration correction factor, $\beta g D^4 q_w/\lambda\nu^2$
$\overline{\mathrm{Gr}}$	average Grashof number, $\overline{\mathrm{Gr}_\mathrm{b}} = gd^3(\rho_b - \overline{\rho})\rho_b/v_b^2$
h	enthalpy, J/kg
k	constant indices
K_v	acceleration correction factor

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Nu	Nusselt number
P	Pressure, Pa
Pr	Prandtl number
$\overline{\mathrm{Pr}}$	average Prandtl number, $\overline{C_{p,b}}\mu_b/\lambda_b$
q^*	buoyance correction factor, $q_w\beta/GC_{p,b}$
q^+	thermal acceleration parameter, $q_w(\beta/C_p)/\overline{\rho u}$
Re	Reynolds number
T	thermodynamic temperature, K
t	Celsius temperature, °C
σ_1	mean relative deviation, MRD
σ_2	mean absolute deviation, MAD
σ_3	standard deviation, SD
F	correction terms

Greek symbols

α	heat transfer coefficient, W/(m^2·K)
β	thermal expansion coefficient, K^{-1}
λ	thermal conductivity W/(m·K)
μ	dynamic viscosity, Pa·s
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
$\overline{\rho}$	average density, $\overline{\rho} = \frac{1}{T_w - T_b}\int_{T_b}^{T_w}$, kg/m^3
ρ_{xy}	correlation coefficient

Subscripts

b	at bulk temperature experimental
cal	calculated value
exp	experimental value
pc	pseudo-critical point
w	at inner wall temperature

Abbreviations

DHT	deteriorated heat transfer
EHT	enhanced heat transfer
LSHR	the large specific heat region
MAD	mean absolute deviation
MRD	mean relative deviation
NHT	normal heat transfer
SD	standard deviation
SCFs	supercritical pressure fluids
SCW	supercritical water
SCWRs	supercritical water-cooled reactors

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References

[1] Kelly JE. Generation IV international forum: A decade of progress through international cooperation. Progress in Nuclear Energy. 2014;**77**:240-246. DOI: 10.1016/j.pnucene.2014.02.010

[2] Lei X, Guo Y, Zhang W, Li H, Li L. Development of heat transfer correlation for supercritical water in vertical upward tubes. Heat Transfer Engineering. 2018;**40**:652-666. DOI: 10.1080/01457632.2018.1436656

[3] Mokry S, Pioro I, Kirillov P, Gospodinov Y. Supercritical-water heat transfer in a vertical bare tube. Nuclear Engineering and Design. 2010;**240**: 568-576. DOI: 10.1016/j.nucengdes.2009.09.003

[4] Pioro IL, Duffey RB. Experimental heat transfer in supercritical water flowing inside channels (survey). Nuclear Engineering and Design. 2005; **235**:2407-2430. DOI: 10.1016/j.nucengdes.2005.05.034

[5] Zhang D, Guo L, Zhao J, Jin H, Cao W, Wang R, et al. Kinetics study for sodium transformation in supercritical water gasification of Zhundong coal. International Journal of Hydrogen Energy. 2018;**43**:13869-13878. DOI: 10.1016/j.ijhydene.2017.12.011

[6] Loewenberg MF, Laurien E, Class AG, Schulenberg T. Supercritical water heat transfer in vertical tubes: A look-up table. Progress in Nuclear Energy. 2008;**50**(2):532-538. DOI: 10.1016/j.pnucene.2007.11.037

[7] Zahlan H, Tavoularis S, Groeneveld DC. A look-up table for trans-critical heat transfer in water-cooled tubes. Nuclear Engineering and Design. 2015;**285**:109-125. DOI: 10.1016/j.nucengdes.2014.12.027

[8] Pioro IL, Khartabil HF, Duffey RB. Heat transfer to supercritical fluids flowing in channels—Empirical correlations (survey). Nuclear Engineering and Design. 2004;**230**: 69-91. DOI: 10.1016/j.nucengdes.2003.10.010

[9] Liao C. Investigation on heat transfer correlations and the criterion for the onset of heat transfer deterioration of supercritical pressure water in vertical upward pipes [master]. Xi'an: Xi'an Jiaotong University; 2014

[10] Dittus FW, Boelter LMK. Heat Transfer in Automobile Radiator of the Tubular Type. Vol. 2. Berkeley, Calif: University of California Press; 1930. pp. 3-22. DOI: doi.org/10.1016/0735-1933(85)90003-X

[11] Jackson JD. Fluid flow and convective heat transfer to fluids at supercritical pressure. Nuclear Engineering and Design. 2013;**264**: 24-40. DOI: 10.1016/j.nucengdes.2012.09.040

[12] Pioro IL, Duffey RB. Heat Transfer and Hydraulic Resistance at Supercritical Pressures in Power-Engineering Applications. New York: ASME Press; 2007. DOI: 10.1115/1.802523

[13] Kurganov VA, Zeigarnik YA, Maslakova IV. Heat transfer and hydraulic resistance of supercritical pressure coolants: Part III: Generalized description of SCP fluids normal heat transfer, empirical calculating correlations, integral method of theoretical calculations. International Journal of Heat and Mass Transfer. 2013;**67**:535-547. DOI: 10.1016/j.ijheatmasstransfer.2013.07.056

[14] Pioro IL, Duffey RB, Dumouchel TJ. Hydraulic resistance of fluids flowing in channels at supercritical pressures (survey). Nuclear Engineering and

Design. 2004;**231**:187-197. DOI: 10.1016/j.nucengdes.2004.03.001

[15] Shitsman ME. Impairment of the heat transmission at supercritical pressures(heat transfer process examined during forced motion of water at supercritical pressures). High Temperature Science. 1963;**1**:237-244

[16] Bishop A, Sandberg R. Forced-convection heat transfer to water at near-critical temperatures and supercritical pressures. In: L, Westinghouse Electric Corp. Tong, Pittsburgh, Pa: Atomic Power Div; 1964

[17] Swenson HS, Carver JR, Kakarala Cd. Heat transfer to supercritical water in smooth-bore tubes. Journal of Heat Transfer. 1965;**87**:477-483. DOI: 10.1115/1.3689139

[18] Vikrev YV, Lokshin VJT. An experimental study of temperature conditions in horizontal steam generating tubes at supercritical pressures. Teploenergetika. 1964;**11**: 79-82

[19] Vikhrev YV, Barulin YD, Kon'Kov AS. A study of heat transfer in vertical tubes at supercritical pressures. Thermal Engineering. 1967;**14**:116-119

[20] Styrikovich MA, Margulova TK, Miropol'Skii ZL. Problems in the development of designs of supercritical boilers. Teploenergetika. 1967;**14**(6):4-7

[21] Herkenrath H, Mörk-Mörkenstein P, Jung U, Weckermann F. Wärmeübergang an Wasser bei Erzwungener Strömung im Druckbereich von 140 bis 250 bar, EURATOM, Berlin (1967). EUR. 1967; **3658**:132

[22] Kondratev N. Heat transfer and hydraulic resistance with supercritical water flowing in tubes. Thermal Engineering. 1969;**16**:73

[23] Ackerman JW. Pseudoboiling heat transfer to supercritical pressure water in smooth and ribbed tubes. Journal of Heat Transfer. 1970;**92**:69. DOI: 10.1115/1.3449698

[24] Ornatsky AP, Glushchenko LP, Siomin ET, et al. The research of temperature conditions of small diameter parallel tubes cooled by water under supercritical pressures. Proceedings of the 4th International Heat Transfer Conference. Vol. VI. Paris-Versailles, France: Elsevier Publishing Company; 1970. Paper No. B 8.11

[25] Yamagata K, Nishikawa K, Hasegawa S, Fujii T, Yoshida S. Forced convective heat transfer to supercritical water flowing in tubes. International Journal of Heat and Mass Transfer. 1972; **15**:2575-2593. DOI: 10.1016/0017-9310(72)90148-2

[26] Lee RA, Haller KH. Supercritical water heat transfer developments and applications. Proceedings of the 5th International Heat Transfer Conference. Vol. IV. Tokyo, Japan; 3–7 September 1974. pp. 335-339. Paper No. B7.7

[27] A. Polyakov: Heat transfer under supercritical pressures, in: Advances in Heat Transfer, Vol. 21, Elsevier, 1991. pp. 1–53. DOI: 10.1016/S0065-2717(08)70333-2

[28] Griem H. A new procedure for the prediction of forced convection heat transfer at near- and supercritical pressure. Heat and Mass Transfer. 1996; **31**:301-305. DOI: 10.1007/BF02184042

[29] Koshizuka S, Oka Y. Computational analysis of deterioration phenomena and thermal-hydraulic design of SCR. In: Proc. Proceedings of the First International Symposium on Supercritical Water-Cooled Reactors, Design And Technology

[30] Yoshida S. Heat transfer to supercritical pressure fluids flaming in tubes. Proc. Proc. SCR-2000. pp. 72–78

[31] Hu Z. Heat transfer characteristics of vertical upflow and inclined tubes in the supercritical pressure and near-critical region [doctor]. Xi'an: Xi'an Jiaotong University; 2001

[32] Xu F. Study of water flow and heat transfer characteristics through pipes under supercritical pressure [doctor]. Xi'an: Xi'an Jiaotong University; 2004

[33] Kirillov P, Pometko R, Smirnov A, Grabezhnaia V, Pioro I, Duffey R. Experimental study on heat transfer to supercritical water flowing in 1-and 4-m-long vertical tubes, Proc. Proceedings of GLOBAL 2005, Oct 9–13, 2005, Tsukuba, Japan; 2005. pp. 9-13

[34] Zhu X, Bi Q, Yang D, Chen T. An investigation on heat transfer characteristics of different pressure steam-water in vertical upward tube. Nuclear Engineering and Design. 2009; **239**:381-388. DOI: 10.1016/j.nucengdes.2008.10.026

[35] Wang J. Investigation on heat transfer and frictional pressure drop at low mass flux in the water-wall tubes of supercritical boiler [doctor]. Xi'an: Xi'an Jiaotong University; 2010

[36] Wang J, Li H, Yu S, Chen T. Investigation on the characteristics and mechanisms of unusual heat transfer of supercritical pressure water in vertically-upward tubes. International Journal of Heat and Mass Transfer. 2011; **54**:1950-1958. DOI: 10.1016/j.ijheatmasstransfer.2011.01.008

[37] Mokry S, Pioro I, Farah A, King K, Gupta S, Peiman W, et al. Development of supercritical water heat-transfer correlation for vertical bare tubes. Nuclear Engineering and Design. 2011; **241**:1126-1136. DOI: 10.1016/j.nucengdes.2010.06.012

[38] Pan J, Yang D, Dong Z, Zhu T, Bi Q. Experimental investigation on heat transfer characteristics of water in vertical upward tube under supercritical pressure. Nuclear Power Engineering. 2011;**32**:75-80

[39] Li H, Yang Y, Gu H, Zhao M, Lu D. Experimental study of supercritical water flow and heat transfer in vertical tube. Proc. Progress Report on China Nuclear Science and Technology. pp. 874-880

[40] Li H, Zhao M, Hu Z, Zhang Y, Wang F. Experimental study of supercritical water heat transfer deteriorations in different channels. Annals of Nuclear Energy. 2018;**119**: 240-256. DOI: 10.1016/j.anucene.2018.05.009

[41] Wang L. Research on heat transfer characteristics of supercritical water in the vertical tube [doctor]. Shanghai: Shanghai Jiaotong University; 2012

[42] Wang F, Yang J, Gu H, Zhao M, Li H. D. Lu: Experimental research on heat transfer performance of supercritical water in vertical tube, atomic energy. Science and Technology. 2013;**47**:933-939

[43] Huang Z, Li Y, Zeng X, Yan X, Xiao Z. Experimental and numerical simulation of supercritical water heat transfer in vertical upward circular tube. Atomic Energy Science Technology. 2012;**46**:799-803

[44] Li Y, Zeng X, Huang Z, Yan X, Huang Y, Xiao Z. Experimental study on heat transfer of supercritical water in simple channels. Nuclear Power Engineering. 2013;**34**:101-107

[45] Zhao M, Gu H, Cheng X. Experimental study on heat transfer of

supercritical water flowing downward in circular tubes. Annals of Nuclear Energy. 2014;**63**:339-349. DOI: 10.1016/j.anucene.2013.07.003

[46] Gu H, Zhao M, Cheng X. Experimental studies on heat transfer to supercritical water in circular tubes at high heat fluxes. Experimental Thermal and Fluid Science. 2015;**65**:22-32. DOI: 10.1016/j.expthermflusci.2015.03.001

[47] Shen Z, Yang D, Xie H, Nie X, Liu W, Wang S. Flow and heat transfer characteristics of high-pressure water flowing in a vertical upward smooth tube at low mass flux conditions. Applied Thermal Engineering. 2016;**102**: 391-401. DOI: 10.1016/j.applthermaleng.2016.03.150

[48] Shen Z, Yang D, Chen G, Xiao F. Heat transfer characteristics of high temperature and pressure water in vertical downward tube. CIESC Jorunal. 2013;**64**:2386-2393

[49] Qu M, Liang Z, Zhao Y, Wan L, Yang D. Experimental and numerical investigation on heat transfer characteristics of ultra-supercritical water in smooth tube with low mass flux. Journal of Xi'an Jiaotong University. 2018;**52**:52-59

[50] Miropolskii L, Shitsman M. Heat transfer to water and steam at variable specific heat (in near-critical region). Soviet Physics-Technical Physics. 1957; **2**:2196-2208

[51] Domin G. Wärmeübergang in Kritischen Und Berkritischen Bereichen Von Wasser in Rohren. Brennst-Wäirme-Kraft. 1963;**15**:527-532

[52] Krasyakova LY, Raykin YM, Belyakov II. Investigation of temperature regime of heated tubes at supercritical pressure. Soviet Energy Technology. 1967;(1):1-4

[53] Grass G, Herkenrath H, Hufschmidt W. Anwendung des Prandtlschen Grenzschichtmodells auf den Wärmeübergang an Flüssigkeiten mit stark temperaturabhängigen Stoffeigenschaften bei erzwungener Strömung. Wärme-und Stoffübertragung. 1971;**4**:113-119

[54] Yeroshenko V, Yaskin LJC. Applicability of various correlations for the prediction of turbulent heat transfer of supercritical helium, 21 1981. pp. 94-96. DOI: 10.1016/0011-2275(81) 90055-2

[55] Watts MJ, Chou CT. Mixed convection heat transfer to supercritical pressure water. Proceedings of the 7th International Heat Transfer Conference. Vol. 3. Munchen, Germany: 1982. pp. 495-500. Paper No. 6–10

[56] Petukhov BS, Kurganov VA, Ankudinov VB. Heat transfer and flow resistance in the turbulent pipe flow of a fluid with near-critical state parameters. High Temperature Science. 1983;**21**: 92-100

[57] Kitoh K, Koshizuka S, Oka Y. Refinement of transient criteria and safety analysis for a high-temperature reactor cooled by supercritical water. Nuclear Technology. 2001;**135**:252-264. DOI: 10.13182/NT01-A3220

[58] Jackson JD. Consideration of the heat transfer properties of supercritical pressure water in connection with the cooling of advanced nuclear reactors. In: Proceedings of the 13th Pacific Basin Nuclear Conference. Shenzhen City, China; 21-25 October 2002. (Abstracts)

[59] Fewster J, Jackson JD. Experiments on supercritical pressure convective heat transfer having relevance to SPWR Proceedings of ICAPP'04. Pittsburgh, PA, USA; 13–17 June 2004. (Paper 4342)

[60] Kuang B, Zhang Y, Cheng X. A new, wide-ranged heat transfer correlation of water at supercritical pressures in vertical upward ducts[C]//Seventh

International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Operation and Safety (NUTHOS-7). Seoul, South Korea; Oct. 2008. pp. 5-9

[61] Cheng X, Yang Y, Huang SF. A simplified method for heat transfer prediction of supercritical fluids in circular tubes. Annals of Nuclear Energy. 2009;**36**(8):1120-1128. DOI: 10.1016/j.anucene.2009.04.016

[62] Yu J, Jia B, Wu D, Wang D. Optimization of heat transfer coefficient correlation at supercritical pressure using genetic algorithms. Heat and Mass Transfer. 2009;**45**:757-766. DOI: 10.1007/S00231-008-0475-4

[63] Bringer RP,Smith JM. Heat transfer in the critical region. Vol. 3. 1957. pp. 49-55. DOI: 10.1002/aic.690030110

[64] Gupta S, Farah A, King K, Mokry S, Pioro I. Developing new heat-transfer correlation for supercritical-water flow in vertical bare tubes, Proc. 18th International Conference on Nuclear EngineeringAmerican Society of Mechanical Engineers. 2010. pp. 809-817. DOI: 10.1115/ICONE18-30024

[65] Wang C. Heat transfer analysis and the evaluation of the correlations for supercritical pressure water in vertical pipes [master]. Xi'an: Xi'an Jiaotong University; 2012

[66] Liu X. Heat transfer of water under supercritical pressures in vertical upward tubes [doctor]. Shanghai: Shanghai Jiaotong University; 2012

[67] Wang C, Li H. Evaluation of the heat transfer correlations for supercritical pressure water in vertical tubes. Heat Transfer Engineering. 2014; **35**:685-692. DOI: 10.1080/01457632.2013.837756

[68] Kong X, Li H, Liao C, Lei X, Zhang Q. A new correlation for heat transfer coefficient prediction of supercritical pressure water flowing in vertical upward tubes. Proc. ASME 2016 Heat Transfer Summer Conference, HT 2016, collocated with the ASME 2016 Fluids Engineering Division Summer Meeting and the ASME 2016 14th International Conference on Nanochannels, Microchannels, and Minichannels, July 10, 2016 - July 14, 2016American Society of Mechanical Engineers, p. Heat Transfer Division. DOI: 10.1115/HT2016-7304

[69] Pujol J. The solution of nonlinear inverse problems and the Levenberg-Marquardt method. Geophysics. 2007; **72**:W1-W16. DOI: 10.1190/1.2732552