Specifics of Forced-Convective Heat Transfer in Supercritical Carbon Dioxide

A. Eugene Saltanov, B. David Mann, C. Glenn Harvel, and D. Igor Pioro
University of Ontario Institute of Technology, Ontario, Canada
(Eugene.saltanov@hotmail.com)

A PhD Level Submission

Summary

The appropriate description of heat-transfer to coolants at supercritical state is one of the main challenges in development of supercritical-fluids applications for the Generation–IV reactors. In this paper the basis for comparison of relatively recent experimental data on supercritical carbon dioxide (CO_2) obtained at facilities of the Korea Atomic Energy Research Institute (KAERI) and Chalk River Laboratories (CRL) of Atomic Energy of Canada Limited (AECL) is discussed, and a preliminary heat-transfer correlation for joint CRL and KAERI datasets is presented.

1. Introduction

The majority of experiments with forced convective flow of fluid at SuperCritical (SC) state where done with water. Starting from early experiments in the late 50's and early 70's [1-6], the general behavior of SuperCritical Water (SCW) was described. Researchers have noticed that at a certain combination of inlet parameters, the wall temperature along the heated part of the tube for SCW flow would experience a sharp increase. Such generic behavior was called a Deteriorated Heat Transfer (DHT). It was also noticed that DHT at SC conditions caused much smoother wall temperature distribution and lesser temperature jumps compared to the case of DHT caused by reaching Critical Heat Flux (CHF) at subcritical conditions. Although researchers spotted similar behavior, the actual data on heat transfer to SCW showed considerable variations [7-8], and, therefore, criteria for the onset of DHT proposed by various authors differ and often contradict each other. In addition to this, numerous semi-empirical models proposed to describe the experimental data since the mid 60's turned out to satisfactorily describe just the data they were designed for. In the end, finding these data is generally a challenging task for the following reasons:

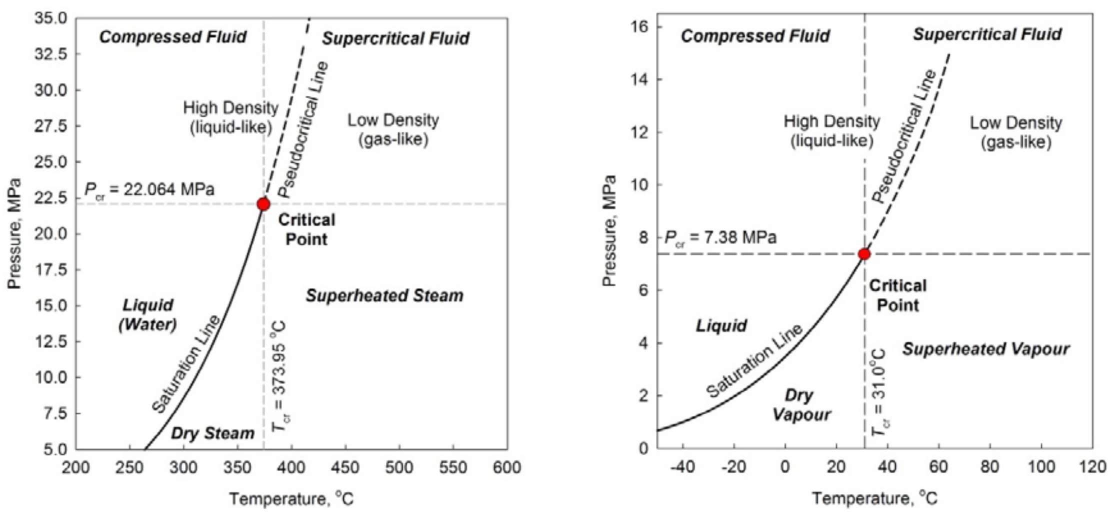
1) Generally, these data are commercial or proprietary.

2) Many datasets, especially, those obtained before 1965, were lost. In some cases, investigators who knew the location of the data died or retired; in some cases, the data were never properly archived; in other cases, laboratories, where the data were obtained were closed (e.g., UKAEA) [9]. Groeneveld *et al*. estimated that only a half of the originally reported data on heat transfer to water at SC conditions is available [9].

3) The bulk of available data are in graphical form. Accuracy of digitized data depends both on the quality of the original graphs and also on the quality of the digitizing software. Moreover, experimentalists would be able to publish just small portions of their data due to the limitations of publications.

Therefore, due to the importance of resolving the problem of accurate prediction of heat transfer to SCW, the International Atomic Energy Agency (IAEA) established a coordinated research project "Heat Transfer Behavior and Thermal-Hydraulics Code Testing for Super-Critical Water-cooled Reactors". The first step of this project is to "establish a base of accurate data for heat transfer, pressure drop, blowdown, natural circulation, and stability for conditions relevant to super-critical fluids [10].

Since the critical parameters of water are very high (22.064 MPa and 374.1°C), performing forced-convection heat-transfer experiments in SCW is a complex and expensive task. Therefore, it is reasonable to study general properties of SC fluids by running experiments with modeling fluids (sometimes, the term 'surrogate fluids' is used instead). CO_2 and R-134a are the two most widely used modeling fluids. Under certain conditions, the results can be later interpreted and scaled to SCW conditions (for a discussion on proper scaling methodology, see References [11-12]). In comparison, critical parameters of CO_2 (7.38 MPa and 30.48°C) are significantly lower than those of SCW (see Figure 1).



(a) (b)

Figure 1. Pressure-temperature diagram for water (a) and CO_2 (b) (data were calculated using NIST Refprop v9.0)

The development of sophisticated theoretical models is very important for improving the understanding of physical processes behind the forced-convective heat-transfer and its deterioration in the near-critical region. However, not all turbulent models implemented in Computational Fluid Dynamics (CFD) codes are applicable to heat transfer at supercritical pressures. Numerous recent worldwide CFD studies showed that models based on the Reynolds number Averaged Navier-Stokes (RANS) equations are able to capture temperature trends at normal conditions and predict the onset of deterioration; however, these models fail to capture deteriorated heat transfer numerically [13-17]. It should be noted that in most of these works, CFD results were validated based on old data presented in [5-6], [18]. Only one study was validated against more recent data [resented in [19]. Therefore, there is still a great reliance on 1D heat-transfer correlations for fast preliminary calculations.

The majority of empirical correlations were proposed in the 1960s – 1970s, when experimental techniques were not at as advanced level as they are today. Also, thermophysical properties of fluids have been updated since that time (for example, a peak in thermal conductivity of water in critical and pseudocritical points within a range of pressures from 22.1 to 25 MPa was not officially recognized until the 1990s) [14], [20]. Although, there were numbers of more recent correlations developed for water [21-24], there were only two recent correlations proposed for CO_2 (see [25-26]) based on the data obtained by Dr. Pioro at Chalk River Laboratories (CRL) [7]. Unfortunately, previous analysis of the latter two correlations (Saltanov *et al.*, 2013) showed that they fail to predict SC CO_2 data obtained in different experiments. Therefore, they should be revised, and the reason for their failure must be established. Also, data on heat transfer to SCW used at SC fossil-fired plants cannot be used directly, because typical hydraulic diameters are around 18 mm, while in SuperCritical Water-cooled Reactors (SCWRs) those will be between 4 – 9 mm. This significantly affects the development and distribution of velocity and thermal fields across the heated channel.

2. Basis for Comparison of the Joint Datasets

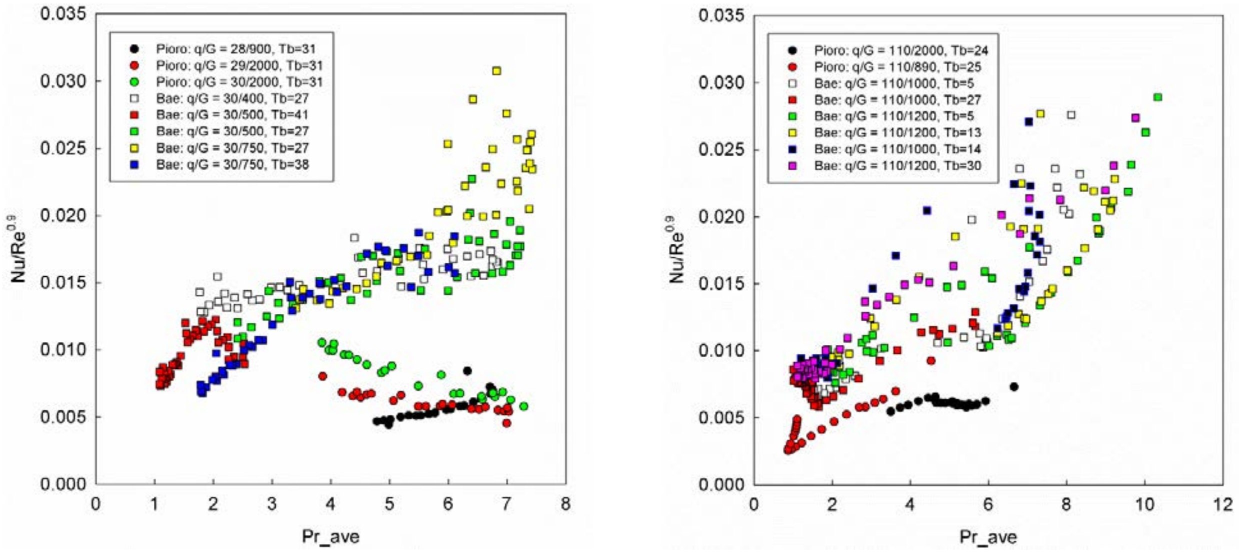
The KAERI and AECL datasets were compared based on the similarity of heat flux at the inlet to test-section (see Figures 2–3).

The following are the major conclusions of this comparison:

- The results are consistent for the same geometry and slight variation of input parameters;
- There is a clear similarity in the pattern of the data between different geometries in the cases of close values of heat and mass fluxes. Similarity based on $\frac{T_b}{T_{pc}}$ may be one of the uniting parameters for the experimental data.

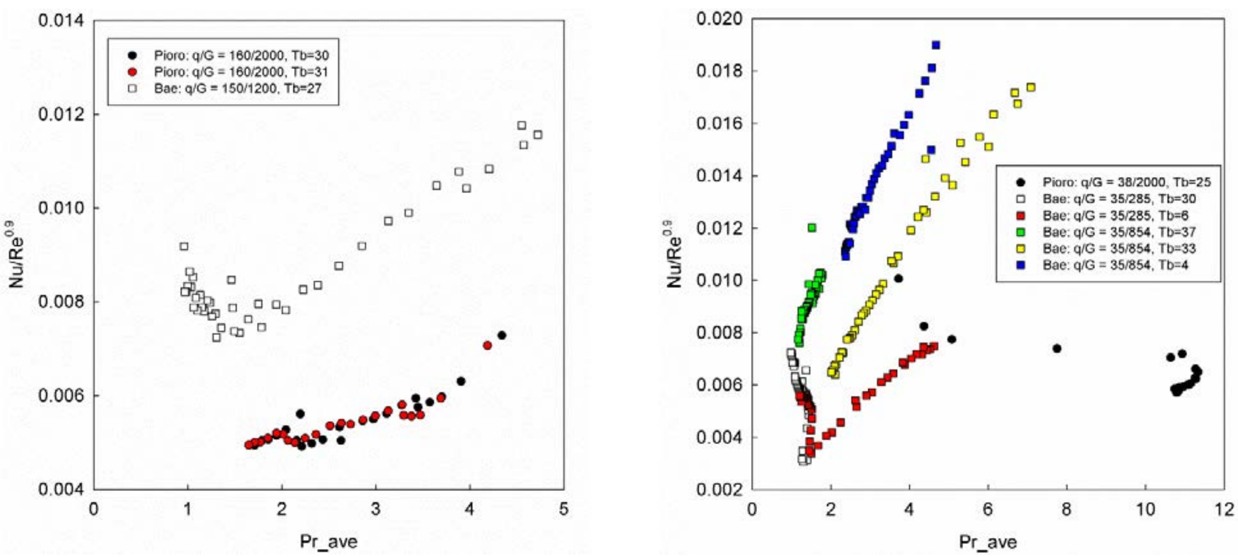
The major problem of this comparison is the lost information on the location. The authors of this paper expect that behavior could be better generalized based on the non-dimensional "coordinate" which is introduced here as follows:

$$X = \frac{h_b - h_{pc}}{q / G} \tag{1}$$



(a) (b)

Figure 2. Comparison of KAERI and AECL data based on similarity of heat flux at the inlet to the test-section (a – P=8.85 MPa, q=30 kW/m^2, d=4.4 mm (KAERI), d = 8.1 mm (AECL); b – P=7.75 MPa, q=110 kW/m^2, d=4.4 mm (KAERI), d = 8.1 mm (AECL));



(a) (b)

Figure 3. Comparison of KAERI and AECL data based on similarity of heat flux at the inlet to the test-section (a – P=8.85 MPa, q=150 kW/m^2, d=4.4 mm (KAERI), d = 8.1 mm (AECL); b – P=7.75 MPa, q=35-38 kW/m^2, d=6.32 mm (KAERI), d = 8.1 mm (AECL));

3. A Preliminary Heat-Transfer Correlation for Joint CRL and KAERI datasets.

Following the methodology discussed in Reference [27], the authors developed the following preliminary correlation for join CRL and KAERI data:

$$\mathbf{Nu_b} = 0.0364\,\mathbf{Re_b^{0.778}}\,\overline{\mathbf{Pr}}_\mathbf{b}^{0.413}\left(\frac{\rho_w}{\rho_b}\right)^{0.656} \tag{2}$$

(All symbols are defined in Section 5). DHT points were removed based on a visual inspection, and points affected by buoyancy were removed as well.

The RMS for this correlation is 23% for HTC and 4% for T_w. The range of applicability of correlation Eq. (2) is shown in Table 1. Due to the limitations on the size of the extended abstract the authors cannot present or discuss more of their work on the subject.

Table 1. Range of applicability of Eq. (2).

***P*, MPa**	***G*, kg/m²s**	***q*, kW/m²**	**T_b,°C**	***D*, mm**
7.57–8.91	199–3048	9.9–616	5–161	4.4–9.0

4. Conclusions

A basis for comparison of the KAERI and AECL datasets was discussed. The discussion prompted an idea to generalize data based on a new non-dimensional “coordinate”, which was introduced in the paper. Based on a standard methodology, a preliminary correlation for joint CRL and KAERI data was presented. Although RMS error is quite high (23%), the correlation is considered as a success, because it is valid for a wide range of experimental parameters and hydraulic diameters.

5. Nomenclature

Symbols

d, *D*	hydraulic diameter, mm
G	mass flux, kg/m^2·s
h	specific enthalpy, J/kg
k	thermal conductivity, W/m·K
P	pressure, Pa
q	heat flux, W/m^2
T	temperature, K

Greek Letters

μ	dynamic viscosity, Pa·s
ρ	density, kg/m^3

Dimensionless Numbers

Nu Nusselt number $\left(\frac{HTC \cdot D}{k}\right)$

Pr_ave, $\overline{\mathbf{Pr}}$ Average Prandtl number $\left(\frac{h_w - h_b}{T_w - T_b} \cdot \frac{\mu}{k}\right)$

Re Reynolds number $\left(\frac{G \cdot D}{\mu}\right)$

Subscripts

ave	average
b	bulk-fluid
pc	pseudocritical
w	wall

Acronyms

CFD	Computational Fluid Dynamics
CHF	Critical Heat Flux
CRL	Chalk River Laboratories
DHT	Deteriorated Heat Transfer
HTC	Heat Transfer Coefficient
IAEA	International Atomic Energy Agency
KAERI	The Korea Atomic Energy Research Institute
RANS	Reynolds number Averaged Navier-Stokes equations
RMS	Root Mean Square
SC	SuperCritical
SCW	SuperCritical Water
SCWR	SuperCritical Water-cooled Reactor
UKAEA	United Kingdom Atomic Energy Authority

6. Acknowledgements

The authors would like to express their great appreciation to Dr. Y.Y. Bae from the KAERI for his valuable comments and suggestions on experimental data.

7. References

[1] Miropolskiy, Z.L. and Shitsman, M.E., 1957. “Heat Transfer to Water and Steam at Variable Specific Heat (at Near-Critical Region)”, (In Russian), *Journal of Technical Physics*, XXVII (10), pp. 2359–2372.

[2] Shitsman, M.E., 1959. “Heat Transfer to Water, Oxygen and Carbon Dioxide in Near Critical Region, (In Russian)”, *Thermal Engineering*, No. 1, pp. 68–72.

[3] Bishop, A.A., Sandberg, R.O. and Tong, L.S., 1964. “Forced Convection Heat Transfer to Water at Near-Critical Temperatures and Supercritical Pressures,” Report WCAP-2056, Westinghouse Electric Corporation, Atomic Power Division, Pittsburgh, PA, USA, December, 85 pages.

[4] Swenson, H.S., Carver, J.R. and Kakarala, C.R., 1965. “Heat Transfer to Supercritical Water in Smooth-Bore Tubes, Journal of Heat Transfer”, Trans. ASME, Series C, 87 (4), pp. 477–484.

[5] Ornatskiy, A.P., Glushchenko, L.F. and Kalachev, S.I., 1971. "Heat Transfer with Rising and Falling Flows of Water in Tubes of Small Diameter at Supercritical Pressures", *Thermal Engineering*, 18 (5), pp. 137–141.

[6] Yamagata, K., Nishikawa, K., Hasegawa, S., et al., 1972. "Forced Convective Heat Transfer to Supercritical Water Flowing in Tubes", *Int. J. Heat & Mass Transfer*, 15 (12), pp. 2575–2593.

[7] Pioro, I.L. and Duffey, R.B., 2007. "Heat Transfer and Hydraulic Resistance at Supercritical Pressures in Power Engineering Applications", ASME Press, New York, NY, USA, 334 pages.

[8] Cheng, X. and Schulenberg, T., 2001. "Heat Transfer at Supercritical Pressures - Literature Review and Application to a HPLWR", Forschungszentrum Karlsruhe, Technik und Umwelt, Wissenschaftliche Berichte, FZKA 6609, Institute für Kern- und Energietechnik, May, 45 pages.

[9] Groeneveld, D., Tavoularis, S., Gudla, P., Yang, S., and Leung, L.K.H., 2007. "Analytical and Experimental Program of Supercritical Heat Transfer Research at the University of Ottawa", Proc. 3rd Int. Symp. on SCWR - Design and Technology (ISSCWR-3), March 12–15, Shanghai, China, Paper# 17, pp. 380–391.

[10] Cleveland, J., Nusret, A., and Duffey, R., 2007. "Status and Plan for the IAEA Coordinated Research Programme on Heat Transfer Behaviour and Thermo-hydraulics Code Testing for SuperCritical Water-Cooled Reactors", Proc. 3rd Int. Symp. on SCWR - Design and Technology (ISSCWR-3), March 12–15, Shanghai, China, Paper# I005, pp. 138–149.

[11] Jackson, J.D. and Hall W.B., 1979. "Forced Convection Heat Transfer to Fluids at Supercritical Pressure", In book: Turbulent Forced Convection in Channels and Bundles, Editors S. Kakaç and D.B. Spalding, Hemisphere Publishing Corp., New York, New York, USA, Vol. 2, pp. 563–612.

[12] Gorban, L.M., Pomet'ko, R.S., and Khryaschev, O.A., 1990. "Modeling of Water Heat Transfer with Freon of Supercritical Pressure, (In Russian)", ФЭИ-1766, Institute of Physics and Power Engineering (ФЭИ), Obninsk, Russia, 19 pages.

[13] Sharabi, M., Ambrosini, W., Forgione, N, and He, S., 2007. "Prediction of Experimental Data on Heat Transfer to Supercritical Water with Two-Equation Turbulence Models", Proc. 3rd Int. Symp. on SCWR - Design and Technology (ISSCWR-3), March 12–15, Shanghai, China, Paper# 28, pp. 413–428.

[14] Sharabi, M., Manera, A., and Andreani, M., 2009. "Implementation of Improved Heat Transfer Correlations in RELAP5 and Application to HPLWR", Proc. 4th Int. Symp. on Supercritical Water-Cooled Reactors (ISSCWR-4), March 8–11, Heidelberg, Germany, Paper# 79, 12 pages.

[15] Gu, H.Y., Cheng, X., and Yang, Y.H., 2009. "CFD Study on Heat Transfer Deterioration Phenomenon in Supercritical Water through Vertical Tube", Proc. 4th Int. Symp. on Supercritical Water-Cooled Reactors (ISSCWR-4), March 8–11, Heidelberg, Germany, Paper# 22, 17 pages.

[16] Shams, A., Visser, D.C., and Roelofs, F., 2011. "Influence of Numerical Tools on the Flow and Heat Transfer of Supercritical Water", Proc. 14th Int. Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-14), September 25–29, Toronto, Canada, Paper #445, 12 pages.

[17] Jaromin, M. and Anglart, H., 2011. "Sensitivity Analysis of Heated Wall Temperature and Velocity Distribution in CFD Simulations of the Upward Flow of Supercritical Water", Proc. 14th Int. Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-14), September 25–29, Toronto, Canada, Paper# 231, 17 pages.

[18] Shitsman, M.E., 1963. "Impairment of the Heat Transmission at Supercritical Pressures", *High Temperatures*, 1 (2), pp. 237–244.

[19] Pismenny, E.N., Razumovskiy, V.G., Maevskiy, A.E., and Pioro, I., 2006. "Heat Transfer to Supercritical Water in Gaseous State or Affected by Mixed Convection in Vertical Tubes", Proc. ICONE-14, July 17–20, Miami, FL, USA.

[20] Pioro, I., Gupta, S., and Mokry, S., 2012. "Heat-Transfer Correlations for Supercritical Water and Carbon Dioxide Flowing Upward in Vertical Bare Tubes", Proc. ASME 2012 Summer Heat Transfer Conf., July 8–12, Rio Grande, Puerto Rico, Paper# 58514, 12 pages.

[21] Griem, H., 1996. "A New Procedure for the Prediction of Forced Convection Heat Transfer at Near- and Supercritical Pressure, Heat and Mass Transfer" (Warme- und Stoffubertragung), Springer-Verlag Publishing House, 31 (5), pp. 301-305.

[22] Jackson, J.D., 2008. "A Semi-Empirical Model of Turbulent Convective Heat Transfer to Fluids at Supercritical Pressures", Proc. ICONE-16, May 11–15, Orlando, FL, USA, Paper #48914, 11 pages.

[23] Mokry, S., Farah, A., King, K., et al., 2009. "Development of a Supercritical Water Heat-Transfer Correlation for Vertical Bare Tubes", Proc. Int. Conf. "Nuclear Energy for New Europe", Bled, Slovenia, Sep. 14–17, Paper #210, 14 pages.

[24] Gupta, S., Mokry, S. and Pioro, I., 2011. "Developing a Heat-Transfer Correlation for Supercritical-Water Flow in Vertical Bare Tubes and Its Application in SCWRS", Proc. ICONE-19, Osaka, Japan, October 24–25, Paper# 43503, 11 pages.

[25] Mokry, S., Pioro, I., Farah, A., et al., 2011. "Development of Supercritical Water Heat-Transfer Correlation for Vertical Bare Tubes", *Nuclear Engineering and Design*, 241, pp. 1126–1136.

[26] Gupta, S., McGillivray, D., Surendran, P., Trevani, L., and Pioro, I., 2012. "Developing Heat-Transfer Correlations for Supercritical CO_2 Flowing in Vertical Bare Tubes", Proc. ICONE20-POWER2012, July 30–August 3, Anaheim, CA, USA, Paper #54626, 13 pages.

[27] Saltanov, E., Pioro, I., and Harvel, G., 2013. "Preliminary Investigation of Heat-Transfer Correlation for Upward Flow of CO_2 at Subcritical Pressure", Proc. ICONE-21, July 30–August 3, Chengdu, China, Paper #16399, 10 pages.