HEAT TRANSFER STUDY ON SUPERCRITICAL CO2 FLOW IN VERTICAL TUBE

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SUMMARY

This paper presents an analysis of a new heat-transfer correlation developed for supercritical carbon dioxide (CO2) flowing in vertical bare tubes. A large set of supercritical CO2 experimental data was obtained from Chalk River Laboratories (CRL) AECL. Data points were obtained for an upward flow of CO2 inside 8-mm ID vertical Inconel-600 tube with a 2.208-m heated length for a wide range of flow conditions: Pressures ranging from 7.4 to 8.8 MPa, mass fluxes from 900 to 3000 kg/m2s, inlet fluid temperatures from 20 to 40°C, and heat fluxes from 15 to 615 kW/m2; and for several combinations of wall and bulk-fluid temperatures that were below, at, or above the pseudocritical temperature.

1. INTRODUCTION

The objective of the present experimental research is to obtain detailed reference dataset on heat transfer in supercritical CO_2 and improve our fundamental knowledge of the heat-transfer processes and handling of supercritical fluids (SCF). The results of the analysis can be applied towards developing the Generation-IV Super Critical Water Reactor (SCWR) concepts. The SCWR is a new conceptual design proposed by AECL, which uses high-temperature (coolant temperatures up to 625°C) and high-pressure (~25 MPa). Such a design would result in much higher thermal efficiencies of up to 50-55% as opposed to current design limitations of about 30-35%. The coolant would pass through its pseudocritical temperature (see Fig 1) before it reaches the channel outlet [1]. Thus it is important to investigate the supercritical fluid behaviour at those conditions. Carbon dioxide is used as a modelling fluid as it a less expensive alternative to using SuperCritical Water.

Heat transfer process for supercritical fluids is difficult to model especially when it passes through pseudocritical regions, as there are very rapid variations in thermophysical properties of the fluid (see Fig 2). Thus, the task of calculating Heat Transfer Coefficient (*HTC*) is very complicated and historically only empirical correlations have been proposed for this purpose, as the exact mechanics of the process is difficult to express using fundamental principles. Previous studies have shown that existing empirical correlations, such as the Dittus-Boelter, Bishop et al., and Jackson correlations, deviate significantly from experimental Heat Transfer Coefficient (HTC) values, especially, within the pseudocritical range (See Fig 3-4). The Swenson et al. correlation provides a relatively better fit for the experimental data, as compared to the previous three correlations within some flow conditions, but deviates from data within other conditions [2]. Besides, these correlations were developed for water and our results indicate that they cannot directly be applied to be used for CO_2. Therefore, new empirical correlation to predict the HTC values is developed based on the CO_2 dataset and latest thermo-physical properties. Statistical error calculations were performed using graphical techniques.

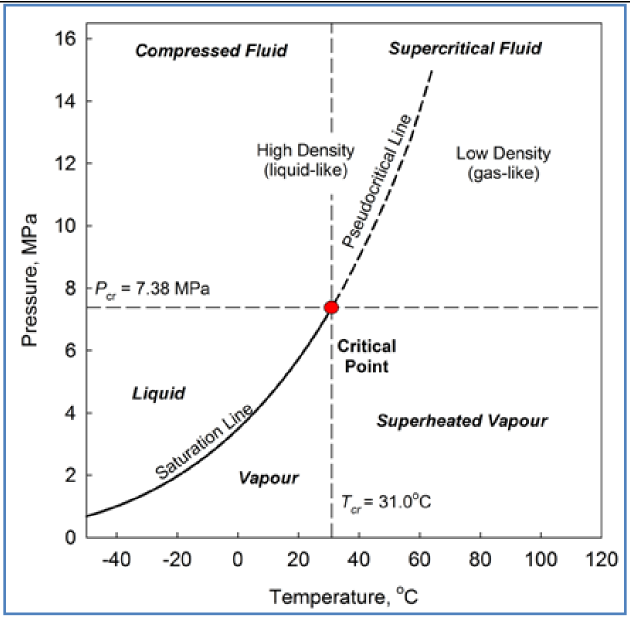

Figure 1: Pressure-Temperature diagram for CO_2 [1]

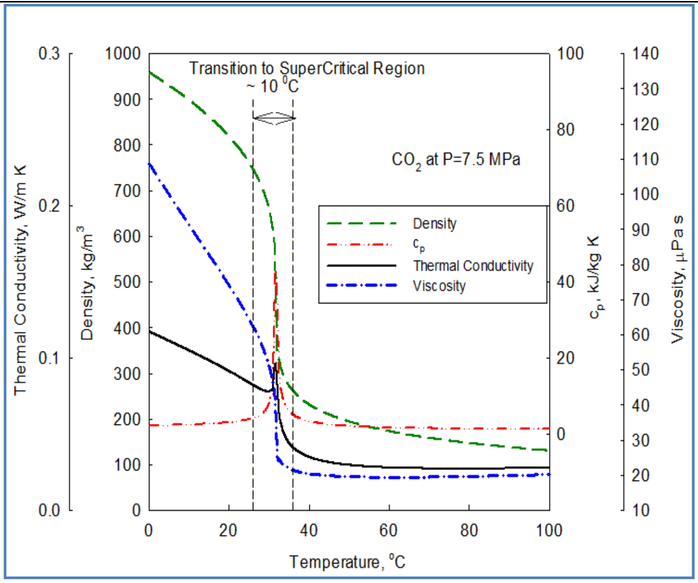

Figure 2: Thermophysical properties profiles of supercritical CO_2 as function of temperature at 7.5 MPa

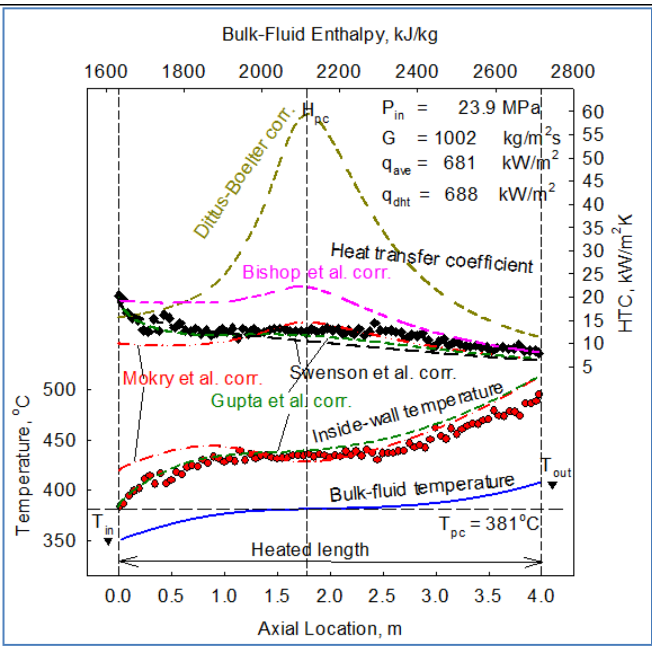

Figure 3: Comparison of *HTC* values calculated through various correlations with experimental data [1] of 4-m circular vertical bare tube (*D*=10mm): P_{in} ~ 24 MPa and *G* ~ 1000 kg/m²s.

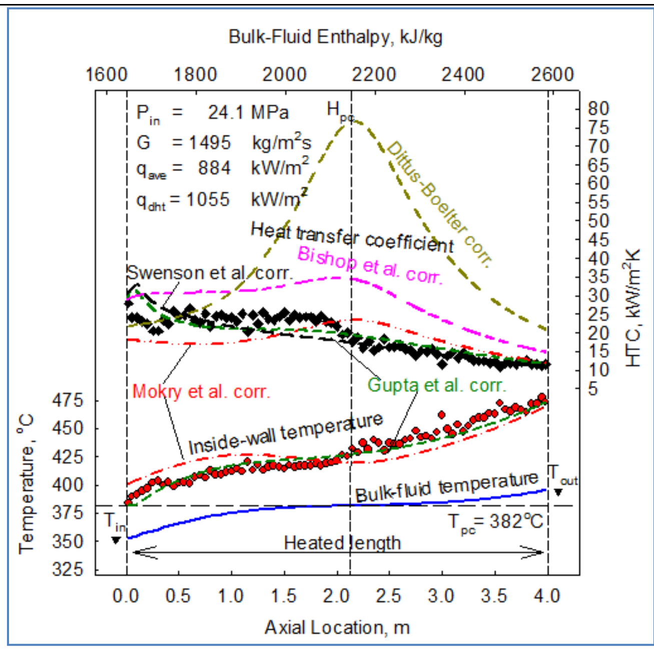

Figure 4. Comparison of *HTC* values calculated through various correlations with experimental data of 4-m circular vertical bare tube (*D*=10mm): P_{in} ~ 24 MPa and *G* ~ 1500 kg/m²s.

[1] The experimental data is taken from Kirillov et. al. and the correlations are given in Pioro et. al. [1]

2. DEVELOPING NEW CORRELATION FOR SC CO_2

2.1 Experimental Dataset

The experimental data used to develop our correlations was obtained from Fuel Channel Thermalhydraulicсs (FCT) laboratory located at Chalk River (CRL), Canada. The test section (see Fig. 5), is made up of 2.4 m long Inconel 600 tube with an inner diameter of 8 mm, an outer diameter of 10mm. Only 2.208 m of the tube is heated. Direct electrical current passes through the tube wall, heats the fluid from the inlet to the outlet power terminals with the use of copper clamps. The test section and mixing chambers are wrapped with thermal insulation to minimize heat loss. Table 1 lists the test-matrix parameters and Table 2 their uncertainties. The dataset includes over 4,600 points.

Table 1: Test-Matrix Parameters

P (MPa)	T_{in} (°C)	T_{out} (°C)	T_w (°C)	q (kW/m^2)	G (kg/m^{2}s)
7.57-8.8	20-40	29-136	29-224	9.3-616.6	706-3169

An analysis of the data showed Deteriorated Heat-Transfer (DHT) and Improved Heat-Transfer (IHT) regions. The objective of this study was to develop an updated heat-transfer correlation for the Normal Heat Transfer (NHT) regime. Therefore, data points in DHT and IHT regions were removed from the dataset. The DHT region is subject to future investigations. Abnormalities, such as defective thermocouple readings were also removed from the dataset. Overall, approximately 88% of the experimental data were used to develop the correlation.

2.2 Methodology for Developing a New Correlation

A dimensional analysis was performed in order to obtain a general empirical form of a correlation for *HTC* calculations. It is well known that *HTC* is not an independent variable, and the values are affected by mass flux, inner diameter, heat flux, thermophysical properties variations, etc. Therefore, a set of the most important variables, which affect the *HTC*, were identified based on theoretical and experimental *HTC* studies at supercritical pressures. The Buckingham *Π*-Theorem [3] was used to produce a model formula, where $\mathbf{Nu_x}$ was represented as a product of various dimensionless terms:

$$\mathbf{Nu_x} = C\ \mathbf{Re_x^{n_1}}\ \mathbf{Pr_x^{n_2}} \left(\frac{k_w}{k_b}\right)^{n_3} \left(\frac{\mu_w}{\mu_b}\right)^{n_4} \left(\frac{\rho_w}{\rho_b}\right)^{n_5} \quad (1)$$

Where, *x* represents the characteristic temperature at which the properties are calculated. Wall Temperature approach (similar to Swenson et. al) was chosen as the characteristic temperature for our correlation. In order to determine the coefficients in the general form proposed by Eq. (1), manual iterations were performed. The experimental dataset, with removed outliers and points in the DHT regime was used to calculate the required parameters through the NIST software [4]. Scatter plots were then created and analyzed using linear regression on a log-log scale.

To finalize the correlation, the complete set of primary data was coupled with the preliminary correlation using the SigmaPlot Dynamic Fit Wizard to perform the final adjustments. This process tuned the constant and exponents to minimize uncertainty. The resulting final correlation is represented by **Eq. (2)** below.

$$\mathbf{Nu_w} = 0.0038\ \mathbf{Re_w^{0.957}}\ \overline{\mathbf{Pr}}_\mathbf{w}^{-0.139} \left(\frac{\rho_w}{\rho_b}\right)^{0.836} \left(\frac{k_w}{k_b}\right)^{-0.754} \left(\frac{\mu_w}{\mu_b}\right)^{-0.222} \quad (2)$$

Table 2: Uncertainty of measured and calculated parameters

Parameter	Uncertainty
Test Section Power	±0.46% for P = 3 kW ±0.30% for P = 35 kW
Absolute Pressure	±0.2%
Differential-Pressure Cells	$\pm 30.1\%\ for\ \Delta p_{min} = 5$ kPa $\pm 2.2\%\ for\ \Delta p_{max} = 70$ kPa
Average Heat Flux	±0.53% for $q_{ave\ min}$ =53.7 kW ±0.39% for $q_{ave\ max}$ =626.2 kW
Temperatures	±0.3°C within 0-100°C ±2.2°C beyond 100°C
Mass Flow rates	±12.5% at t=19°C and p=8.36 MPa for m_{min}= 46 g/s (G=902 kg/m^{2}s) ±1.6% at t=19°C and p=8.36 MPa for m_{max}= 155 g/s (G=3039 kg/m^{2}s)
Electrical Resistivity	±0.20% for L=2461mm
Thermophysical Properties (near pseudocritical point)	$\Delta\rho = \pm 7\%; \Delta H = \pm 2.5\%;$ $\Delta c_p = \pm 4.5\%;\ \Delta k = \pm 2\%;$ $\Delta\mu = \pm 7\%;$

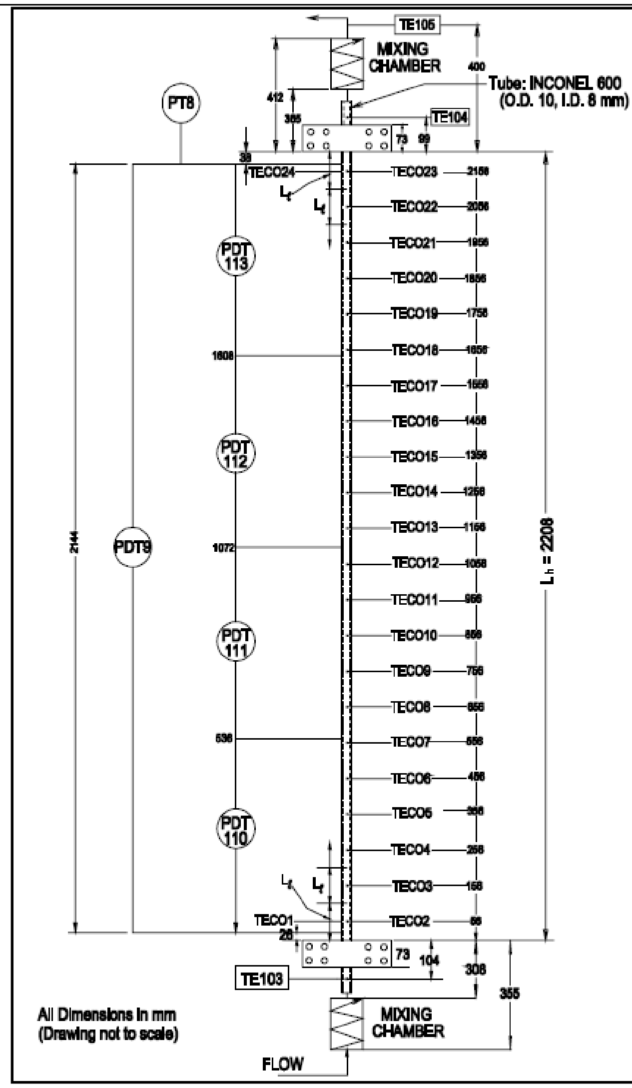

Figure 5: Test Section of MR-1 Loop [1]

Figures 6 and 7 show scatter plots of the experimental *HTC* and T_w values, versus the calculated values using Eq. (2). The results indicate that the uncertainties associated are about ±20-30% for *HTC* values and about ±15-20% for the calculated wall temperature which is a significant improvement from the previous existing correlations.

3. CONCLUSIONS

1. An important task for the nuclear-power industry is increasing the thermal efficiency of power plants at least to 45 – 50%. This increase can be achieved if high-temperature (>500°C) and high pressure (~25 MPa) nuclear reactors are designed that will make use of SCFs (such as SCWR).

2. CO_2 can be used as a modelling fluid to study the behaviour of SCFs. As CO_2 reaches critical point at much lower temperatures and pressures, the cost of performing experiments on SC CO_2 is significantly lower than that on supercritical water (SCW).

3. Extensive literature survey and error analysis of the existing *HTC* correlations showed that their predicted values can deviate significantly from experimental values, especially within the pseudocritical regions. It also appears that correlations developed for SCW cannot be directly applied to SC CO_2. Thus, experimental test matrix for CO_2 was used to develop a new preliminary heat-transfer correlation. The uncertainty associated with the correlation is about ±20-30% for *HTC* values and about ±15-20% for the calculated wall temperature (for the referenced dataset). These errors are significantly lower than previous correlations. However, further error analysis needs to be performed to determine its applicability with other independent datasets.

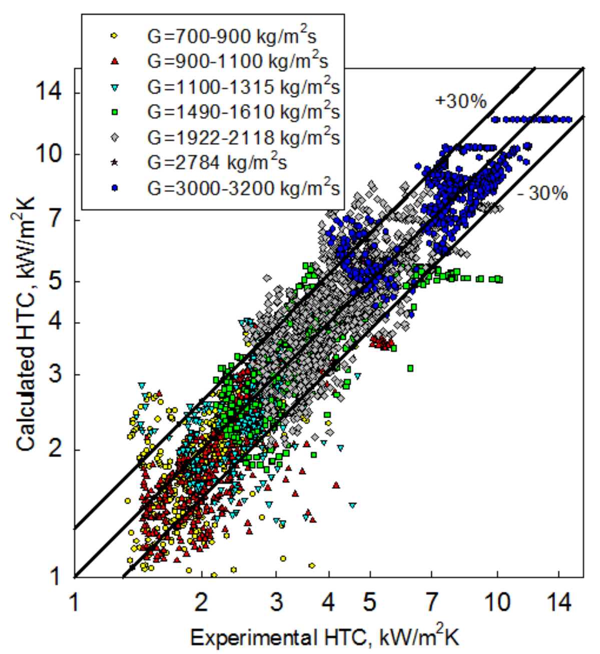

Figure 6: Comparison of data fit for *HTC* values using proposed correlation - Eq. (2).

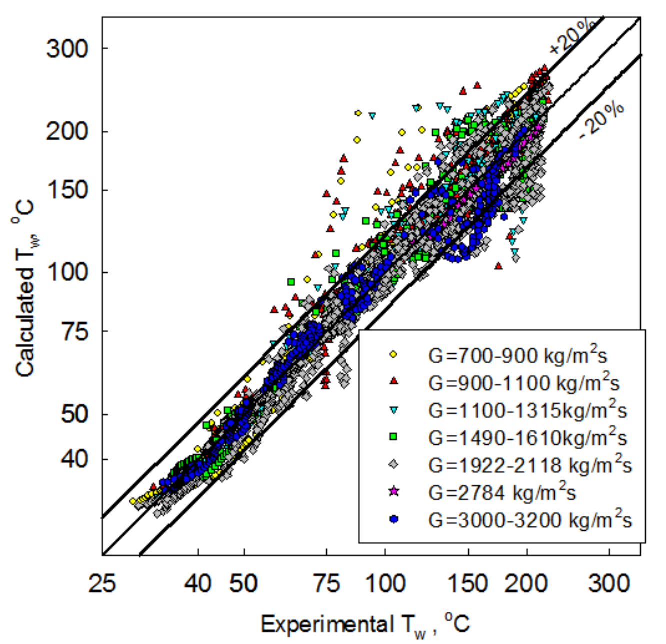

Figure 7: Comparison of data fit for T_w values using proposed correlation - Eq. (2).

4. REFERENCES

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