FEW CHALLENGES ASSOCIATED WITH DEVELOPING 1-D HTC CORRELATIONS FOR SUPERCRITICAL CO_2

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A Master's Level Submission

Summary

Canada among many other countries is in pursuit of developing next generation (Gen-IV) nuclear-reactor concepts. SuperCritical Fluids (SCFs) are expected to play a major role in the Gen-IV Nuclear Power Plant (NPP) applications.

SC CO_2 is proposed to be used as a modeling fluid to study the thermodynamic behavior of SCFs (especially water) as CO_2 reaches supercritical conditions at relatively moderate temperature and pressures. A major objective in conducting SC CO_2 experiments is to develop 1-D heat-transfer correlations that can be used to predict temperature profiles and used in other rudimentary heat transfer calculations. This paper presents some of the challenges associated with 1-D heat-transfer correlations.

1. Introduction

One of the main objectives of Generation-IV concepts is to achieve high thermal efficiencies of 45-50%. This can be achieved by increasing the operating temperatures and pressures of heat transport fluids beyond their critical pressure and temperature ranges. At these conditions, the fluids known as SuperCritical Fluids (SCFs) act as a single phase medium and resemble properties of dense gas [1].

SuperCritical Water-cooled reactor (SCWR) is a Gen-IV design concept that is being developed by AECL, Canada and that will utilize SC water in primary loop operating between temperatures of 350 – 600 ^{0}C with pressures up to 25 MPa. The SC-steam Rankine cycle can be used in a SuperCritical Water-cooled NPP (SCW NPP) with direct and indirect cycles. Other reactor concepts such as liquid-metal and molten-salt reactors can be also connected to the SC-"steam" Rankine cycle or SC CO_2 gas-turbine cycle through heat exchangers. Thus, furthering our knowledge of HT processes in SCFs is a very active and exiting area of research.

An important aspect towards development of SCF applications in novel Gen IV concepts is to understand the thermodynamic behaviour and prediction of Heat Transfer Coefficients (HTCs) at supercritical conditions. SC CO_2 is proposed to be used as a modelling fluid to investigate mechanism associated with SCW and possibly, other fluids as well. A major advantage of using SC CO_2 as a modelling fluid instead of SCW is significant reduction in experimental costs. CO_2 achieves supercritical conditions at much lower temperatures and pressures - P_{cr} = 7.37 MPa and T_{cr} = 30.97°C compared to those of water - P_{cr} = 22.06 MPa and T_{cr} = 373.95°C [2]. In addition, SC CO_2 is also proposed to be used as a working fluid in the Brayton gas-turbine cycle as a secondary power cycle in some Generation-IV nuclear-reactor concepts such as a Sodium-cooled Fast Reactor (SFR), Lead-cooled Fast Reactor (LFR) and Molten-Salt-cooled Reactor (MSR). SC CO_2 is also proposed to be used in advanced air-conditioning and Enhanced Geothermal Systems (EGS) [3].

Figures 1A and 1B, show transition of CO_2 through various phases as its temperature and pressure are increased.

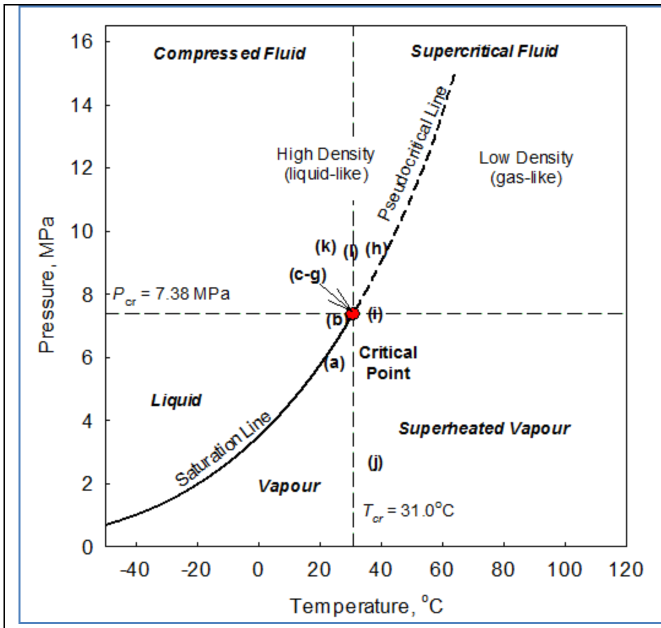

Figure 1A: Pressure-Temperature diagram for CO_2 [1].

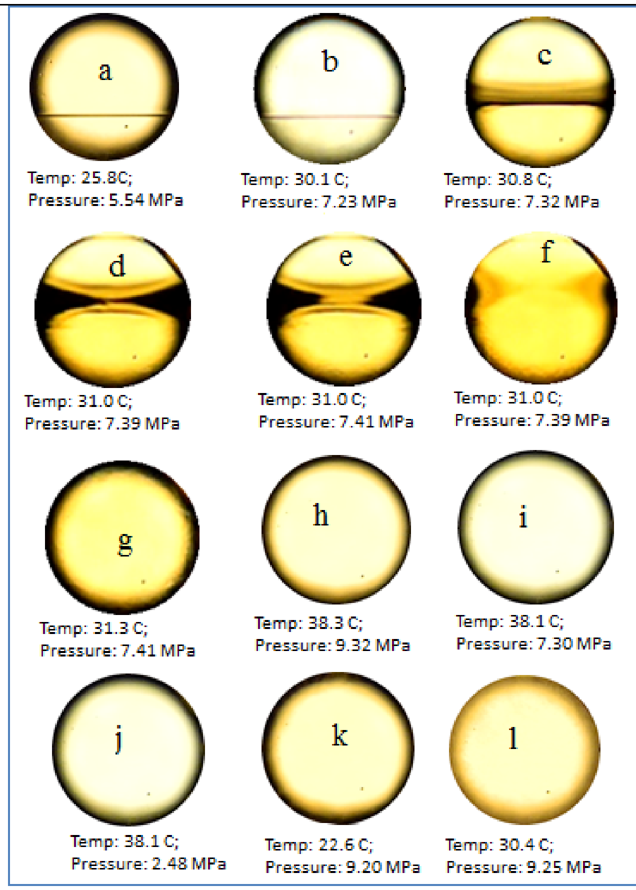

Figure 1B: Transition of CO_2 through various phases (Pictures taken from SC CO_2 experiment performed by Faculty of Science, UOIT)

2. Heat Transfer Coefficient (HTC) Calculations for SC Flows

A critical step towards any elementary heat transfer calculations is to accurately predict the Heat Transfer Coefficient (HTC). HTC calculations can be very complex especially in Supercritical flow conditions, primarily due to the fact that there are very rapid variation of thermophysical properties during the transition of fluids to supercritical regions (see Figure 3). Traditional HTC correlations fail to account for these sharp property changes and there are no theoretical models that can accurately map the behaviour of SCFs in the transition phase.

Furthermore, HTC is highly dependent on process conditions and can be significantly affected by nature and geometry of the heated surface. For example, the local flow conditions can be significantly impacted by additions of fins etc. on the heat transfer surface. Calculations of complex geometries are beyond the scope of the present research and can usually only be achieved by complex CFD codes and are fine tuned for that particular geometry.

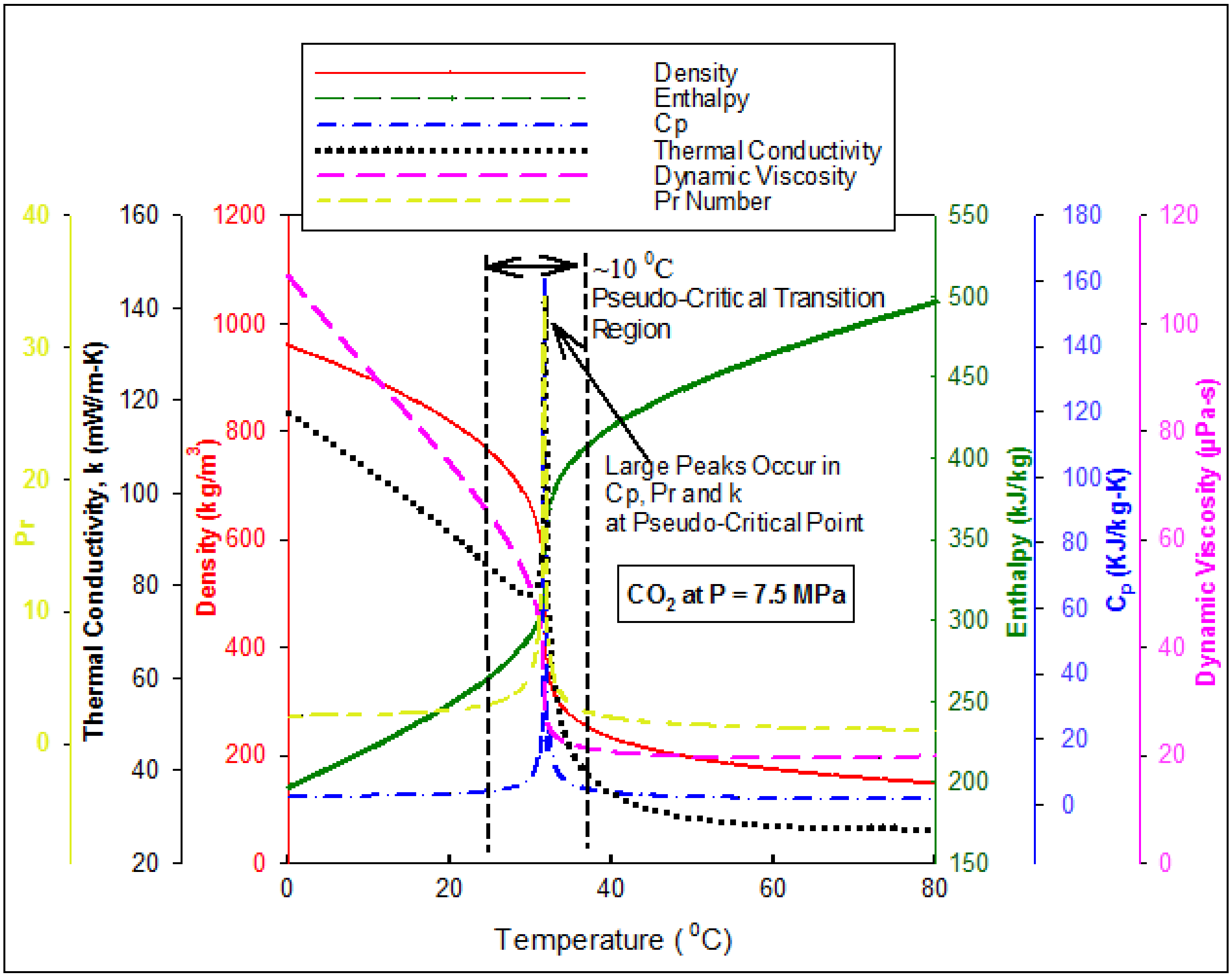

Figure 3: Thermophysical-properties profiles of SC CO_2 as function of temperature at 7.5 MPa: pseudocritical region in which all properties changes the most significantly is about ±5°C from the pseudocritical temperature [1].

However, for ball park preliminary calculations generic correlations for bare-tube SC correlations can be developed. A number of empirical 1-D heat-transfer correlations have been proposed for rudimentary calculations of HTC in forced convection bare-tube geometry application. Previous studies have shown that existing correlations such as Dittus-Boelter [4], Bishop et al. [5] etc. can produce large errors while predicting HTC values and deviate significantly from experimental data within the pseudo-critical region (see Figure 4)

2.1 Development of New Empirical Correlations

New correlations are developed by applying data-fitting techniques to a model equation with dimensionless terms. Using statistical techniques three correlations were proposed by Gupta et al. [1] for Heat Transfer (HT) in SC CO_2 (see Table 1). These SC CO_2 correlations were developed at the University of Ontario Institute of Technology (UOIT, Canada) by using a large set of experimental SC-CO_2 data (~4,000 data-points) obtained at the Chalk River Laboratories (CRL) AECL. These correlations predict HTC values with an accuracy of ±30% and wall temperatures (T_w) with an accuracy of ±20% for the analyzed dataset.

While these new correlations (Table 1) predict the AECL data with significantly improved accuracy, an important step towards their validity was to test their precision and applicability against other independent SC CO_2 datasets with different flow conditions. Literature survey was conducted to filter for papers that contained SC CO2 data-points. An Excel dataset was compiled by digitizing the graphs from He et. al (2005) [6] , Kim et al. (2005) [7] and Koppel (1960) [8] papers using UN-SCAN-IT Graph Digitizing Software (Silk Scientific Inc.).

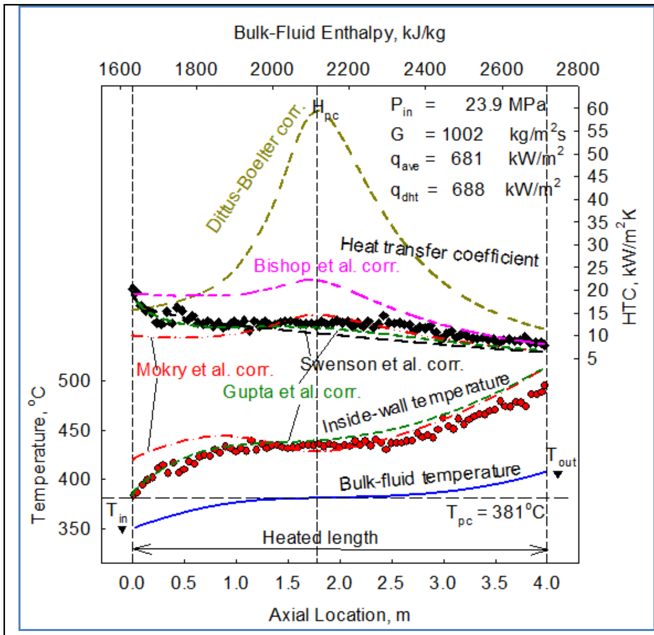

Figure 4A: Comparison of HTC values calculated through various correlations with experimental data of 4-m circular vertical bare tube (D=10mm): SCW, P_{in} ~ 24 MPa and G ~ 1000 kg/m^{2}s.

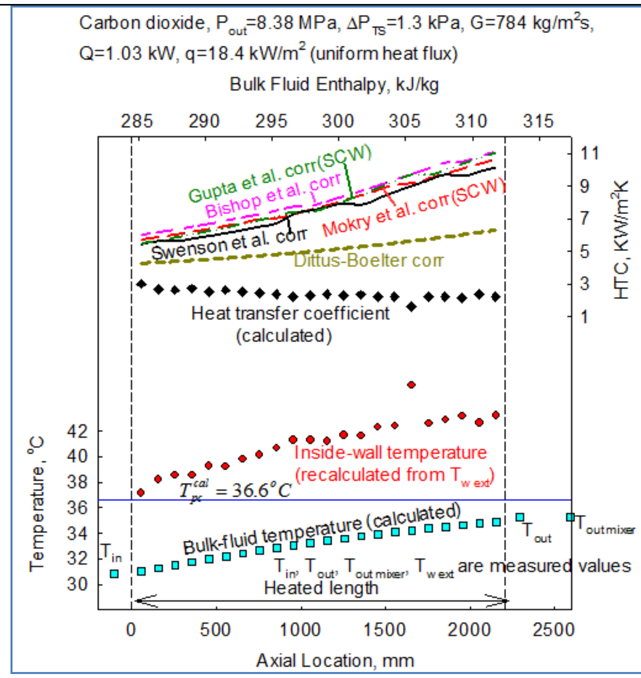

Figure 4B: Comparison of HTC values calculated through various correlations with experimental CRL data ($SCCO_2$) - vertical bare tube (D=8.06 mm): P_{in} ~ 8.38 MPa and G ~ 784 kg/m^{2}s.

Table 1: SC CO_2 correlations developed using CRL dataset [1]

Model Equation (Eq. 1)	$\mathrm{Nu_x} = C\,\mathrm{Re_x^{n_1}}\,\mathrm{Pr_x^{n_2}}\left(\frac{k_w}{k_b}\right)^{n_3}\left(\frac{\mu_w}{\mu_b}\right)^{n_4}\left(\frac{\rho_w}{\rho_b}\right)^{n_5}$
Bulk-Fluid-Temperature Approach (Eq. 2)	$\mathbf{Nu_b = 0.0094\,Re_b^{0.892}\,\overline{Pr_b}^{-0.14}\left(\frac{\rho_w}{\rho_b}\right)^{0.93}\left(\frac{k_w}{k_b}\right)^{0.23}\left(\frac{\mu_w}{\mu_b}\right)^{-1.13}}$
Film-Temperature Approach (Eq. 3)	$\mathbf{Nu_f = 0.0043\,Re_f^{0.94}\left(\frac{\rho_w}{\rho_b}\right)^{0.57}\left(\frac{k_w}{k_b}\right)^{-0.52}}$
Wall-Temperature Approach (Eq. 4)	$\mathbf{Nu_w = 0.0038\,Re_w^{0.957}\,\overline{Pr_w}^{-0.14}\left(\frac{\rho_w}{\rho_b}\right)^{0.84}\left(\frac{k_w}{k_b}\right)^{-0.75}\left(\frac{\mu_w}{\mu_b}\right)^{-0.22}}$

Mean and RMS error values were calculated for the HTC and T_w numbers predicted by the new correlations. The predicted HTC deviated by average of ±50% and T_w by ±30% for He, Kim and Koppel data. This marks a significant decrease in accuracy of these new correlations. It can be concluded that new correlations developed for SC CO_2 were highly tuned for their base data-set and their application cannot be extended to other flow conditions.

3. Conclusions

1. SCFs are expected to play a major role in the GenIV NPP applications. Important step towards successful development of these applications is to understand the Heat Transfer (HT) and thermodynamics of SCFs.

2. Well established existing HTC correlations for forced convective HT produce significant errors when they are applied to calculate HTC and *Tw* values for SC conditions, especially within the pseudo-critical region.

3. Many new empirical HTC correlations are being suggested world-wide developed from various SC experimental setups. While these correlations show good results for the data-sets they were developed for; they fail to transfer the results when compared against different experimental setups. Three independent $SCCO_2$ datasets were analyzed and results of our analysis indicate that the correlations are highly tuned for the reference data-sets they were developed from and thus they have very narrow ranges of applicability. Limited range of applicability for 1D SCCO2 HTC correlations poses a significant challenge.

4. More investigation in this area is warranted to develop a correlation that can predict wide range of SC flow conditions accurately and consistently. There is a need to standardize SC test apparatus and procedures to obtain a reliable reference SC database that may be then used to data-fit to empirical models. As future work it may be possible to propose a correlation that is developed using SC IAEA database. Nevertheless, presently it appears that there is no single correlation known to predict a wide range of SC experimental flow conditions consistently and accurately.

4. References

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