HEAT TRANSFER STUDY ON SUPERCRITICAL CO_2 FLOW IN VERTICAL TUBE

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ABSTRACT

This paper presents an analysis of a new heat-transfer correlation developed for supercritical carbon dioxide (CO_2) flowing in vertical bare tubes. A large set of supercritical CO_2 experimental data was obtained from Chalk River Laboratories (CRL) AECL. Data points were obtained for an upward flow of CO_2 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/m^{2}s, inlet fluid temperatures from 20 to 40°C, and heat fluxes from 15 to 615 kW/m^2; 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. 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.

In support of developing SCFs applications, heat transfer analysis at supercritical conditions is very important. However, 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). Figure 3, shows transition of CO_2 thorough various phases as its temperature and pressure are increased. The transition from single phase liquid to single phase gas does not involve a distinct phase change under these conditions. Phenomena such as dryout (or critical heat flux) are therefore not relevant [2]. However, at supercritical conditions, deteriorated heat transfer, i.e., lower heat transfer coefficient (*HTC*) values—compared to those for normal or regular heat transfer may exist [3] (see Fig. 4). 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.

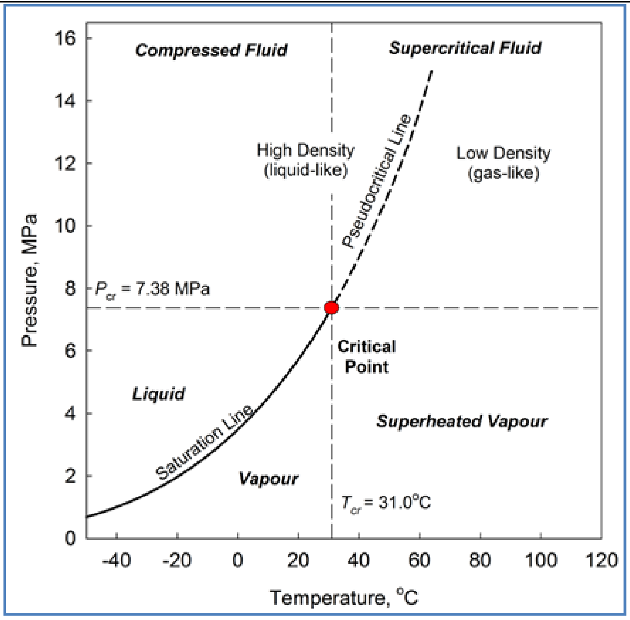

Figure 1: Pressure-Temperature diagram for CO_2 [1]

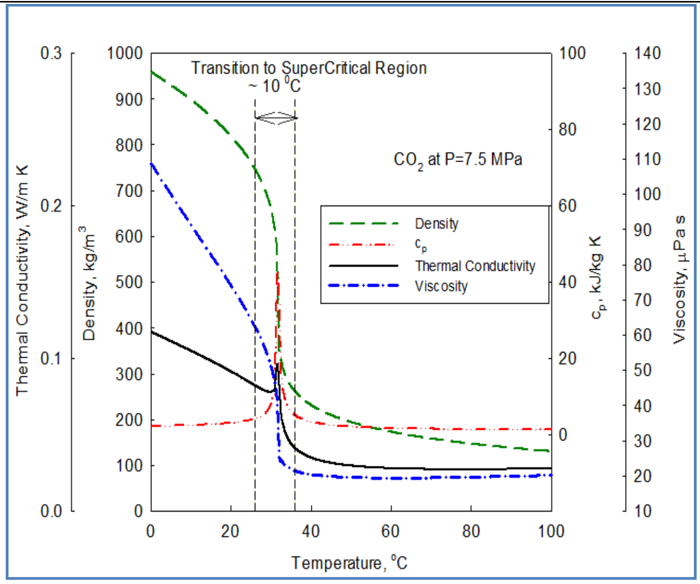

Figure 2: Thermophysical properties profiles of supercritical CO_2 as function of temperature at 7.5 MPa

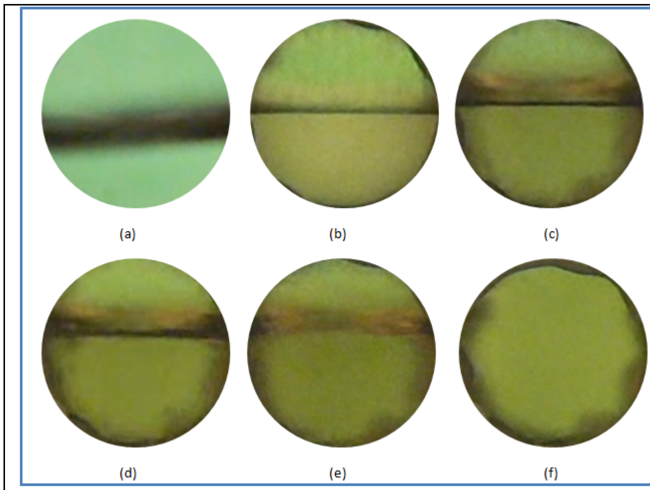

Figure 3: Transition of CO_2 through various phases (a)Two phase (b) Boiling and Condensation starting to occur (c)-(d) Transition to vapour phase (e) Transition through critical point and (f) Supercritical CO_2 (single phase)
(Pictures from a SC CO_2 Experimental Setup at Faculty of Science, UOIT – Courtesy of Donald McGillivray and Liliana Trevani)

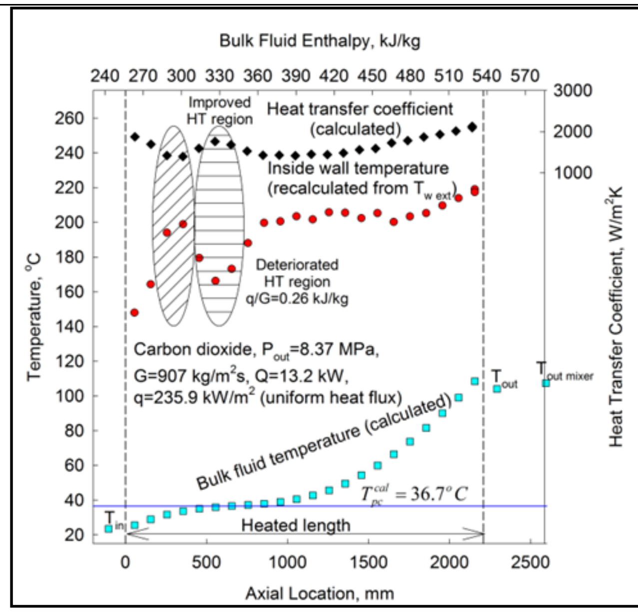

Figure 4: DHT and IHT regimes in Supercritical CO_2 [1]

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. 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 [4]. 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. Statistical error calculations were performed using graphical techniques.

2. BACKGROUND

2.1 Scaling Parameters between SCFs

As discussed previously, there are significant changes in the thermo-physical properties of CO_2 especially during the transition to the supercritical conditions. Other fluids such as water and R134a also demonstrate similar trends within the psedocritical region. Thus, CO_2 may be used as a modelling fluid to investigate mechanics associated with SC Water and possibly other fluids as well. Preliminary parameters used for scaling SCF are listed in Table 1. These scaling parameters were deduced from those proposed by Jackson and Hall in 1979 [5] and Gorban' et al. in 1990 [6]. Table 2 shows the critical parameters of CO_2, R134a and water calculated using NIST [7].

However, thermo-physical properties of different fluids may vary significantly with respect to absolute values. To demonstrate this idea, some common thermo physical properties were plotted for Water, CO_2 and R134a as they transition through the pseudo-critical region. Figure 5-10 show the thermo-physical property profiles vs. reduced temperature (i.e $T_r = T / T_{cr}$) at their respective equivalent pressures (P=25 MPa for water, P=8.4 for CO_2 and P=4.6 MPa for R134a using the scaling parameters shown in Table 1.)

Table 1: Scaling Parameters for SCFs modelling [1]

Pressure (P)	$\left(\frac{P}{P_{cr}}\right)_{CO_2} = \left(\frac{P}{P_{cr}}\right)_{H_2O} = \left(\frac{P}{P_{cr}}\right)_{R134a}$
Bulk fluid temperature (K)	$\left(\frac{T_b}{T_{cr}}\right)_{CO_2} = \left(\frac{T_b}{T_{cr}}\right)_{H_2O} = \left(\frac{T_b}{T_{cr}}\right)_{R134a}$
Mass Flux (G)	$\left(\frac{GD}{\mu_b}\right)_{CO_2} = \left(\frac{GD}{\mu_b}\right)_{H_2O} = \left(\frac{GD}{\mu_b}\right)_{R134a}$

Table 2: Critical parameters of selected fluids [7]

Fluid	P_{cr}, MPa	T_{cr}, °C	ρ_{cr}, kg/m^3
CO_2	7.3773	30.978	467.6
Freon R-134a	4.0593	101.06	511.9
Water (H_2O)	22.064	373.95	322.39

In general, an analysis of the graphs in Figures 5-10 shows that property profiles for all 3 fluids are fairly similar. However, there are significant variations between the absolute values of the properties of different fluids (especially for the case of water). These differences in absolute values, would pose difficulties to propose a single generic *HTC* correlation that could be applied to different SCFs even after scaling parameters are considered. Thus, it appears that *HTC* correlations that are developed for SC water cannot be directly applied towards SC CO_2.

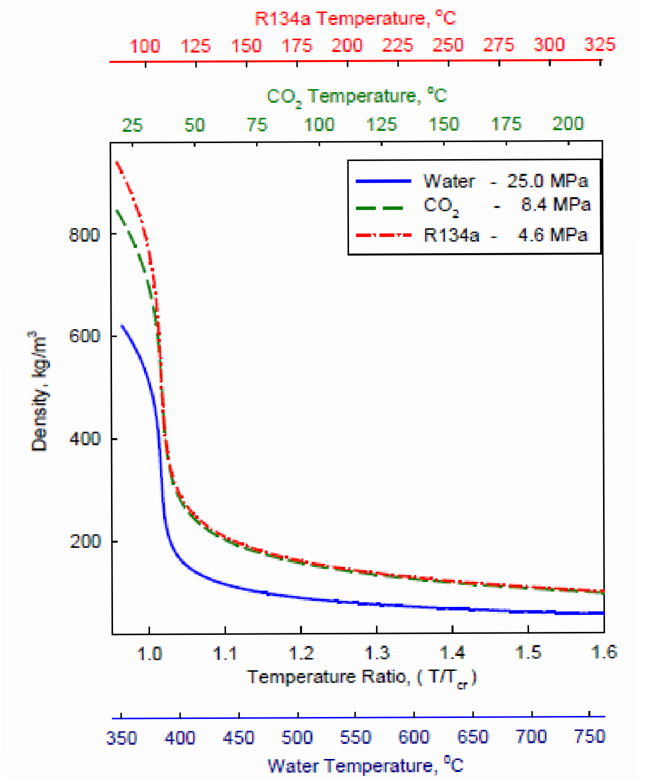

Figure 5: Density vs. reduced temperature

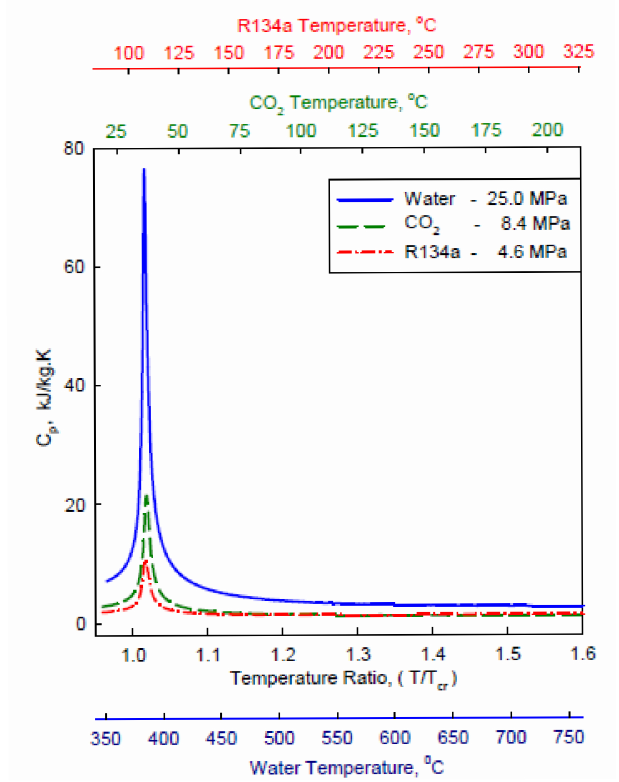

Figure 6: Specific heat vs. reduced temperature

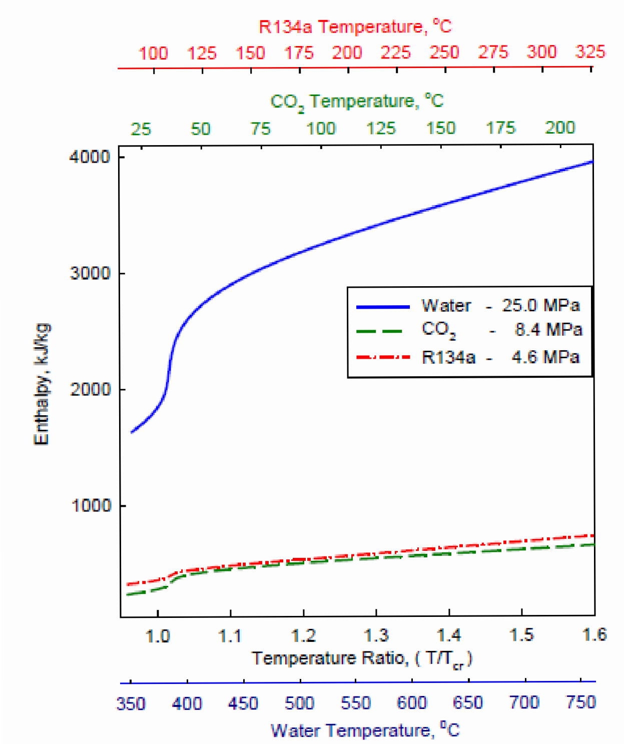

Figure 7: Enthalpy vs. reduced temperature

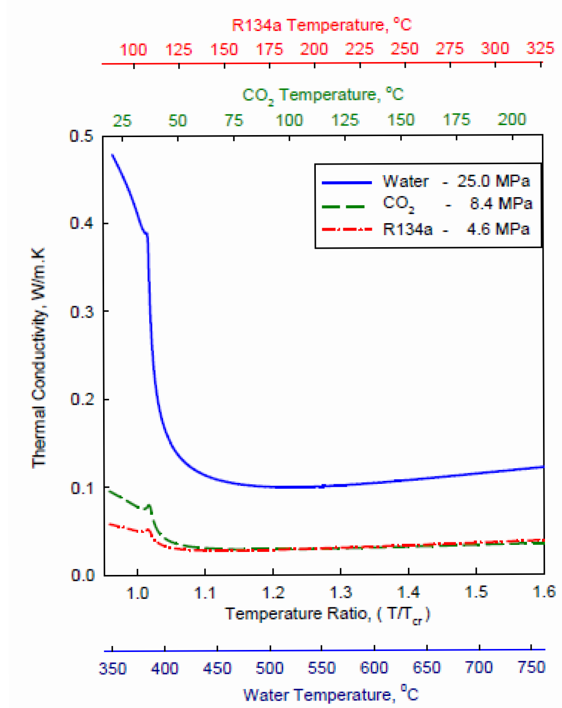

Figure 8: Thermal conductivity vs. reduced temperature

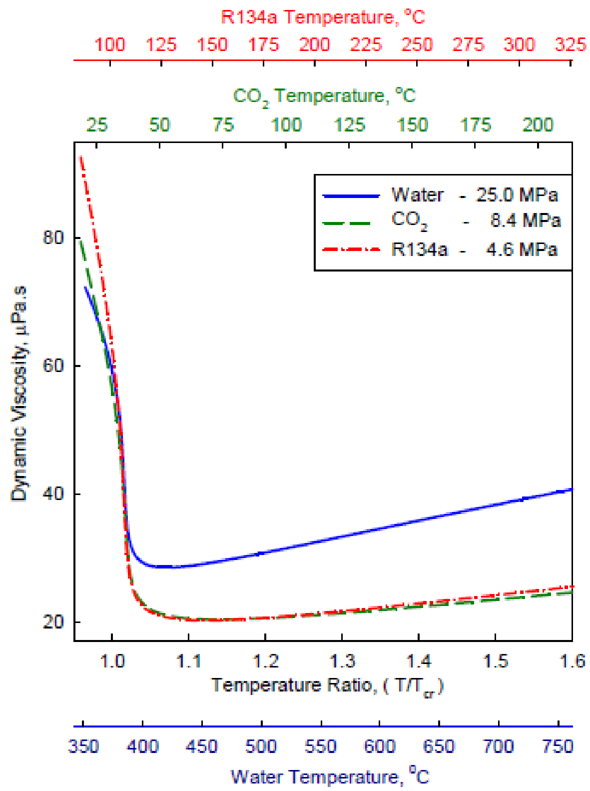

Figure 9: Dynamic Viscosity vs. reduced temperature

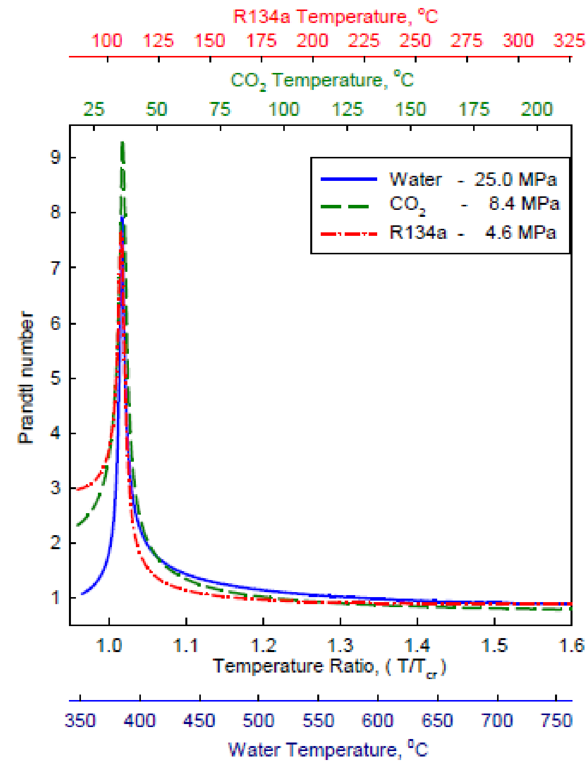

Figure 10: Prandtl number vs. reduced temperature

2.2 Historical Note on Use of Supercritical Fluids in Power Generation

In the 1950s, the idea of using supercritical water appeared to be rather attractive for thermal-power industry [1]. The objective was increasing the total thermal efficiency of coal-fired power plants. Thermal efficiency is a direct function of the temperature and pressure drop across the turbine, thus higher operating ranges would directly correlate to higher efficiencies. After various experimental and pilot projects, Supercritical water technology was successfully applied in coal—fired thermal power plants and is the largest application of a fluid at supercritical pressures in industry.

Between late 1950s and early 1960s, studies were also conducted to investigate the possibility of using supercritical water in nuclear reactors [1]. Several designs of nuclear reactors using supercritical water were proposed in Great Britain, France, the USA, and the former USSR. However, the idea was abandoned for almost 30 years with the emergence and great success of Light Water Reactors (LWRs). SCWR technology regained interest in the 1990s following LWRs maturation. As a part of Generation IV International Forum (GIF), SCWR concepts (which include Pressure-Vessel (PV) and Pressure-Tube (PT) reactors) are under development worldwide. Currently AECL Canada is working towards developing a preliminary design of a PT-SCWR concept. Therefore, development of heat-transfer correlations for supercritical fluids based on modern sets of experimental and thermophysical properties data is an important task.

3. EXISTING CORRELATIONS FOR FORCED CONVECTIVE HEAT TRANSFER IN BARE TUBES

A number of empirical generalized correlations have been proposed to calculate the *HTC* in forced convection for various fluids (mainly water) at supercritical pressures. Some of the most widely used heat—transfer correlation are presented in Table 3. Among these, Dittus-Boelter, Bishop et al., Swenson et al. and Jackson et al. are very commonly used for heat transfer applications.

The majority of these empirical correlations were proposed in the 1960s and 1970s, when experimental techniques were not as advanced as they are today. Also, thermophysical properties have been updated since that time. For example, a peak in thermal conductivity in critical and pseudocritical points, was not officially recognized until the 1990s [1]. As a result, most of these correlations do not fit current experimental data with the desired accuracy. Figure 11-12 shows a comparison of *HTC* values calculated through various correlations for SCW data from Kirillov [8]. It can be noted that differences in calculated *HTC* values can be up to several hundred percent especially within the pseudocritical range. Swenson et al. and newer correlations such as Mokry et al. and Gupta et al. are relatively more accurate even within the pseudocritical ranges. However, these correlations cannot be directly applied to SC CO_2.

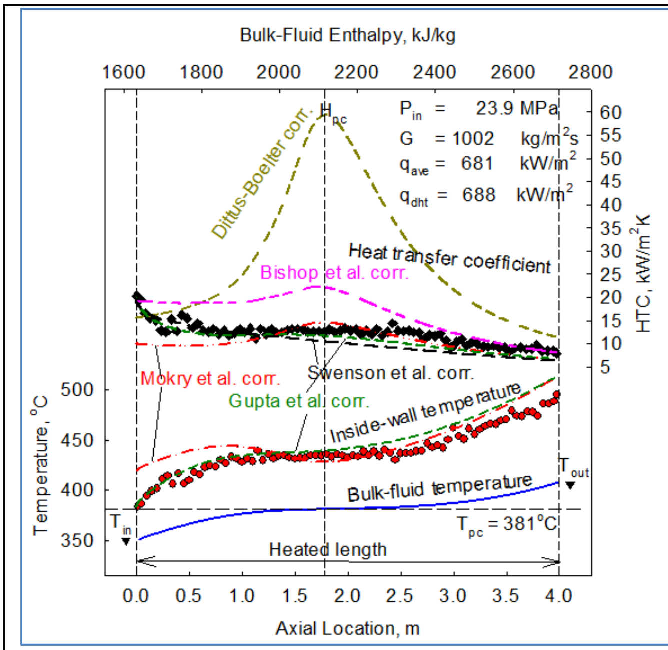

Figure 11: Comparison of *HTC* values calculated through various correlations with experimental data of 4-m circular vertical bare tube (*D*=10mm): P_{in} ~ 24 MPa and *G* ~ 1000 kg/m²s.

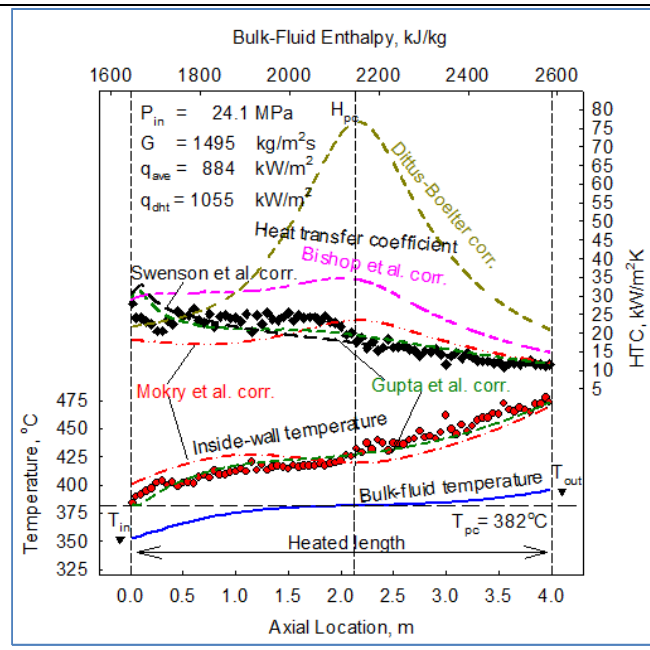

Figure 12. Comparison of *HTC* values calculated through various correlations with experimental data of 4-m circular vertical bare tube (*D*=10mm): P_{in} ~ 24 MPa and *G* ~ 1500 kg/m²s.

Therefore, empirical heat-transfer correlations based on bare-tube CO_2 data and latest thermophysical properties should be developed and used as a preliminary, but conservative approach. This approach is based on the fact that values of *HTC* in bare tubes are generally lower than those in bundle geometries.

Table 3: Summary of Some Important HTC Correlations

Author	Correlation	Operating Parameters
Dittus-Boelter (1930)	$\mathbf{Nu_b} = 0.0243\mathbf{Re_b^{0.8}Pr_b^{0.4}}$	Subcritical Pressures
Bringer and Smith (1957)	$\mathbf{Nu_x} = 0.0266\ \mathbf{Re_x^{0.77}Pr_b^{0.55}}\ (for\ Water)$ $\mathbf{Nu_x} = 0.0375\ \mathbf{Re_x^{0.77}Pr_b^{0.55}}\ (for\ CO_2)$ $t_x = t_b\ If\ (t_{pc} - t_b)/(t_w - t_b) < 0$ $t_x = t_{pc}\ If\ 0 \le (t_{pc} - t_b)/(t_w - t_b) \le 1$ $t_x = t_w\ If\ (t_{pc} - t_b)/(t_w - t_b) > 1$	SCW (*P=34.5* MPa)
Krasnoshchekov and Protopopov (1960)	$\mathbf{Nu} = \mathbf{Nu_0}\left(\frac{\mu_b}{\mu_w}\right)^{0.11}\left(\frac{k}{k}\right)^{-0.33}\left(\frac{\bar{c}}{c_{pb}}\right)^{0.35}$ $\mathbf{Nu_0} = \frac{\frac{\xi}{8}\mathbf{Re_b}\overline{\mathbf{Pr}}}{12.7\sqrt{\frac{\xi}{8}}\left(\overline{\mathbf{Pr}}^{\frac{2}{3}} - 1\right) + 1.07}$ $\xi = \frac{1}{(1.82\log_{10}\mathbf{Re_b} - 1.64)^2}$	*P*=22.3-32 MPa (water) *P*=8.3 MPa (CO_2)
Bishop et al. (1964)	$\mathbf{Nu_b} = 0.0069\mathbf{Re_b^{0.9}}\ \overline{\boldsymbol{Pr}}_{\boldsymbol{b}}^{\mathbf{0.66}}\left(\frac{\rho_w}{\rho_b}\right)^{0.43}$	*P:* 22.8-27.6 MPa T_b=282 -527°C *G*=651-3662 kg/m²s *q*=0.31-3.46 MW/m²
Swenson et al. (1965)	$\mathbf{Nu_w} = 0.00459\mathbf{Re_w^{0.923}}\overline{\mathbf{Pr}}_{\mathbf{w}}^{\mathbf{0.613}}\left(\frac{\rho_w}{\rho_b}\right)^{0.231}$	*P:* 22.8-41.4 MPa T_b=75-576°C T_w=93-649°C *G*=542-2150 kg/m²s
Gorban' et al. (1990)	$\mathbf{Nu_b} = 0.0059\mathbf{Re}_b^{0.90}\mathbf{Pr}_b^{-0.12}\ (for\ water)$ $\mathbf{Nu_b} = 0.0094\mathbf{Re}_b^{0.86}\mathbf{Pr}_b^{-0.15}\ (for\ R-12)$	$T_b > T_{cr}$
Jackson (2002)	$\mathbf{Nu} = 0.0183\mathbf{Re}_b^{0.82}\mathbf{Pr}_b^{0.5}\left(\frac{\rho_w}{\rho_b}\right)^{0.3}\left(\frac{\bar{\bar{c}}_p}{c_{pb}}\right)^{n}$ $n = 0.4$ For $T_b < T_w < T_{pc}$ and for $1.2 \cdot T_{pc} < T_b < T_w$ $n = 0.4 + 0.2\left(\frac{T_w}{T_{pc}} + 1\right)$ For $T_b < T_{pc} < T_w$; and $n = 0.4 + 0.2\left(\frac{T_w}{T_{pc}} + 1\right)\left[1 - 5\left(\frac{T_b}{T_{pc}} - 1\right)\right]$ For $T_{pc} < T_b < 1.2 \cdot T_{pc}$ and $T_b < T_w$	Supercritical pressures
Sarah Mokry et al. (2009)	$\mathbf{Nu_b} = 0.0061\ \mathbf{Re_b^{0.904}}\ \overline{\mathbf{Pr_b}}^{0.684}\left(\frac{\rho_w}{\rho_b}\right)^{0.564}$ (developed for SC H_2O)	Supercritical Ranges
Gupta et al. (2011)	$\mathbf{Nu_w} = 0.0033\ \mathbf{Re_w^{0.94}}\ \overline{\mathbf{Pr_w}}^{-0.76}\left(\frac{\mu_w}{\mu_b}\right)^{0.4}\left(\frac{\rho_w}{\rho_b}\right)^{0.156}$ (developed for SC H_2O)	Supercritical Ranges

4. DEVELOPING NEW CORRELATION FOR SC CO_2

4.1 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 experimental dataset was obtained at the MR-1 test facility (see Fig. 13) at the CRL lab, which is a former steam/water high pressure and high-temperature pump loop adapted for use with supercritical CO_2 [1].

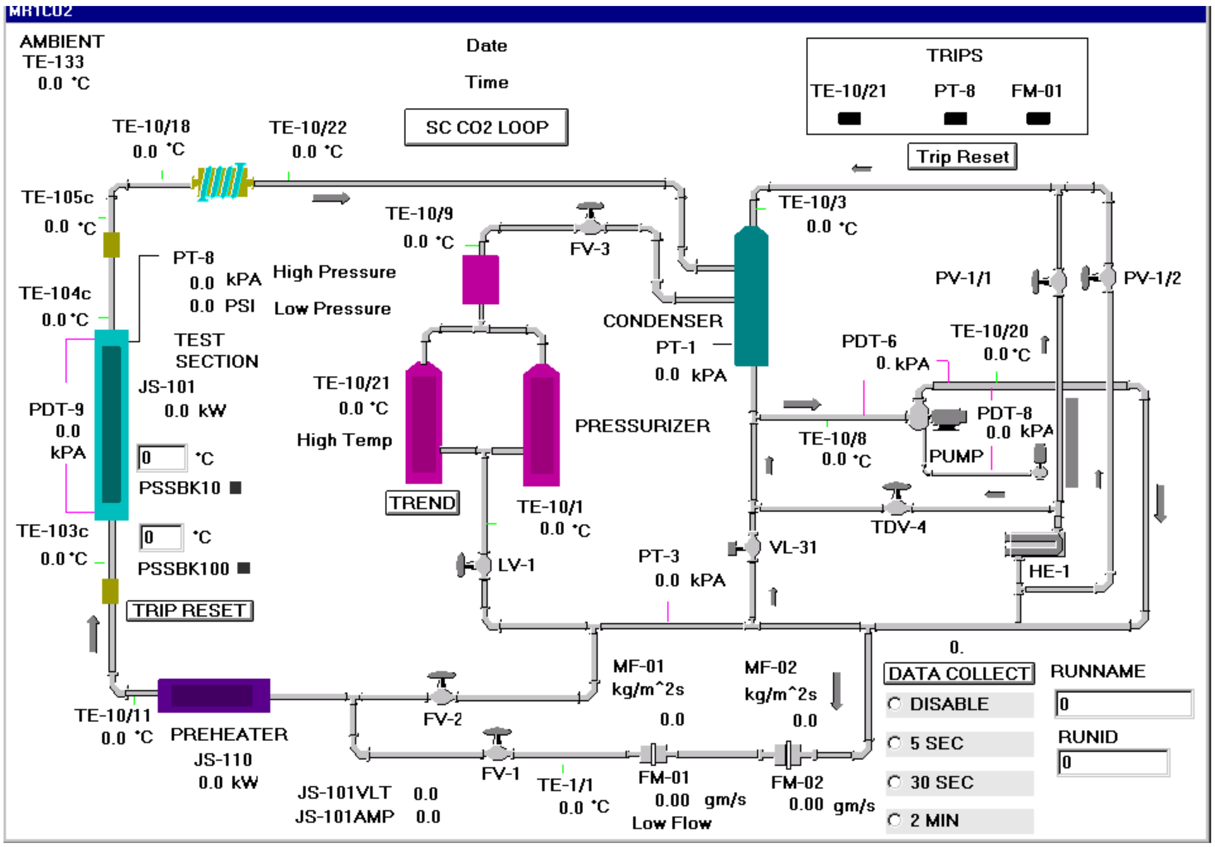

Figure 13: Fuel Channel Thermalhydraulics MR-1 Loop Schematic [1]

The test section (see Fig. 14), 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. The test section is attached with structural supports to a post to maintain its vertical orientation. Table 4 lists the test-matrix parameters showing the minimum and maximum range of operating parameters where the dataset was obtained. Table 5 lists the uncertainties of measured and calculated parameters in relation to the experimental dataset (for reference purposes only).

Table 4: 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

The dataset includes over 4,600 points. 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 NHT regime. Therefore, data points in the DHT 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. Also, the very first and last points of most datasets were removed. Temperatures at these outlying points were likely affected by test-section clamps, which were at a lower temperature than the heated part of tube. Overall, approximately 88% of the experimental data were used to develop the correlation.

Table 5: 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)	$\Delta\rho = \pm 7\%; \Delta H = \pm 2.5\%;$ $\Delta c_p = \pm 4.5\%;\ \Delta k = \pm 2\%;$ $\Delta\mu = \pm 7\%;$

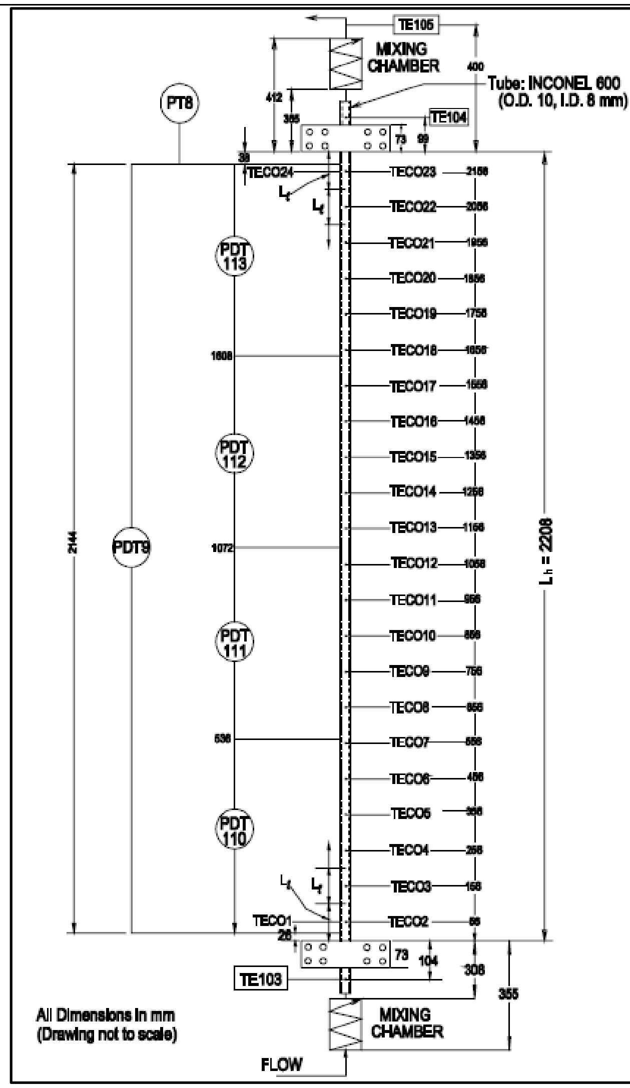

Figure 14: Test Section of MR-1 Loop [1]

4.2 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 [9] was used to produce a model formula, where $\mathbf{Nu_x}$ was represented as a product of various dimensionless terms:

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

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 [7]. Scatter plots were then created and analyzed using linear regression on a log-log scale.

4.3 Proposed New Correlation

Preliminary coefficients C, n_1, n_2, etc. that were determined using manual iterations were then further refined. Some restraints put on values of these coefficients and plotting techniques were employed to obtain a preliminary correlation. 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.

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

It must be noted that the above correlation is applicable only for the referenced CO_2 dataset from Chalk River Labs (as no investigations has been conducted to determine its applicability for other datasets) and its range of applicability is within the flow conditions shown in Table 4. More investigations need to be conducted to see how well the correlation predicts HTC values from other independent datasets.

4.4 Graphical Error Analysis

Figures 15 and 16 show scatter plots of the experimental *HTC* and T_w values, versus the calculated values using Eq. (2). The results indicate that the spread of Experimental vs. Calculate graphs is about ±25-30% for *HTC* values and about ±15-20% for the calculated wall temperature (for the referenced dataset) which is a significant improvement from the previous correlations. The mean and root mean square (RMS) errors of the proposed correlation, as well as some of the existing correlations are shown in Table 6. Note that the proposed correlation shows the least errors for HTC and is better than any of the previous correlations by a significant margin for the referenced dataset. Also, since the correlation was developed from data-points ranging from sub-critical regions to super-critical regions, it also seems to predict the transition values (in pseudocritical range) much better than previous correlations.

Table 6: Mean and RMS Errors in predicted HTC and Tw[1] values

	HTC		Tw[1]	
	Mean Error%	RMS % (relative deviation)	Mean Error%	RMS % (relative deviation)
Proposed new correlation (Wall Approach)	**0.8%**	**20.3%**	0.8%	4.5%
Swenson et. al (1965) Corr.	89.3%	131.6%	-3.7%	4.9%
Mokry et. al (2009) Corr.	68.2%	123.0%	**0.3%**	7.2%
Gupta et. al (2011) Corr.	77.6%	129.8%	-2.2%	**4.2%**

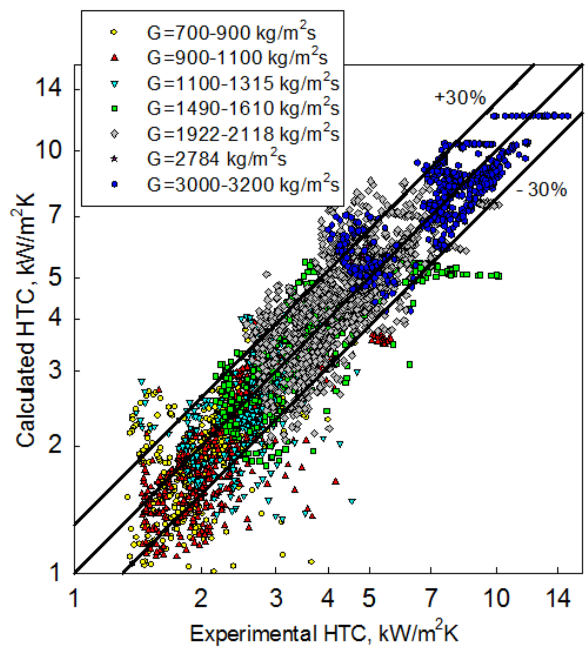

Figure 15: Comparison of data fit for *HTC* values using proposed correlation - Eq. (2).

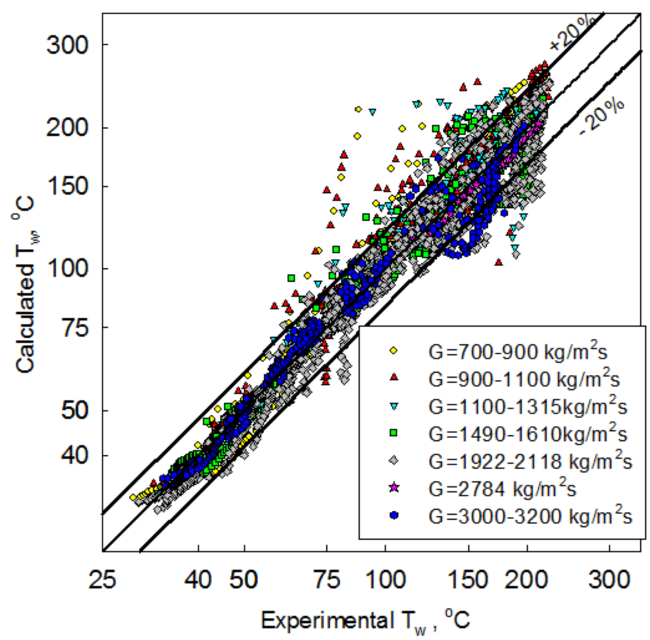

Figure 16: Comparison of data fit for T_w values using proposed correlation - Eq. (2).

5. CONCLUSIONS

1. Fossil fired plants have implemented the use of SCW to achieve 45--50 % thermal efficiencies. Therefore, 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. Thus the cost of performing experiments on SC CO_2 is significantly lower than that on SCW. Scaling parameters may be used to correlate results between different fluids as thermo-physical properties show similar trends when transitioning between

[1] T_w errors are calculated using the formula Error $= [T_{w-Cal} - T_{w-Exp}]/T_{w-Exp}(K)$,

Mean Error$=\frac{\sum_{i=1}^{n} Error_i}{n}$ and RMS error $=\sqrt{\frac{\sum_{i=1}^{n} Error_i^2}{n}}$

pseudocritical regions. However, expressions for scaling parameters are preliminary and require further consideration, as the absolute values of thermophysical properties vary significantly within the pseudocritical range.

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 (spread) associated with the correlation is about ±20-30% for *HTC* values and about ±15-20% for the calculated wall temperature (for the referenced dataset). Further error analysis needs to be performed to determine its applicability with other independent datasets.

6. NOMENCLATURE

C	constant
c_p	specific heat at constant pressure, J/kg·K
$\bar{c}_p$	average specific heat, J/kg·K, $\left(\frac{H_w - H_b}{T_w - T_b}\right)$
D	inside diameter, m
f	function
G	mass flux, kg/m^{2}s
H	enthalpy, J/kg
h	heat transfer coefficient, W/m^{2}K
k	thermal conductivity, W/m·K
L	length, m
P	pressure, Pa
q	heat flux, W/m^2
T	temperature, ºC
x	axial location, m

Greek letters

μ	dynamic viscosity, Pa·s
ρ	density, kg/m^3
δ	thickness, mm
ξ	friction factor

Dimensionless numbers

Nu	Nusselt number $\left(\frac{h \cdot D}{k}\right)$
Pr	Prandtl number $\left(\frac{\mu \cdot c_p}{k}\right)$
$\overline{\mathbf{Pr}}$	average cross-sectional Prandtl number $\left(\frac{\mu \cdot \bar{c}_p}{k}\right)$
Re	Reynolds number $\left(\frac{G \cdot D}{\mu}\right)$

Subscripts

ave	average
b	bulk
calc	calculated
cr	critical
dht	deteriorated heat-transfer
exp	experimental
h	heated
in	inlet
out	outlet
pc	pseudocritical
w	wall

Abbreviations:

AECL	Atomic Energy Canada Limited
Ave.	Average (error)
CRL	Chalk River Laboratories
DHT	Deteriorated Heat-Transfer
FCT	Fuel Channel Thermalhydraulics
HT	Heat Transfer
ID	Inside Diameter
IHT	Improved Heat-Transfer
HTC	Heat Transfer Coefficient
ID	Inside Diameter

LWR	Light Water Reactor	RMS	Root-Mean-Square (error)
NHT	Normal Heat Transfer	SC	SuperCritical
NIST	National Institute of Standards and Technology	SCF	SuperCritical Fluid
		SCW	SuperCritical Water
NPP	Nuclear Power Plant	SCWR	SuperCritical Water Reactor

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