ASSESSMENT OF HEAT TRANSFER CORRELATIONS AGAINST SURROGATE FLUID HEAT TRANSFER DATA

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Abstract

AECL R&D work covers experiments, analysis, sub-channel code development and applications, and neutronic and thermalhydraulic coupling analysis to improve the understanding of heat transfer, stability, and critical flow. The latest advances in thermalhydraulics and safety R&D at AECL have been summarized. A compilation of experimental data on heat transfer with supercritical non-aqueous flows over bundle subassemblies and in tubes is presented. Several tube-data based supercritical heat-transfer correlations were assessed against the bundle data. None of these correlations closely predict the experimental data.

1. Introduction

Among various Generation-IV International Forum (GIF) participants in the design of the Super-Critical Water-cooled Reactor (SCWR) concept, Canada has interest mainly on the pressure-tube type design concept, which is a natural extension of the existing CANDU®[1] reactor. Thermalhydraulics characteristics at supercritical water flow conditions are required in support of the design and qualification of the fuel bundle and safety analyses for the SCWR. The lack of qualified experimental data on heat transfer and pressure drop for supercritical water flow has been identified as a significant risk. This is due to the drastic deterioration of heat-transfer characteristics in the vicinity of the critical point. Fundamental understanding of thermalhydraulics characteristics has relied on experimental information obtained with tubes, annuli, and bundle subassemblies. Experimental data obtained with tubes and bundles at supercritical water conditions are required for the development of heat-transfer correlations. The tube data provide a fundamental understanding of the SC heat transfer phenomena, but may not be directly applicable to bundle geometries with a large degree of flow and enthalpy imbalances. Full-scale bundle (or bundle sub-assemblies) experiments were performed at some institutes, but most data are proprietary information and details of these experiments are generally unavailable. Based on the published information on small bundles, there are differences in SC heat-transfer characteristics between tubes and bundles. The sub-channel effect in bundles appears to have improved the SC heat transfer.

Testing with SCW flow is costly and inflexible due to the severe operating conditions. Surrogate fluids have been adopted in sub- and supercritical heat-transfer studies. A large amount of experimental data on SC heat transfer is available for carbon dioxide and various types of refrigerants in tubes. The objective of this study is to compile a surrogate-fluid database on supercritical heat transfer for tubes and bundles, and use these data to assess the existing tube-data based correlations for the supercritical heat-transfer.

2. Heat Transfer in Tubes and Bundles for the Surrogate Fluids

[1] CANDU-Canada Deuterium Uranium (a registered trademark of Atomic Energy of Canada Limited (AECL))

2.1 Heat Transfer in Tubes

A supercritical heat-transfer database for surrogate fluids in tubes was assembled to examine parametric and asymptotic trends of these databases. A total of 3787 data points were compiled for Freon-12, CO_2, N, and He (see Table 1). After applying fluid-to-fluid modeling parameters, the surrogate-fluid data were converted into water-equivalent values, which in turn were used to verify the water-data based correlations.

Table 1 : Surrogate Fluid Database for Tubes

Reference	P (MPa)	T_{in} (K)	q (kW/m^2)	G (kg/m^{2}s)	Comments
	Carbon Dioxide				
Adebiyi and Hall (1976) [1]	7.6	283.1 – 303.2	5.2 – 26.9	104.4 – 392.2	Tube ID : 22.1 mm, L=2440 mm, Horizontal
Ankudinov and Kurganov (1982) [2]	7.7	293.1	297.3 – 952.9	2050 – 3230	Tube ID : 8.0 mm, L=1840 mm, Horizontal, Upward, Downward
Bae (2006) [3]	8.2	278.1	10 – 90	400 – 750	Tube ID : 4.4 mm, L= 2000 mm, Upward
Bourke et al. (1970) [4]	7.44 – 10.32	288.1 – 308.1	8 – 270	311.1 – 1234.4	Tube ID : 22.8 mm, L= 4560 mm, Upward, Downward
He et al. (2004) [5]	7.6	283.1	2.6 – 15.1	102.3 – 289.2	Tube ID : 19.0 mm, L= 2451 mm, Upward
He et al. (2005) [6]	9.5	304.1 – 324.1	30 – 70	590.3 – 1641.0	Tube ID : 0.95 mm, L= 55 mm
Ikryannikov et al. (1972) [7]	8.1 – 9.1	288.8 – 299.2	9.0 – 84.3	190.0 – 381.0	Tube ID : 29.0 mm, L= 2262 mm
Kim et al. (2005) [8]	8.0	288.8 – 305.1	3.0 – 180.0	209.0 – 1230.0	Tube ID : 7.8 mm, L= 1200 mm
Krasnoshchekov et al. (1967) [9]	7.9 – 9.7	293.1 – 383.1	266.8 – 2644.3	1136.7 – 7521.3	Tube ID : 4.1 mm, L= 208.1 mm
Kurganov *et al.* (1991 [10]/ 1992 [11] / 1993 [12], / 1998 [13])	7.7 – 9.0	282.0 – 333.0	40.0 – 1053.0	396.0 – 3250.0	Tube ID : 8 mm and 22.7 mm, L= 2800 mm, 2951 mm and 5220 mm, Upward, Downward, Horizontal
Petukhow and Polyakov (1988) [14]	9.0	397.1	30.3 – 30.8	182.0	Tube ID : 29.0 mm, L= 2378 mm
Pioro et al. (2004/2005) [15], [16]	8.2	307.5 – 315.5	189.2	1978.0	Tube ID : 8.0 mm, L= 2208 mm
Shiralkar and Griffith (1969/1970) [17], [18]	7.6	268.6 – 303.4	126.2 – 454.3	678.1 – 3390.6	Tube ID : 3.2 mm and 6.4 mm, L= 1524 mm
Tanaka et al. (1971) [19]	7.9	287.0 – 308.0	488.5 – 639.7	1129.8 – 2426.6	Tube ID : 6.0 mm, L= 1000 mm, Upward
	Freon-12				
Pometko (2005) [20]	1.08 – 4.46	293.1 – 413.1	6 – 290	500 – 2000	Tube ID : 10 mm, L=1000 mm, Upward
	Helium				
Bogachev et al. (1985) [21]	0.25	5.1	0.58 – 1.29	47.16	Tube ID : 1.8 mm, L=410 mm for Upward, L=388 mm for Downward
Brassington and Cairns (1977) [22]	0.62 – 1.41	4.4 – 15	0.32 – 1.08	18.90 – 50.63	Tube ID : 17.8 mm, L=1000 mm, Upward
	Nitrogen				
Dimitrov (1989) [23]	4	101 – 125	11.1 – 18.8	11.9 – 25.5	Tube ID : 21.0 mm, L=1471 mm, Upward

Figure 1 shows the variation of wall temperatures with the bulk enthalpy and the heat flux. The wall temperature increases with increasing heat flux. At the lowest heat flux, the wall temperature increases gradually with the bulk temperature (enthalpy), however, at higher heat fluxes, one or two humps appear before the pseudo-critical point, showing the deterioration of the heat transfer in the vertical

upward flow. As shown in **Figure 2**, the heat transfer coefficient reaches a maximum at the pseudo critical point.

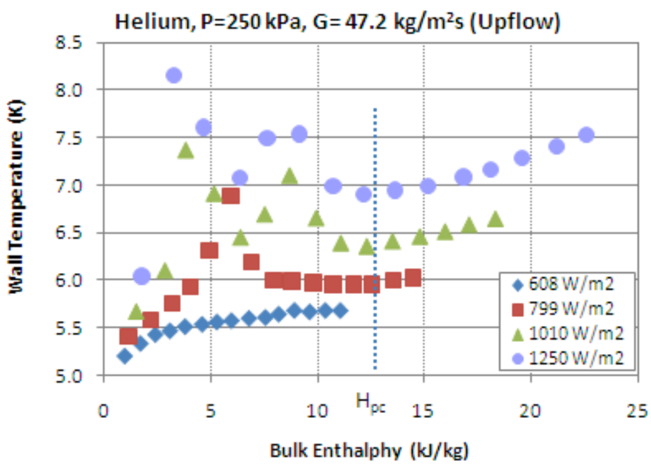


Figure 1 Variation of the Wall Temperature With Bulk Enthalpy and Heat Flux (Bogachev, 1985).

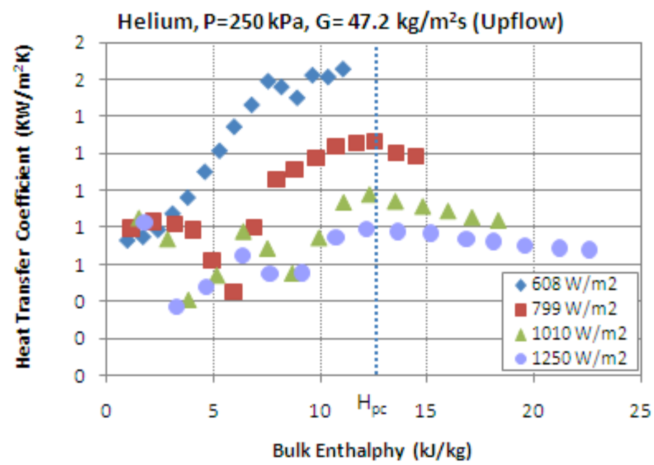


Figure 2 Variation of Heat Transfer Coefficient With Bulk Enthalpy and Heat Flux (Bogachev, 1985).

Figure 3 shows the effect of flow direction in vertical tubes. Wall temperatures are higher in the upward flow case than in the downward flow case at similar conditions. Moreover, the wall temperature gradually increases with the bulk temperature for the downward flow, whereas, at similar conditions, drastic variations in the wall temperature are observed for the upward flow. **Figure 4** shows the flow orientation effect by comparing wall temperatures along tubes with vertical (upward/downward) flow against those with horizontal flow at similar conditions. Wall temperatures for the downward and horizontal flows are quite similar, whereas those in the upward flow deviate from the downward flow, becoming much higher at locations close to the tube exit.

2.2 Heat Transfer in Bundles

Aoki *et al.* (2006) [24], Mori (2004) [25] and Yamashita *et al.* (2006) [26] carried out experiments with a 3-rod bundle in a vertical test section cooled upward and downward by Freon-22. Mori (2004) [25] also performed experiments in tubes and annular geometries to study the effect of geometry on the heat transfer. **Figure 5** shows the effect of heat flux on the wall temperature in the upward flow. As observed for tubular test sections, increasing the heat flux increases the wall temperature. At high heat fluxes, wall temperatures vary significantly below the pseudo-critical point in the upward flow, showing the deterioration of the heat transfer.

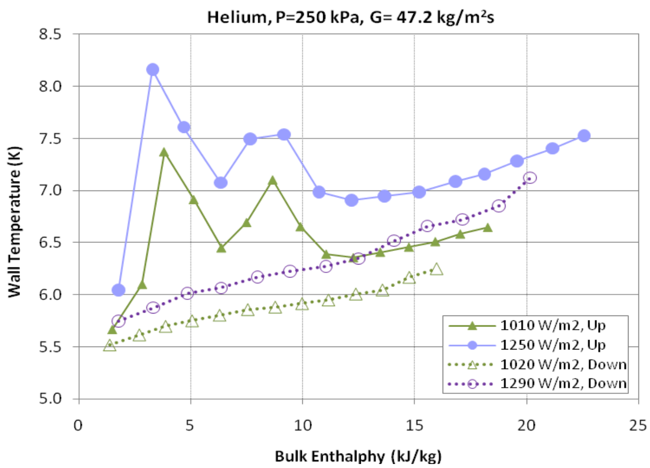


Figure 3 Comparison of Upward and Downward Flow (Bogachev, 1985).

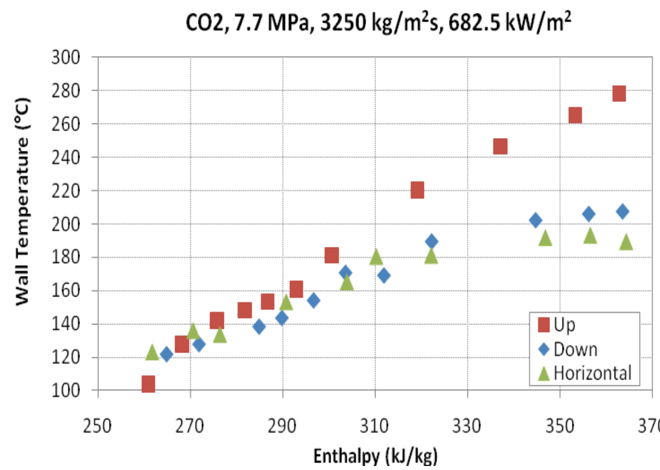


Figure 4 Orientation Effect (Kurganov, 1998).

The effect of flow direction in a vertical tube is presented in **Figure 6**. Local temperature spikes are observed below the pseudo-critical point in the upward flow, showing that the heat transfer is deteriorated. Wall temperatures in the upward flow are also higher than those of the downward flow before the pseudo-critical point at similar flow conditions. **Figure 7** presents the effect of geometry on the heat transfer coefficient and the wall temperature. The wall temperatures measured in a tube, in an annular geometry and the 3-rod bundle are compared at similar conditions. Some enhancements shown as an increase in the heat transfer coefficient are observed near pseudo-critical point in the 3-rod bundle. The heat transfer in the tube is, on the other hand, deteriorated at similar conditions, with a drastic decrease in the heat transfer coefficient (or increase in the wall temperature).

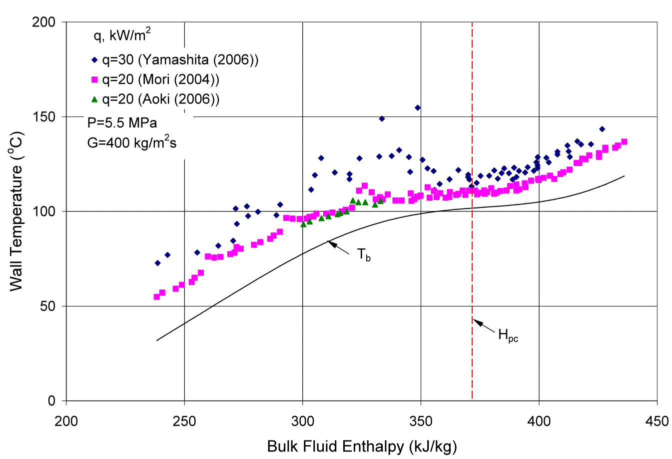


Figure 5 Variation of the Wall Temperature with Bulk Enthalpy and Heat Flux in Bundles.

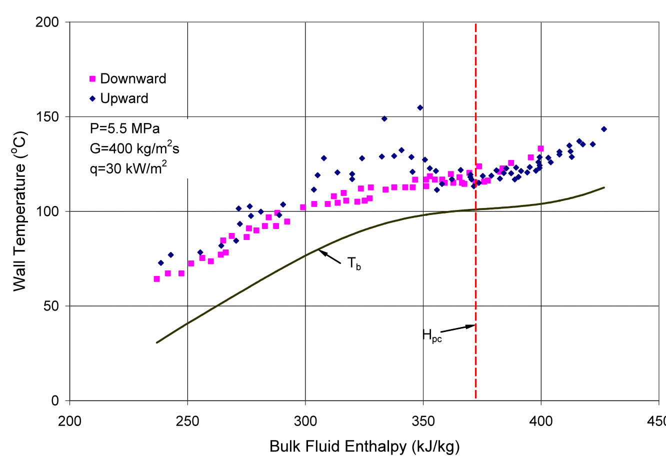


Figure 6 The Effect of Flow Orientation in Bundles (Yamashita et al., 2006).

3. Fluid-to-Fluid Scaling

Several scaling analyses for fluid to fluid modeling are available in the open literature. Scaling criteria from Pioro and Duffey (2007) [27] were used in this analysis, and are presented in Table 2.

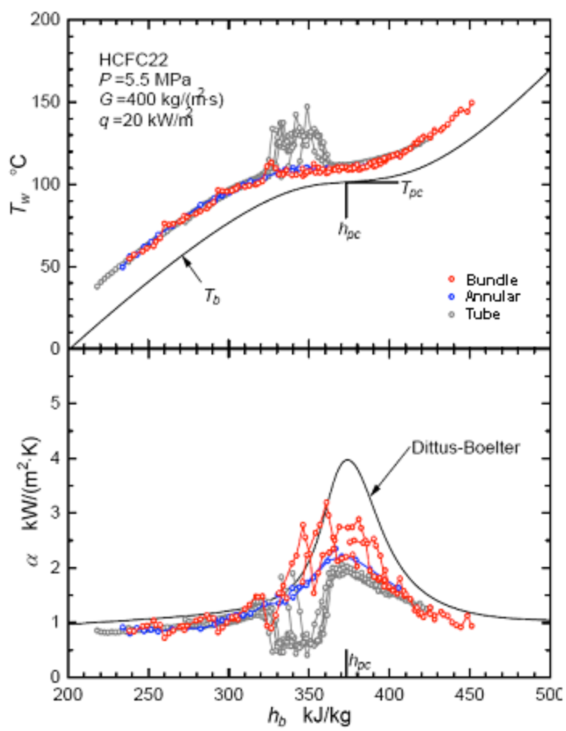


Figure 7 The Effect of Geometry (Mori, 2004).

Table 2 : Similarity parameters suggested for fluid-to-fluid modeling (Pioro and Duffey, 2007)

Similarity Criteria	Equation
Geometric	$\left(\frac{L}{D_{hy}}\right)_A = \left(\frac{L}{D_{hy}}\right)_B$
Pressure	$\left(\frac{P}{P_c}\right)_A = \left(\frac{P}{P_c}\right)_B$
Bulk Fluid Temperature	$\left(\frac{T_b}{T_{cr}}\right)_A = \left(\frac{T_b}{T_{cr}}\right)_B$
Wall Superheat	$\left(\frac{T_w - T_b}{T_{cr}}\right)_A = \left(\frac{T_w - T_b}{T_{cr}}\right)_B$
Mass Flux	$\left(\frac{GD_{hy}}{\mu_b}\right)_A = \left(\frac{GD_{hy}}{\mu_b}\right)_B$
Heat Transfer Coefficient	$Nu_A = Nu_B$

4. Assessment of Tube Base Correlations against the Surrogate Fluid Databases for Tubes and Bundles

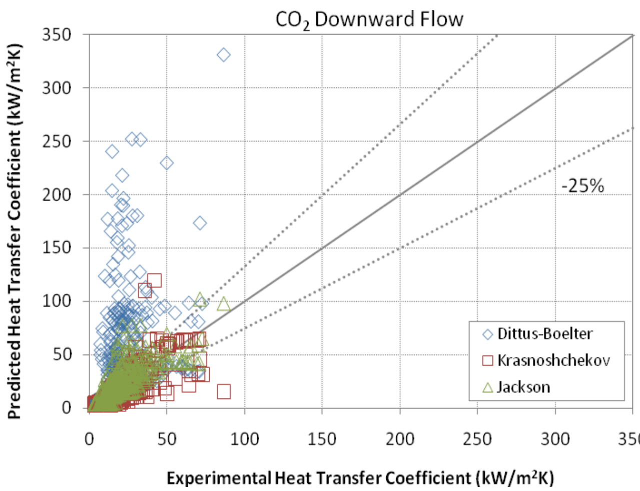
4.1 Assessment against Tube Database

The Dittus–Boelter correlation [28], the Krasnoshchekov correlation [9], and the Jackson correlation [30] were assessed against the water equivalents of R12, CO_2, Helium and Nitrogen databases. Table 3 presents the prediction accuracy of the correlations against the water equivalent values of the surrogate fluid data in tubes. The Dittus-Boelter correlation significantly overpredicts the CO_2 data. Its predictions, in general, do not agree well with the data, except for the helium downward flow. The Krasnoshchekov correlation predicts the upward flow better than the downward flow for CO_2 and helium. It systematically underpredicts the heat transfer coefficient for all fluids, except CO_2 horizontal flow. The Jackson correlation predicts CO_2 downward flow better than the upward flow and horizontal flow, as well as predicts better than the other correlations for CO_2 downward flow. However, it significantly underpredicts the Freon-12 and nitrogen data. It predicts quite accurately the upward helium data; however, predictions become poor for the downward flow. The differences could be caused by the limitation of the correlations, because correlations are derived covering only the range over which the experiments were performed.

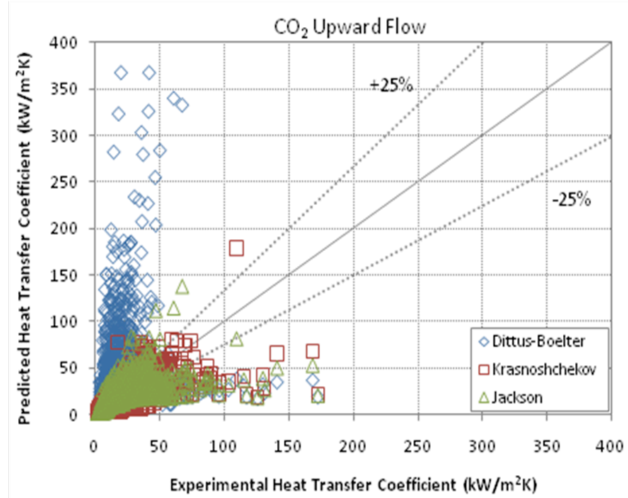
Figure 8 (a) and (b) through **Figure 11** compare experimental heat transfer coefficients with predictions of the correlations. Most of the predictions of the Krasnoshchekov correlation and the Jackson correlation lie within ±25% for the CO_2 data (**Figure 8** (a) and (b)) for downward and upward flows. Large scatters in the helium predictions are observed for the Dittus-Boelter and Krasnoshchekov correlations. In addition, heat transfer coefficients are systematically underpredicted by the correlations for Freon-12 (**Figure 9**) and nitrogen (**Figure 11**) upward flow.

Table 3 : Prediction Results of the Correlations against the Water Equivalent Values of Surrogate Databases

	Upward			**Downward**			**Horizontal**		
Correlation	**# of Data Point**	**Ave. error (%)**	**SD (%)**	**# of Data Point**	**Ave. error (%)**	**SD (%)**	**# of Data Point**	**Ave. error (%)**	**SD (%)**
	CO_2								
Dittus-Boelter	2771	96.2	193.2	436	106.2	235.9	186	92.4	249.7
Krasnoshchekov	2771	-5.1	41.2	436	-22.3	35.7	186	23.1	53.1
Jackson	2771	11.7	44.1	436	2.6	55.5	186	15.3	44.0
	Freon-12								
Dittus-Boelter	101	-46.3	24.5						
Krasnoshchekov	101	-37.6	36.7						
Jackson	101	-45.7	24.9						
	Helium								
Dittus-Boelter	179	32.0	58.0	52	9.6	46.2			
Krasnoshchekov	179	-12.1	27.7	52	-18.7	38.1			
Jackson	179	0.08	15.63	52	-23.2	13.6			
	Nitrogen								
Dittus-Boelter	62	-44.8	21.9						
Krasnoshchekov	62	-73.9	13.2						
Jackson	62	-65.4	13.5						



(a)



(b)

Figure 8 Comparison of Experimental Heat Transfer Coefficient with the Predictions of the Correlations for CO_2 (a) Downward and (b) Upward Flows

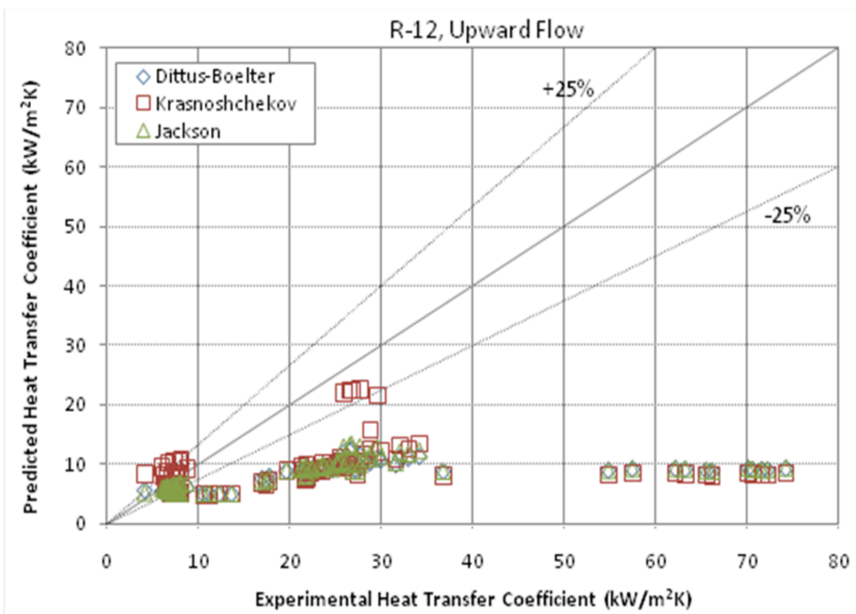
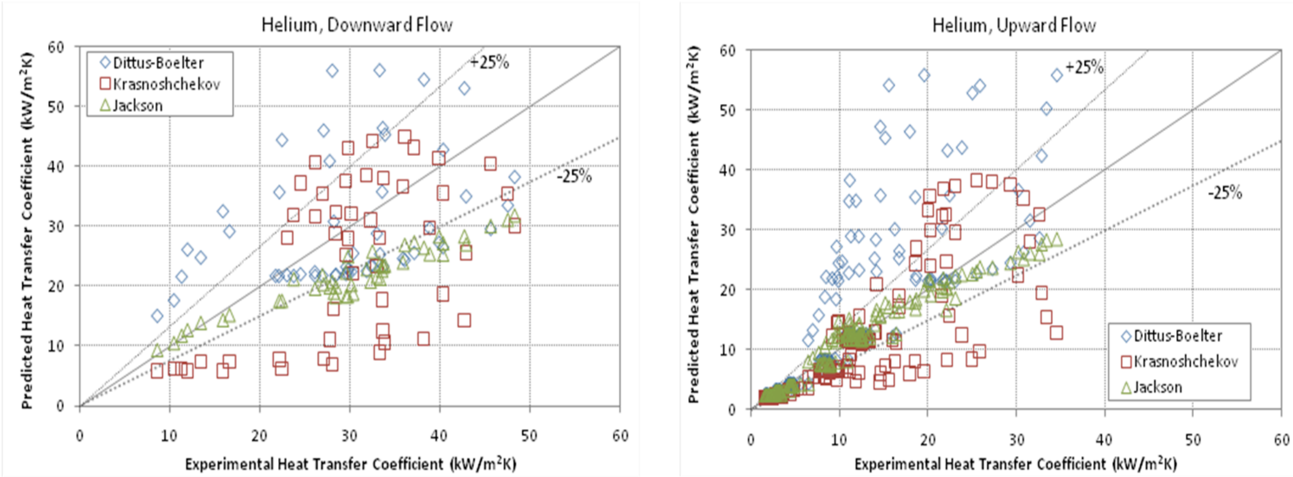


Figure 9 Comparison of Experimental Heat Transfer Coefficient with the Predictions of the Correlations for Freon-12 Upward Flow



(a) (b)

Figure 10 Comparison of Experimental Heat Transfer Coefficient with the Predictions of the Correlations for Helium (a) Downward and (b) Upward Flows

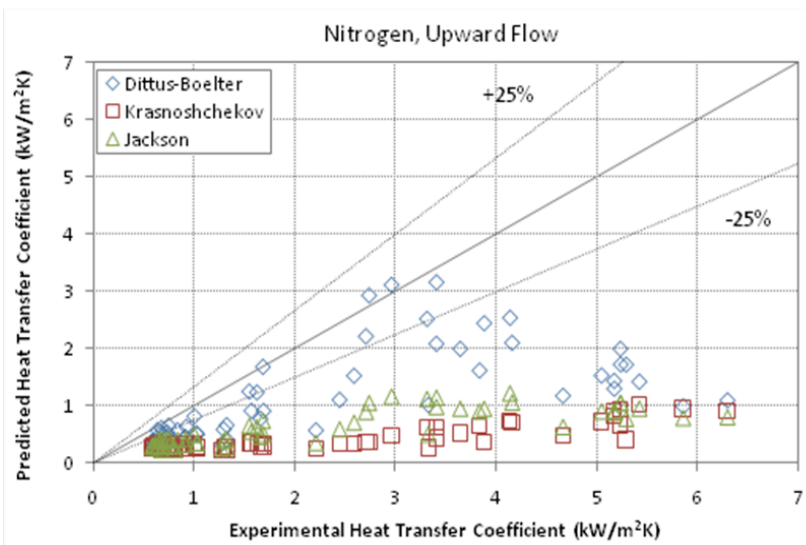


Figure 11 Comparison of Experimental Heat Transfer Coefficient with the Predictions of the Correlations for the Nitrogen Upward Flow

4.2 Assessment against Bundle Database

The tube-data based correlations were assessed against the 3-rod bundle data. Table 4 presents the prediction accuracies of the correlations. Heat transfer coefficients are significantly overpredicted by all the correlations. The overpredictions are improved for the downward flow as compared to upward flow.

Table 4 : Prediction Results for Upward and Downward HCFC-22 Flow in Bundle

Correlation	# of Data Point	Ave. error (%)	SD (%)

	Upward		
Dittus-Boelter	192	55.4	47.0
Krasnoshchekov	192	28.4	48.4
Jackson	192	33.1	22.3
	Downward		
Dittus-Boelter	56	48.5	61.4
Krasnoshchekov	56	23.9	33.1
Jackson	56	24.4	18.3

Figure 12 through **Figure 14** show the comparison of experimental heat transfer coefficients with the predictions using the correlations of Dittus-Boelter, Krasnoshchekov and Jackson, respectively. Large scatters in the prediction are observed for both Dittus-Boelter and Krasnoshchekov correlations. Systematically, Jackson correlation overpredicts the data; however, scatters are reduced as compared to the other correlarions. Predictions for the downward flow are slightly improved as compared to the upward flow.

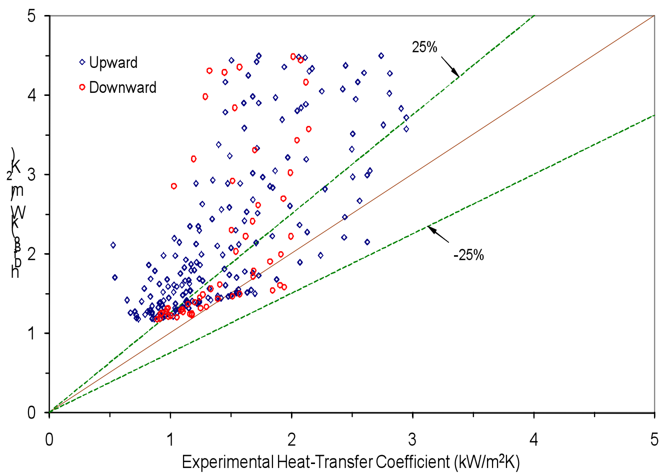


Figure 12 Comparison of Experimental Heat Transfer Coefficient with the Predictions of the Dittus-Boelter Correlation for Upward and Downward Flow of Freon-22

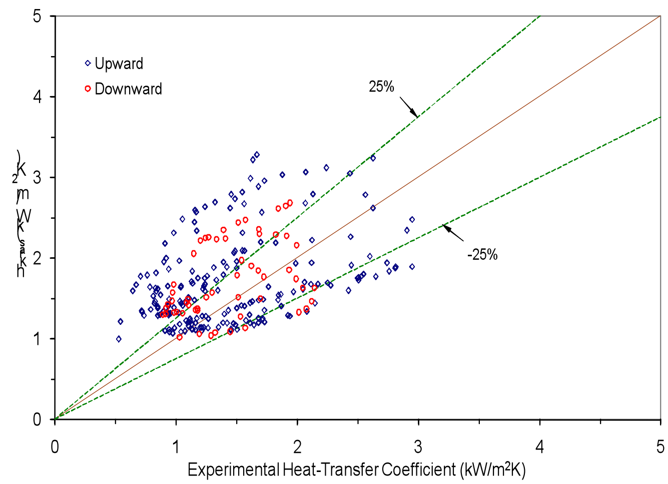


Figure 13 Comparison of Experimental Heat Transfer Coefficient with the Predictions of the Krasnoshchekov Correlation for Upward and Downward Flow of Freon-22

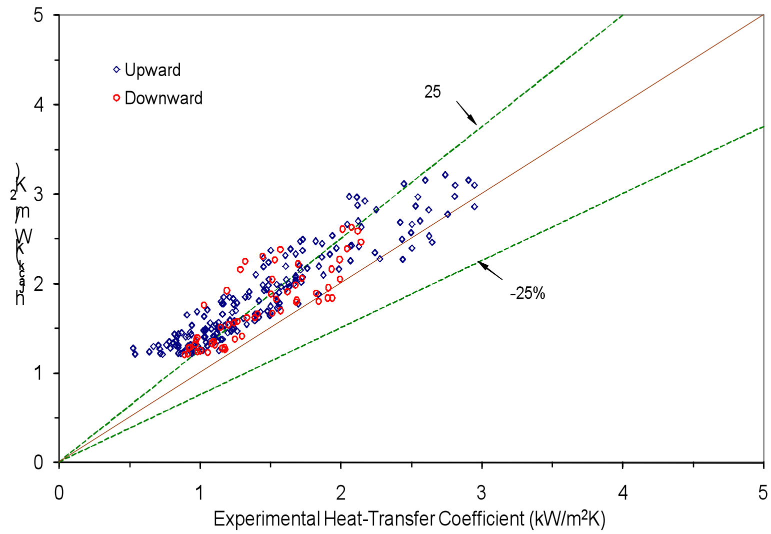


Figure 14 Comparison of Experimental Heat Transfer Coefficient with the Predictions of the Jackson Correlation for Upward and Downward Flow of Freon-22

5. Conclusion

Surrogate fluid databases for tubes and bundles have been assembled. The data follow the general parametric trends (e.g., wall temperatures increase with increasing heat flux, wall temperatures are higher in upward flow than in downward and horizontal flows). Some enhancements in the heat transfer coefficient are observed near pseudo-critical point in the 3-rod bundle, as compared to that in tubes.

The databases were converted to water equivalent values, using the fluid-to-fluid scaling parameters suggested by Pioro and Duffey [27]. The three most commonly used correlations, Dittus-Boelter, Krasnoshchekov and Jackson, were then assessed against the water equivalent values of the surrogate fluid data. The Dittus-Boelter correlation significantly overpredicts the CO_2 data. Dittus-Boelter predictions agree better with the data than the other correlations only for the helium downward flow. The Krasnoshchekov correlation predicts the upward flow better than the downward flow for CO_2 and helium. It systematically underpredicts the heat transfer coefficient for all fluids, except CO_2 horizontal flow. The Jackson correlation predicts CO_2 downward flow better than the upward flow and horizontal flow, as well as predicts better than the other correlations for CO_2 downward flow. However, it significantly underpredicts the Freon-12 and nitrogen data. It accurately predicts the upward helium data; however, predictions become poor for the downward flow.

The heat transfer coefficients were significantly overpredicted with large uncertainties by the correlations for the bundle data. Nevertheless, the Krasnoshchekov's correlation provides the lowest bias and the Jackson's provides the lowest uncertainty. Predictions for the downward flow are slightly improved as compared to the upward flow.

6. References

[1] Adebiyi, G.A. and Hall, W.B., "Experimental Investigation of Heat Transfer to Supercritical Pressure Carbon Dioxide in a Horizontal Pipe", Int. J. Heat Mass Transfer, Vol. 19, 1976, pp.715-720.

[2] Ankudinov, V.B. and Kurganov, V.A., "Intensification of Deteriorated Heat Transfer in Heated Tubes at Supercritical Pressures", High Temperatures (translated from Teplofizika Vysokikh Temperatur, pp.1208-1212), Vol. 19, No. 6, 1981, pp.870-874.

[3] Bae, Y.Y., "Recent Progress of Heat Transfer Study and Safety Analysis Code Development in Korea", Presentation at the SCWR T/H&S PMB, Paris, France, 2006, March 21-22.

[4] Bourke, P.J, Pulling, D.J., Gill, L.E. and Denton, W.H., "Forced Convective Heat Transfer to Turbulent CO_2 in the Supercritical Region", Int. J. Heat Mass Transfer, Vol. 13, 1970, pp.1339-1348.

[5] He, S., Kim, W.S., Jiang, P.X., and Jackson, J.D., "Simulation of Mixed Convection Heat Transfer to Carbon Dioxide at Supercritical Pressure", Proc. Instn. Mech. Engrs., Part C: J. Mechanical Engineering Science, Vol. 218, 2004, pp.1281-1296.

[6] He, S., Jiang, P.X., Xu, Y.J., Shi, R.F., Kim, W.S. and Jackson, J.D., "A Computational Study of Convection Heat Transfer to CO_2 at Supercritical Pressures in a Vertical Mini-Tube", International Journal of Thermal Sciences, Vol. 44, 2005, pp.521-530.

[7] Ikryannikov, N.P., Petukhov, B.S. and Protopopov, V.S., "An Experimental Investigation of Heat Transfer in the Single-Phase Near-Critical Region with Combined Forced and Free Convection", High Temperatures (translated from Teplofizika Vysokikh Temperatur, pp.96-100), Vol. 10, No. 1, 1972, pp.80-83.

[8] Kim, J.K., Jeong, H.K., Yoo, J.Y. and Lee, J.S., "Experimental Study on Heat Transfer Characteristics of Turbulent Supercritical Flow in Vertical Circular/Non-Circular Tubes", Proceedings of the 11th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH-11), Avignon, France, 2005 October 2-6.

[9] Krasnoshchekov, EA., Protopopov, V.S. Fen V. and Kuraeva, l.V., "Experimental Investigation of Heat Transfer for Carbon Dioxide in the Supercritical Region", Proceedings of the 2nd all Soviet Union Conference on Heat and Mass Transfer, Minsk, Belarus, 1964 Published as Rand Report R-451-PR, Edited by C. Gazley, Jr., J.P. Harnett and E.R.C Ecker, Vol. 1, 1967, pp.26-35.

[10] Kurganov, V.A., "Predicting Normal and Deteriorated Heat Transfer with Mixed Convection of Heat Carrier at Supercritical Pressure in Vertical Tubes", Thermal Engineering, Vol. 38, No. 1, 1991, pp.40-44, (translated from Teploenergetika, pp.63-68).

[11] Kurganov, V.A. and Kaptilnyi, A.G., "Velocity and Enthalpy Fields and Eddy Diffusivities in a Heated Supercritical Fluid Flow", Experimental Thermal and Fluid Science, Vol. 5, 1992, pp.465-478.

[12] Kurganov, V.A. and Kaptilnyi, A.G., "Flow Structure and Turbulent Transport of a Supercritical Pressure Fluid in a Vertical Heated Tube Under Conditions of Mixed Convection. Experimental Data", Int. J. Heat Mass Transfer, Vol. 36, No. 13, 1993, pp.3383-3392.

[13] Kurganov, V.A., "Heat Transfer and Pressure Drop in Tubes under Supercritical Pressure of the Coolant, Part 1: Specifics of the Thermophysical Properties, Hydrodynamics, and Heat Transfer of the Liquid. Regimes of Normal Heat Transfer", Thermal Engineering, Vol. 45, No. 3, 1998, pp.177-185.

[14] Petukhov, B.S. and Polyakov, A.F., "Heat Transfer in Turbulent Mixed Convection", Chapter 7.1 : Heat Transfer at Supercritical Pressures, Hemisphere Publishing Corp., New York, NY., USA, 1988, pp.183-201.

[15] Pioro, I.L. and Khartabil, H.F., "Experimental Study on Heat Transfer to Supercritical Carbon Dioxide Flowing Upward in a Vertical Tube", Proceedings of the 13th International Conference on Nuclear Engineering (ICONE-13), Beijing, China, 2005 May 16-20.

[16] Pioro, I.L. and Khartabil, H.F., "Heat Transfer to Supercritical Fluids Flowing in Channels-Empirical Correlations (survey)", Nuclear Engineering and Design, Vol. 230, 2004, pp.69-91.

[17] Shiralkar, B. and Griffith, P., "Deterioration of Heat Transfer to Fluids at Supercritical Pressure and High Heat Fluxes", Journal of Heat Transfer, Transactions of ASME, Vol. 91, 1969, pp.27-36.

[18] Shiralkar, B. and Griffith, P., "The Effect of Swirl, Inlet Conditions, Flow Direction and Tube Diameter on the Heat Transfer to Fluids at Supercritical Pressure", Journal of Heat Transfer, Transactions of ASME, Vol. 92, 1970, pp.465-471.

[19] Tanaka, H., Nishiwaki, N., Hirata, M. and Tsuge, A., "Forced Convection Heat Transfer to Fluid Near Critical Point Flowing in Circular Tube", Int. J. Heat Mass Transfer, Vol. 14, 1971, pp.739-750.

[20] Pometko, R., "Modelling of Heat Transfer to Supercritical Pressure Water Using Freon", Proceedings of the 11th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH-11), Avignon, France, 2005 October 2-6.

[21] Bogachev, V.A., Yeroshenko, V.M., Snyitina, O.F. and Yaskin, L.A., "Measurements of Heat Transfer to Supercritical Helium in Vertical Tubes Under Forced and Mixed Convection Conditions", Cryogenics, Vol. 25, 1985, pp.198-201.

[22] Brassington, D.J. and Cairns, D.N.H., "Measurements of Forced Convective Heat Transfer to Supercritical Helium", Int. J. Heat Mass Transfer, Vol. 20, 1977, pp.207-214.

[23] Dimitrov, D., Zahariev, A., Kovachev, V. and Wawryk, R., "Forced Convective Heat Transfer to Supercritical Nitrogen in a Vertical Tube", Int. J. Heat and Fluid Flow, Vol. 10, No. 3, 1989, pp.278-280.

[24] Aoki, N., Murakami, Y., Mori, H. and Ono, M., "Transient Heat Transfer in a Sub-bundle Channel during Pressure Reduction from Supercritical to Subcritical Pressure", Nippon Kikai Gakkai Doryoku, Enerugi Gijutsu Shinpojiumu Koen Ronbunshu, Vol. 11, 2006, pp.257-258, in Japanese.

[25] Mori, H., 2004, Research Work on Heat Transfer at Supercritical Conditions, http://therme.mech.kyushu-u.ac.jp/pdf/2005/2005_scr.pdf, in Japanese.

[26] Yamashita, Y., Murakami, Y., Mori, H. and Ono, M., "Heat Transfer to a Supercritical Pressure Fluid Flowing Downward in a Sub-bundle Channel", Nippon Kikai Gakkai Doryoku, Enerugi Gijutsu Shinpojiumu Koen Ronbunshu, Vol. 11, 2006, pp.255-256, in Japanese.

[27] Pioro, I.L. and Duffey. R., "Heat Transfer and Hydraulic Resistance at Supercritical Pressures in Power Engineering Applications", ASME Press, 2007.

[28] Dittus, F.W. and Boelter, L.M.K., "Heat Transfer in Automobile Radiators of the Tubular Type", Univ. Calif. Publ. Eng. Vol. 2. No. 13, 1930, pp.443-461.

[29] Krasnoshchekov, E.A. and Protopopov, V.S., 1959, "Heat Transfer at Supercritical Region in Flow of Carbon Dioxide and Water in Tubes", (In Russian), Thermal Engineering, No. 12, pp.26-30.

[30] Jackson, J.D., "Consideration of the Heat Transfer Properties of Supercritical Pressure Water in Connection With the Cooling of Advanced Nuclear Reactors", Proceedings of the 13th Pacific Basin Nuclear Conference, Shenzhen City, China, 2002 October 21-25.