SPECIFICS OF HEAT TRANSFER TO SCW(LIQUID-LIKE STATE) FLOWING IN A 1-M VERTICAL BARE TUBE WITH UPWARD FLOW

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SuperCritical Water (SCW) is widely used in advanced coal-fired power plants around the world with the main objective to increase thermal efficiency of the Rankine cycle from ~43% at subcritical pressures up to 55% at SuperCritical Pressures (SCPs). Unfortunately, the vast majority of modern Nuclear Power Plants (NPPs) equipped with subcritical-pressure water-cooled reactors have significantly lower thermal efficiencies (30–36% (up to 38% for Generation III+ reactors)) compared to those of advanced thermal power plants.

SuperCritical Water-cooled Reactor (SCWR) is a Generation-IV nuclear-reactor concept. The main advantage of NPPs with SCWRs will be higher thermal efficiencies (45% or even higher). Currently, there are some ideas to develop Small Modular Reactors (SMRs) at SCPs. Therefore, for safe and reliable operation of future SCWRs more experimental data are required in bundle-flow geometries cooled with SCW. However, such experiments are extremely complicated and expensive. Therefore, as a preliminary, but a universal approach, experimental data obtained in vertical bare tubes (with diameters and heated length) similar to those of fuel bundles cooled with SCW are used.

Current paper provides new experimental data obtained in a short (1 m) vertical bare tube (ID 10 mm) cooled with upward flow of SCW. Analysis of this dataset is included.

1. INTRODUCTION

NPPs are one of the main sources of concentrated, reliable, and clean energy. The vast majority of NPPs are equipped with subcritical-pressure water-cooled reactors, therefore, their thermal efficiencies(30-36% (up to 38% for Generation III+ reactors)) are significantly lower than those of SCP coal-fired power plants (up to 55%) and of combined-cycle power plants (up to 62%) [1, 2]. Based on experience in using SCW in thermal-power industry for about 60 years it is very attractive to use SCW in nuclear reactors, i.e., in the GenerationIV SCWR concept [1, 2]. Also, there are discussions on developing SMRscooled with SCW [3].

For SCW SMRs shorter fuel-bundle strings will be used. Therefore, to address this issue a short 1-m heated length vertical bare tube (ID 10 mm) cooled with SCW at pressures of 24.5-25.0 MPa was used in the current experiments. These experiments have been performed by Professor P.L. Kirillov and his co-workers at the IPPE (Obninsk, Russia) [4].

In general, at SCPs three Heat Transfer (HT)regimes at forced convectioncan be identified [1, 2, 4, 5]:

1) Normal HT (NHT), which characterized with Heat Transfer Coefficients (HTCs) similar to those of subcritical-pressure convective HT far from critical or pseudocritical regions, when they are calculated according to the conventional single-phase Dittus-Boelter-type correlations:

$$\mathbf{Nu} = 0.023\,\mathbf{Re}^{0.8}\mathbf{Pr}^{0.4} \qquad (1)$$

2) Improved HT (IHT) is characterized with higher values of the HTC compared to those for NHT; and, hence, lower values of wall temperature within some part of a test section or within the entire test section. In our opinion, the IHT regime or mode includes peaks or “humps” in the HTC near or within the critical or pseudocritical regions. And

3) Deteriorated HT (DHT) is characterized with lower values of the HTC compared to those for NHT; and, hence, has higher values of wall temperature within some part of a test section or within the entire test section.

One of the most important / dangerous HT regimes is the DHT. Experimental data currently available to predict the DHT regime in bare tubes are limited and inconsistent [1, 2, 4, 5]. There are a number of HT correlations have been developed for SCW, but, unfortunately, all of them can predict HTC profiles only at NHT and IHT regimes [1, 2, 4, 5]. Therefore, to predict, at least, heat flux at which the DHT starts, thePioro-Mokry correlation is used [5]:

$$q_{\mathrm{dht}} = -58.97 + 0.745G, \qquad (2)$$

where:mass flux (G) is in kg/m^{2}s and q_{dht} – in kW/m^2.

Also, it is known that the DHT regime quite often appears, when wall or bulk-fluid temperatures are within the pseudocritical region [1, 2, 4, 5]. Due to this 6 HT experiments from the Kirillov et al. dataset[4] related to “liquid-like” cooling with SCW were chosen for further analysis.Pseudocritical region is the region that is located within the approximately ±25°C around the pseudocriticalpoint, and within this region all thermophysical properties of SC fluid undergo significant variations. The pseudocritical point is characterized with P and T_{pc},, where P is the pressure above the critical pressure and the temperature ($T_{\mathrm{pc}} > T_{\mathrm{cr}}$) corresponding to the maximum value of specific heat at this particular pressure.

This paper is focused on tests in which a bulk-fluid temperature is always below the pseudocritical temperature (T_{pc}), but a wall temperature can be below, equal or above the T_{pc}.

2. IPPE SUPERCRITICAL-WATER TEST FACILITY

The SKD-1 loop utilizes de-ionized and distilled water loop at high pressures and high temperatures [2, 4]. The operating pressure is up to 28 MPa. SCW passes through a flowmeter, preheater, test-section mixer, main coolers, and then returns back to the pump. A 600-kW (AC) power supply is used to deliver power to the test section.

The data for this study were obtained within the following conditions: Vertical stainless-steel (12Cr18Ni10Ti (similar to SS-304)) smooth tube: D = 10 mm, δ_w= 2 mm, and L_h= 1 m; tube internal-surface roughness R_a= 0.63 – 0.8 μm; and upward flow. Table 1 lists maximum uncertainties of measured and calculated parameters. Test matrix was proposed to be as close as possible to operating conditions of future SCWRs [1-3].

All thermophysical properties of SCW were obtained from the NIST REFPROP (2013) Ver. 9.1 [6]. Inlet and outlet bulk-fluid temperatures and outside-wall temperatures were measured as well as the inlet pressure and pressure drop over the test section. Heat flux was estimated based on measured voltage and current (power) through the test section and internal-tube heat-transfer area. Inner-wall temperature was calculated based on heat flux, thermal conductivity, wall thickness, and assuming uniformly distributed heat sources (electrical current).

Table 1. Maximum uncertainties of measured and calculated parameters [4].

Parameters		**Max. Uncertainty**
Measured Parameters	Test-Section power	±1.0%
	Inlet Pressure	±0.25%
	Wall Temperatures	±3.0°C
Calculated Parameters	Mass-flow rate	±1.5%
	Heat loss	≤3%

3.EXPERIMENTAL RESULTS

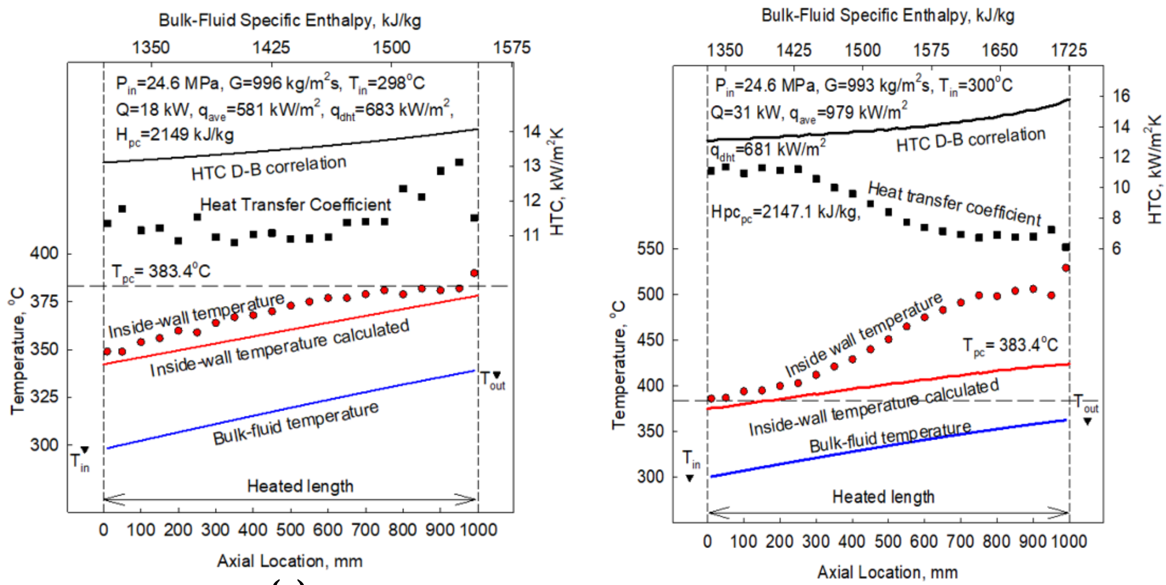
Experimental data are shown in Figs. 1-3. Experimental data are presented as profiles of bulk-fluid temperature (calculated through the heat balance and based on inlet bulk-fluid temperatures;internal-walltemperature;and HTC (for both parameters experimental and calculatedthrough the Dittus-Boelter correlation(Eq. (1)) values were shown). All experimental data were obtained within the following conditions: Bulk-fluid temperature was always below the T_{pc}; but internal-wall temperature was below, equal or above theT_{pc}.For comparison purposes q_{dht} values are also shown in all graphs (Figs. 1-3), which were calculated according to Eq. (2). Comparison of these data with the experimental heat flux shows that almost all tests were obtained within the DHT regime.

Figure 2 shows experimental data at P=24.6 MPa; G≈995 kg/m^{2}s; T_{in}≈300°C;and at two values of heat flux: (a) 581 and (b) 979 kW/m^2. Data in Fig. 1a were obtained at heat flux lower by ~20% that the predicted q_{dht}. Therefore, two HT regimes can be identified here: 1) NHT (L_h=0 – 800 mm) and 2) IHT (L_h=800 – 1000 mm, when wall temperature is close to T_{pc}).The HTCs predicted through the Dittus-Boelter correlation are higher by about 20 experimental HTCs. Data in Fig. 1b were obtained at heat flux higher by ~30% that the predicted q_{dht}. Therefore, two HT regimes can be identified here: 1) NHT (L_h=0 – 300 mm) and 2) DHT (L_h=300 – 1000 mm). Within the heated length of 750 – 1000 mm (DHT regime) experimental HTCs are lower by ~40% compared to those within the NHT regime.

Figure 2 shows experimental data at P≈24.9 MPa; G≈495 kg/m^{2}s; T_{in}≈350°C; and at two values of heat flux: (a) 390 and (b) 433 kW/m^2. Data in Fig.2a were obtained at heat flux higher by ~20% that the predicted q_{dht}. Therefore, three HT regimes can be identified here: 1) NHT (L_h=0 – 100 mm); 2) DHT (L_h=100 – 750 mm); and 3) IHT (L_h=750 – 1000 mm, when bulk-fluid temperature is close to T_{pc}). Data in Fig. 2b were obtained at heat flux higher by ~30% that the predicted q_{dht}. Therefore, two HT regimes can be identified here: 1) NHT (L_h=0 – 100 mm) and 2) DHT (L_h=100 – 1000 mm). Both Figs. 2a and 2b show a peak in wall-temperature profile within the heated length of 200 – 500 mm (DHT regime) / dip in the HTC profile.

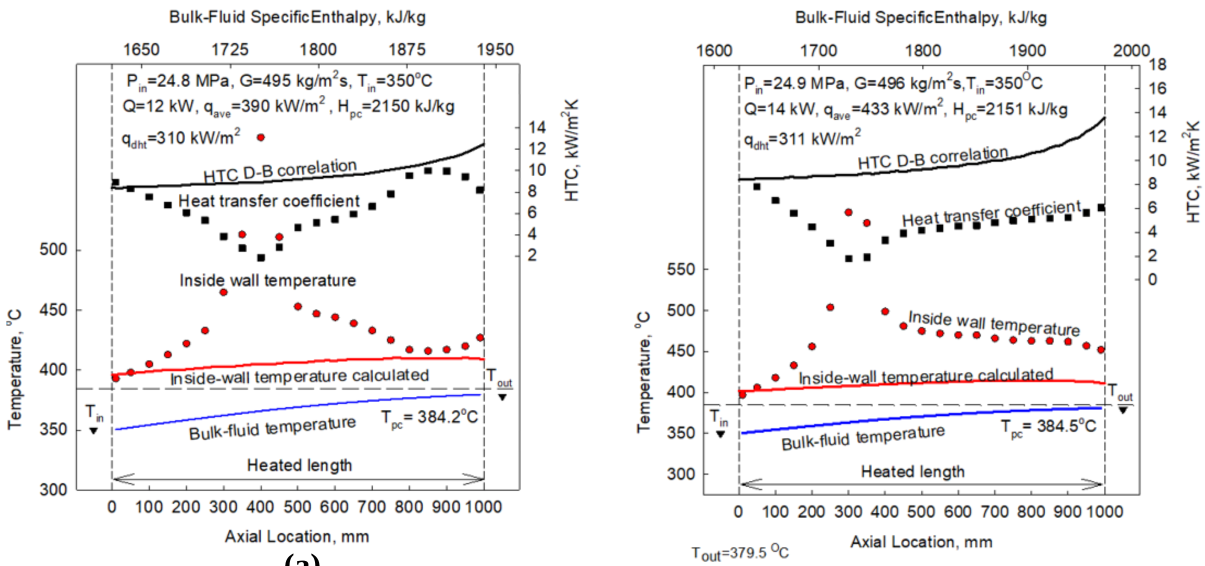
Figure 3a,b shows experimental data at P=24.9 MPa; G=200 kg/m^{2}s; (a) T_{in}=349°C and (b) 301°C; and at two values of heat flux: (a) 88 and (b) 227 kW/m^2. Data in Fig.3a were obtained at heat flux almost the same as the predicted q_{dht}. Therefore, three HT regimes can be identified here: 1) NHT (L_h=0 – 100 mm); 2) DHT (L_h=100 – 450 mm); and 3) IHT (L_h=700 – 1000 mm, when wall and bulk-fluid temperaturesare close to T_{pc}). Data in Fig. 3b were obtained at heat flux higher in 2.5 times than the predicted q_{dht}. Therefore, two HT regimes can be identified here: 1) NHT (L_h=0 – 50 mm and 250 – 950 mm) and 2) DHT (L_h=50 – 950mm). Both Figs. 2a and 2b show a peak in wall-temperature profile within the heated length of 100 – 300 mm (DHT regime) / dip in the HTC profile.

In general, the NHT regime can be predicted with a reasonable accuracy through the Dittus-Boelter correlation. However, the Dittus-Boelter correlation overestimates HTC values within the pseudocritical region due to the peak in specific heat.



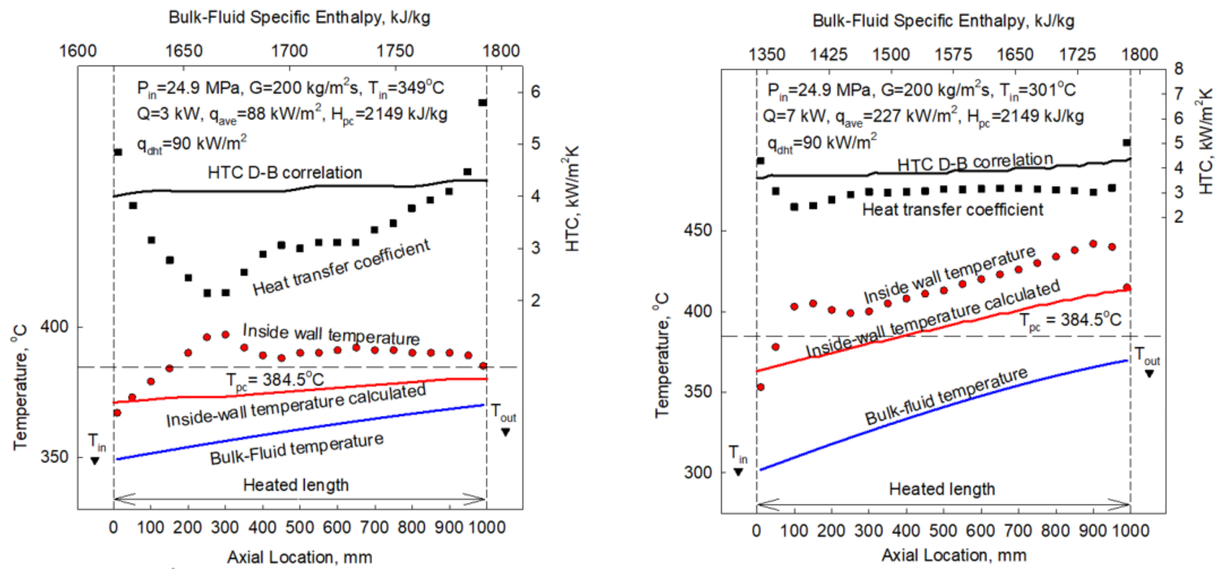
(a) **(b)**

Fig. 1. Profiles of bulk-fluid and internal-wall temperatures, and HTC along heated length of vertical bare tube with upward flow of SCW at various heat fluxes ((a) 581 and (b) 979kW/m^2): P=24.6 MPa; G≈995 kg/m^{2}s; and T_{in}≈300°C. Points – experimental data; curves – calculated data; curves for HTC and T_{wall} are calculated through Dittus-Boelter correlation (Eq. (1)).



(a) (b)

Fig. 2. Profiles of bulk-fluid and internal-wall temperatures, and HTC along heated length of vertical bare tube with upward flow of SCW at various heat fluxes ((a) 390 and (b) 433 kW/m^2): P≈24.9 MPa; G≈495 kg/m^{2}s; and T_{in}≈350°C.



(a) (b)

Fig. 3. Profiles of bulk-fluid and internal-wall temperatures, and HTC along heated length of vertical bare tube with upward flow of SCW at various heat fluxes ((a) 88 and (b) 227 kW/m^2) and inlet temperatures ((a) 349°C and (b) 301°C): P=24.9 MPa and G=200 kg/m^{2}s.

4. CONCLUSIONS

Experiments conducted in the SKD-1 SCW loop with the test section as a vertical bare tube, upward flow, bulk-fluid temperature below the pseudocriticaltemperature, but internal-wall temperature below, equal, and above the T_{pc}at the corresponding pressure, and experimental heat flux in the vast majority cases above the corresponding q_{dht} values, showed that:

1. In a short tube (1-m heated length) NHT regime can be predicted with a reasonable accuracy with the Dittus-Boelter correlation. However, the Dittus-Boelter correlation overestimates HTC values within the pseudocritical region due to the peak in specific heat.
2. Due to high experimental heat flux, which is higher than the q_{dht} values at the

corresponding mass flux in some runs, the DHT regime exists over significant heated length of the test section, and in majority cases there are peak in wall-temperature profiles / dip in the HTC profiles within the DHT regime. Exceptions are only first HTC inlet points, which are almost the same as those predicted with the Dittus-Boelter correlation.

3. Important conclusion is that the DHT regime is quite stable, i.e., if operating conditions are not changed, then the wall-temperature profile is also stable along the heated length.

NOMENCLATURE

c_{p}	specific heat at constant P, J/kg K	Subscripts	
D	inside diameter, m	ave	average
G	mass flux, kg/m^{2}s	dht	deteriorated heat transfer
HTC	Heat Transfer Coefficient, $\mathrm{W/m^2K}$	out	outlet
H	specific enthalpy, $\mathrm{J/kg}$	pc	pseudocritical point
k	thermal conductivity, $\mathrm{W/m \cdot K}$		Abbreviations and Acronyms
L_{h}	heated length, m	AC	Alternating Current
$\dot{m}$	mass flow rate, $\mathrm{kg/s}$	DHT	Deteriorated Heat Transfer
P	pressure, Pa	HT	Heat Transfer
Q	heat transfer rate, W	HTC	Heat Transfer Coefficient
q	heat flux, $\mathrm{W/m^2}$	ID	Inner Diameter
T	temperature, $\mathrm{°C}$	IHT	Improved Heat-Transfer
Greek Letters		IPPE	Institute of Physics & Power Eng.
δ_{w}	wall thickness, m	NHT	Normal Heat Transfer
μ	dynamic viscosity, $\mathrm{Pa \cdot s}$	NPP	Nuclear Power Plant
ρ	density, $\mathrm{kg/m^3}$	SCP	SuperCritical Pressure
Non-dimensional Numbers		SCW	SuperCritical Water
Nu	Nusselt number $\left(\frac{HTC \cdot D}{k}\right)$	SCWR	SuperCritical Water-cooled Reactor
Pr	Prandtl number $\left(\frac{\mu \cdot c_p}{k}\right)$	SMR	Small Modular Reactor
Re	Reynolds number $\left(\frac{G\,D}{\mu}\right)$		

REFERENCES

[1] Handbook of Generation IV Nuclear Reactors, 2016. Editor: I.L. Pioro, Elsevier – Woodhead Publishing (WP), Duxford, UK, 940 pages.
[2] Pioro, I. and Duffey, R., 2007. Heat Transfer and Hydraulic Resistance at Supercritical Pressures in Power-Engineering Applications, ASME Press, New York, USA, 334 pages.
[3] Yetisir, M., Pencer, J., McDonald, M., Gaudet, M., Licht, J., and Duffey, R., 2012. The SUPERSAFE©Reactor: A Small Modular Pressure Tube SCWR, AECL Nuclear Review, Vol. 1, No. 2, pp. 13-18.
[4] Kirillov, P., Pometko, R., Smirnov, A., et al., 2005. Experimental Study on Heat Transfer to Supercritical Water Flowing in 1- and 4-m-Long Vertical Tubes. In: Proc. GLOBAL'05, Tsukuba, Japan, Oct. 9–13, Paper No. 518.
[5] Mokry, S., Pioro, I., Farah, A., King, K., Gupta, S., Peiman, W., and Kirillov, P., 2011. Development of Supercritical Water Heat-Transfer Correlation for Vertical Bare Tubes, Nuclear Eng.& Design, Vol. 241, No. 4, pp. 1126-1136.
[6] NIST REFPROP, 2013. Reference Fluid Thermodynamic and Transport Properties, NIST Standard Reference Database 23, Ver. 9.1, Developers: E.W. Lemmon, M.L. Huber, and M.O. McLinden, Applied Chemicals and Materials Division,National Institute of Standards Technology (NIST), Boulder, CO, 80305, USA.