# EVALUATION OF FLUID-TO-FLUID SCALING METHOD FOR WATER AND CARBON DIOXIDE AT SUPERCRITICAL PRESSURE

**S. Zwolinski[1], M. Anderson[1], M. Corradini[1], and J. Licht[2]**
[1] University of Wisconsin - Madison, Wisconsin, United States of America
[2] Atomic Energy of Canada Limited, Chalk River, Ontario, Canada

## Abstract

A flow loop at the University of Wisconsin used for supercritical water (SCW) experiments is being modified to perform similar tests with supercritical carbon dioxide ($SCO_2$). Scaled equivalent conditions in $SCO_2$ are determined by conserving key non-dimensional parameters from the SCW tests. The predicted heat transfer in the $SCO_2$ will be compared to measured data to evaluate the validity of the scaling method. As a secondary basis for verification, FLUENT CFD simulations for the scaled $SCO_2$ conditions are compared to simulations of the SCW experiments, which demonstrate good agreement with optically-measured turbulence data.

## 1. Introduction

It is well known that worldwide energy consumption is increasing at a rapid pace, and shall only continue to do so for the foreseeable future. To meet this demand, new power plants must offer increased output at a lower cost relative to current designs. Nuclear power is expected to play a key role in filling this order, with several new reactor designs receiving significant attention worldwide. Of these designs, the Supercritical Water-Cooled Reactor (SCWR) concept is considered particularly attractive. It is largely based on existing light water reactor (LWR) technology, essentially blending the direct cycle of the boiling water reactor (BWR) with the single-phase working fluid of the pressurized water reactor (PWR) to create a system with high thermal efficiency and simplified plant design [1]. Clearly, a fundamental understanding of the heat transfer to water at supercritical pressures is imperative for the continued development of such reactors.

In terms of heat transfer, fluids at supercritical pressures present interesting challenges. Though no phase change takes place, at a given supercritical pressure strong variations in thermo-physical properties occur over a small range of temperatures in the vicinity of the pseudo-critical point. These abrupt variations have a significant effect on heat transfer behaviour, and – depending on heat flux and mass flow conditions – can cause both enhancement and deterioration relative to normal single-phase heat transfer (e.g. [2], [3]). The prediction of deteriorated conditions in the SCWR core is particularly important, as very high local cladding temperatures are possible, which could lead to fuel damage. Thus, in recent years a significant effort has been made to develop and improve heat transfer correlations for supercritical fluids [4], and work continues in this area. Experimental studies with supercritical water are essential to continuing this effort; however, due to the high pressure (>220 bar) and temperatures (>374°C) required, such experiments are technically challenging and costly. Reproducing the conditions expected to be prototypic of the SCWR presents an even greater challenge, as operating pressures and temperatures are expected to be as high as 250 bar and 500-550°C, respectively [1].

To alleviate the difficulties associated with experiments using supercritical water, often a surrogate fluid is used. Supercritical carbon dioxide, which is itself being studied for application in Brayton power cycles, is an attractive substitute for water as the pressure and temperature requirements are only 74 bar and 31°C. However, to make use of the results of experiments using $SCO_2$ in modelling SCW, reliable scaling laws must be available. Several fluid-to-fluid scaling methods have been proposed ([4], [5], [6], [7]), but there have been few studies concerning their validity for application to heat transfer, and as yet none have been tested experimentally [6].

The purpose of this paper is to describe a computational study and planned experimental study designed to directly test proposed heat transfer scaling methods for supercritical fluids. Specifically, scaling between SCW and $SCO_2$ is examined. Using scaling laws proposed by Jackson [6], conditions in an extensive set of SCW experiments conducted at the University of Wisconsin [8, 9] have been scaled to $SCO_2$. The flow loop used for the SCW experiments is being adjusted to operate with $SCO_2$ in the same test section geometry, using much of the same measurement equipment and techniques. In addition, select representative scaled-similar test runs have been modeled using the computational fluid dynamics (CFD) code FLUENT, and the model results compared between the two fluids as an initial indicator of scaling law performance.

## 2. Scaling between SCW and $SCO_2$

### 2.1 Method

The scaling method chosen to determine conditions in the planned $SCO_2$ experiments is that proposed by Jackson [6], with a modified temperature ratio. In general, six non-dimensional quantities are preserved. As is standard for most thermal hydraulic scaling applications, geometric effects are accounted for by preserving the ratio of length scale to hydraulic diameter, $D_h$, as:

$$\left(\frac{x}{D_h}\right)_1 = \left(\frac{x}{D_h}\right)_2 \tag{1}$$

Pressure is scaled by preserving the reduced value, as in Eq. (2), where $P_o$ is a reference pressure.

$$\left(\frac{P_o}{P_c}\right)_1 = \left(\frac{P_o}{P_c}\right)_2 \tag{2}$$

Eq. (3), defined as the thermal loading parameter, is used to preserve the dimensionless imposed heat flux. In this study, the reference heat flux $q_w$ is the average rod surface heat flux, and both thermal conductivity $k_o$ and temperature $T_o$ are referenced at bulk flow conditions at the measurement location.

$$\left(\frac{q_w D_h}{k_o T_o}\right)_1 = \left(\frac{q_w D_h}{k_o T_o}\right)_2 \tag{3}$$

The Reynolds and Nusselt numbers, Eq. (4) and (5), are preserved to scale the mass flux G and heat transfer, respectively. The prediction of heat transfer in $SCO_2$ given by Eq. (5) will be compared to measured values as the primary indicator of the validity of the scaling method.

$$\left(\frac{GD_h}{\mu_o}\right)_1 = \left(\frac{GD_h}{\mu_o}\right)_2 \tag{4}$$

$$\left(\frac{hD_h}{k_o}\right)_1 = \left(\frac{hD_h}{k_o}\right)_2 \tag{5}$$

In Jackson's approach, the temperature is scaled in the same fashion as the pressure, by preserving the reduced value given in Eq. (6).

$$\left(\frac{T_o}{T_c}\right)_1 = \left(\frac{T_o}{T_c}\right)_2 \tag{6}$$

As discussed in [6], for the same working fluid, scaling using the reduced pressure and temperature necessarily results in preservation of the Prandtl number and compressibility group $\beta_o T_o$, where $\beta_o$ is the coefficient of thermal expansion at the reference temperature. However, for different fluids at supercritical pressures, this relationship does not necessarily hold. As discussed in [7], the dependence of properties on the reduced temperature can vary significantly between fluids. Carbon dioxide in particular displays this behaviour, owing in part to the relatively small difference between the critical point and freezing temperature (109°C) as compared to water (374°C). For a given reduced pressure, the temperature at which drastic changes in properties occur is expected to scale more accurately with the pseudo-critical temperature.

To account for the relative distance from the pseudo-critical point, Cheng proposed a modified non-dimensional temperature θ, called the pseudo – steam quality, defined as:

$$\theta = \left(\frac{T_o - T_{pc}}{T_{pc} - T_c}\right) \tag{7}$$

where $T_{pc}$ is the pseudo-critical temperature. However, this choice seems to limit the model applicability to pressures a certain magnitude above or below the critical pressure. To avoid imposing this limit, the following modified reduced temperature scaling:

$$\left(\frac{T_o}{T_{pc}}\right)_1 = \left(\frac{T_o}{T_{pc}}\right)_2 \tag{8}$$

was employed in this study. It should be noted that this choice shifted the scaled experimental $SCO_2$ bulk temperatures by only 3-4°C relative to using the reduced temperature, which may prove to have a relatively small impact on the experimental heat transfer comparison.

## 2.2 Experimental conditions

The SCW experiments conducted by Licht [8, 9] covered a range of flow conditions in both circular-annular and square-annular geometry in the vertical upward flow configuration. Heat flux, mass flux, and bulk temperature were varied to cover the transition, forced, and mixed convection flow regimes in order to observe heat transfer enhancement, and deterioration brought on by buoyancy effects [3, 5].

In the square-annular experiments, a special optical test section was used to allow for local axial and radial turbulence measurements via a two-component laser Doppler velocimetry (LDV) system. In all, forty-seven test cases were performed encompassing two mass flux values, three heat flux values, and approximately eight bulk temperatures ranging from 25 to 400°C. Replicating these experiments in $SCO_2$ is of particular interest; therefore, the conditions in these square-annular tests have been scaled. The conditions to be tested are summarized in Table 1 below.

Table 1. Conditions in SCW and scaled – similar $SCO_2$ experiments

| Supercritical Water | | | Supercritical Carbon Dioxide | | |
|---|---|---|---|---|---|
| Bulk Temperature [C] | Mass Flux [kg/m$^2$-s] | Heat Flux [kW/m$^2$] | Bulk Temperature [C] | Mass Flux [kg/m$^2$-s] | Heat Flux [kW/m$^2$] |
| 300 | 315, 1000 | 0, 220, 440 | -4 | 400, 1270 | 0, 22, 43 |
| 340 | 315, 1000 | 220, 440 | 15 | 345, 1095 | 20, 40 |
| 370 | 315, 1000 | 220, 440 | 30 | 300, 950 | 18, 36 |
| 380 | 315, 1000 | 220, 440 | 35 | 280, 890 | 16, 32 |
| 397 | 315, 1000 | 220, 440 | 42 | 250, 780 | 18, 36 |

All of the SCW tests in Table 1 were conducted at 250 bar, corresponding to 84 bar in $SCO_2$. Twenty-seven of the forty-seven SCW cases can be replicated; water cases at bulk temperatures below 300°C cannot, regardless of scaling method, due to the excessively low corresponding temperatures in $SCO_2$. This is again due to the difference in the relative location of the critical point with respect to the freezing temperature of carbon dioxide, as mentioned earlier.

In general, lower-temperature tests could be run in $CO_2$ using a different facility. However, the size (two meters wide by three meters high), heat input, and mass flow requirements of the UW-SCW loop result in cost-prohibitive heat removal requirements at $SCO_2$ temperatures below -5°C. When using SCW as the test fluid, loop cooling can be accomplished using building water flowing through copper tubing coiled around the loop piping [8,9]. However, for low-temperature $SCO_2$, the coils are ineffective and a large heat exchanger system using a refrigerant (i.e., ethylene glycol) is required.

## 3. Computational fluid dynamics simulations

In the SCW experiments, Licht made used of the CFD software FLUENT 6.3 to gain insight into the flow behaviour in the boundary layer, verifying the simulation results through comparison to the local turbulence data collected in the square annular geometry. As detailed in [8], in general, for carefully chosen model parameters the simulations were found to agree quite well with measurements. Similar computational agreement has been achieved in comparison to other published data sets, for example in Kiss [10], where the Reynolds-averaged Navier Stokes (RANS) solvers in the ANSYS CFX 11 software were used to model the conditions of the of Herkenrath [11], Swenson [12], and Yamagata [2] experiments. In view of this, comparison of CFD predictions for SCW and $SCO_2$ at scaled conditions is expected to offer credible insight into the viability of the scaling method even before measured $SCO_2$ data are available.

### 3.1 Computational modelling scheme

In the present study, version 12 of the FLUENT software was used to simulate the scaled $SCO_2$ tests. For consistency, the radial geometry was modelled the same way as in [8], with a full-scale $1/8^{th}$ section with symmetry boundaries on the non-wall edges (Figure 1). Likewise, the same 1.1 meter heated length was modelled, though the overall axial length was changed from 2.1 to 1.6 meters by reducing the inlet development length. This allowed for increased axial mesh refinement, improving the cell aspect ratios to ensure that the maximum 1:35 limit recommended by the FLUENT user's guide was met. For all calculations, the Reynolds stress method (RSM) was used to resolve the turbulence information. Fluid thermophysical properties were referenced from the NIST real-gas model, a feature unavailable in FLUENT 6.3. To ensure that these changes in modelling mechanics did not affect the comparisons between SCW and $SCO_2$ simulations, cases were run for both fluids in the new scheme. The validity of comparison to the measured SCW data was confirmed in that no noticeable change was observed between the SCW simulation results in [8] and the new results.

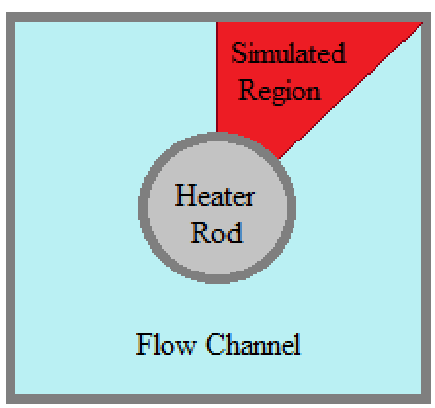
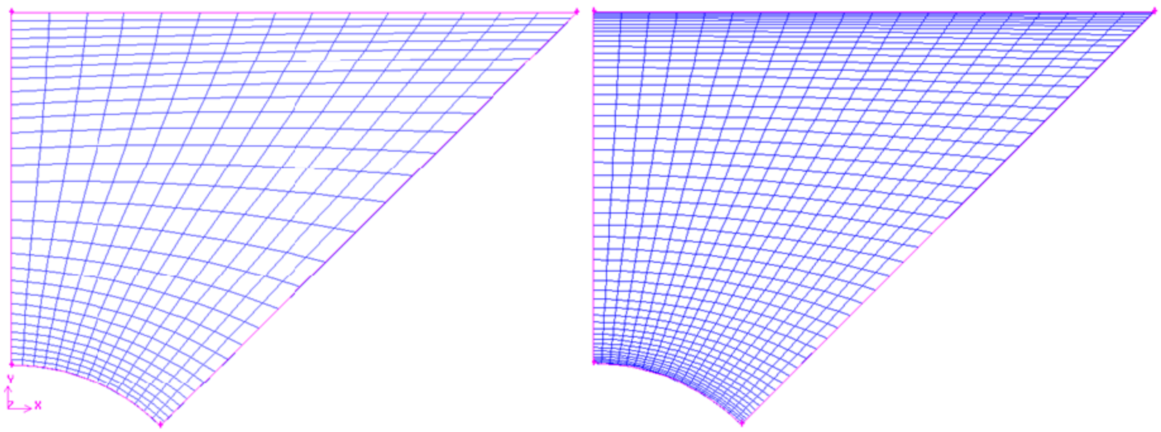



Figure 1. Schematic of the radial computational domain

Depending on the mass flux, two meshing schemes and wall function treatments were used. For the high mass flux cases (corresponding to SCW at 1000 kg/m$^2$-s in Table 1), it was found that the density-based solver with the standard wall function provided acceptable accuracy. This method requires that the mesh nodes closest to the wall are located at $y+ \approx 30$, bridging the gap between this node and the wall using a functional relationship. The radial meshing was done in exactly the same fashion as the previous standard wall function models [7], with 15 divisions along the circumferential direction, and 30 divisions along the symmetry boundaries, distributed using a bell shape (Figure 2a). In the axial direction, the development length and test section were divided into 700 and 1500 divisions, respectively. The inlet and outlet conditions were the mass-flow and pressure-outlet type.



(a) (b)

Figure 2. Radial mesh for (a) standard wall function and (b) enhanced wall treatment calculations

For the low mass flux cases (corresponding to SCW at 315 kg/m$^2$-s), the enhanced wall treatment was applied. This method fully resolves the viscous sublayer, therefore requiring mesh nodes down to y+ ≈ 1. Here, 50 radial and 20 circumferential divisions were applied (Figure 2b). In the axial direction, 500 and 1100 divisions were applied to the development and test section portions, respectively. Unlike in the high mass flux cases, the pressure – based solver was used, as the density based solver was found to be quite unstable when used in conjunction with the enhanced wall treatment. The outlet boundary condition was correspondingly changed to outflow for these cases.

In total, seven pairs of SCW - $SCO_2$ cases were simulated to observe the effects of mass flux, heat flux, and bulk temperature on the turbulence behaviour for both fluids. These tests are summarized in Table 2. Again, all SCW cases were at 250 bar, and all $SCO_2$ cases at 84 bar.

Table 2. SCW and scaled $SCO_2$ case pairs simulated in FLUENT

| | Supercritical Water | | | Supercritical Carbon Dioxide | | |
|---|---|---|---|---|---|---|
| Case Number | Bulk Temperature [C] | Mass Flux [kg/m$^2$-s] | Heat Flux [kW/m$^2$] | Bulk Temperature [C] | Mass Flux [kg/m$^2$-s] | Heat Flux [kW/m$^2$] |
| 1 | 300 | 985 | 0 | -3 | 1310 | 0 |
| 2 | 300 | 985 | 220 | -3 | 1310 | 22 |
| 3 | 300 | 985 | 440 | -3 | 1310 | 43 |
| 4 | 370 | 985 | 220 | 30 | 940 | 19 |
| 5 | 397 | 985 | 440 | 42 | 775 | 50 |
| 6 | 300 | 285 | 220 | -4 | 380 | 22 |
| 7 | 397 | 285 | 440 | 42 | 780 | 36 |

## 3.2 Simulation results

The calculation results were compared primarily on the basis of their agreement with the four main turbulence parameters discussed in [8]. These are the normalized axial velocity, axial and radial turbulent intensity, and Reynolds stress, defined respectively in equations 9 – 12 below:

$$U_{norm} = \frac{\overline{U}}{U_o} \tag{9}$$

where $\overline{U}$ is the mean local axial velocity. Of course, the simulation results output only a single value; here, the "mean" refers to the statistical average value from the measured data. $U_o$ is the maximum bulk velocity.

$$I_{axial,norm} = \frac{\sqrt{\overline{u'^2}}}{U_o} \tag{10}$$

$$I_{radial,norm} = \frac{\sqrt{\overline{v'^2}}}{U_o} \tag{11}$$

where u' and v' are the fluctuating components of axial and radial velocity, respectively, and

$$R_{norm} = \frac{\overline{u'v'}}{U_o^2} \tag{12}$$

where the mean product of the fluctuating components is defined as the Reynolds stress.

In general, FLUENT predictions in scaled $SCO_2$ agreed almost exactly with the analogous results in SCW, regardless of mass flux, heat flux, and bulk temperature. For example, in case 1 of Table 2, the prediction results of Figure 3 are obtained. In all of the following plots, solid symbols denote measured SCW data, solid lines denote SCW FLUENT simulation results, and open symbols denote $SCO_2$ FLUENT simulation results.

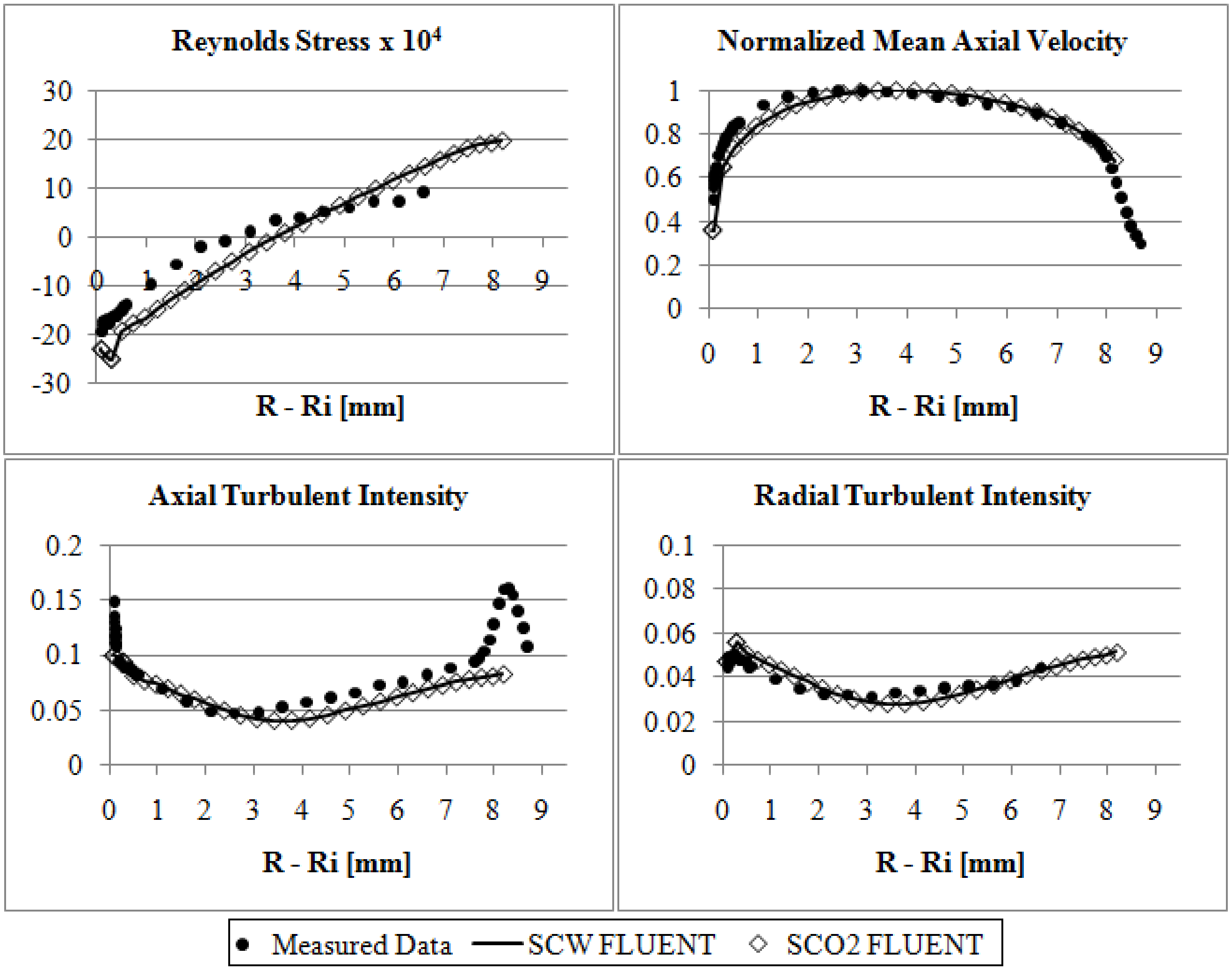



Figure 3. Turbulence parameter comparison for SCW - $SCO_2$ Case Number 1

Here, the normalized values described previously are plotted against the relative radius R – $R_i$, which is simply the distance from the heated wall at $R_i$.

Note that, while simulations for both fluids are not in perfect agreement with the LDV measured data, they are in exact agreement with each other. The most glaring inconsistencies between the simulation and data are near the walls, notably the channel outer wall. This is presumably due to physical factors not modelled in FLUENT, including the presence of spacers around the heater rod and possible additional turbulence generated by the main pump [8]. Interestingly, increased heat flux only seems to exacerbate the problem in terms of the turbulent intensities, as demonstrated in Figure 4.

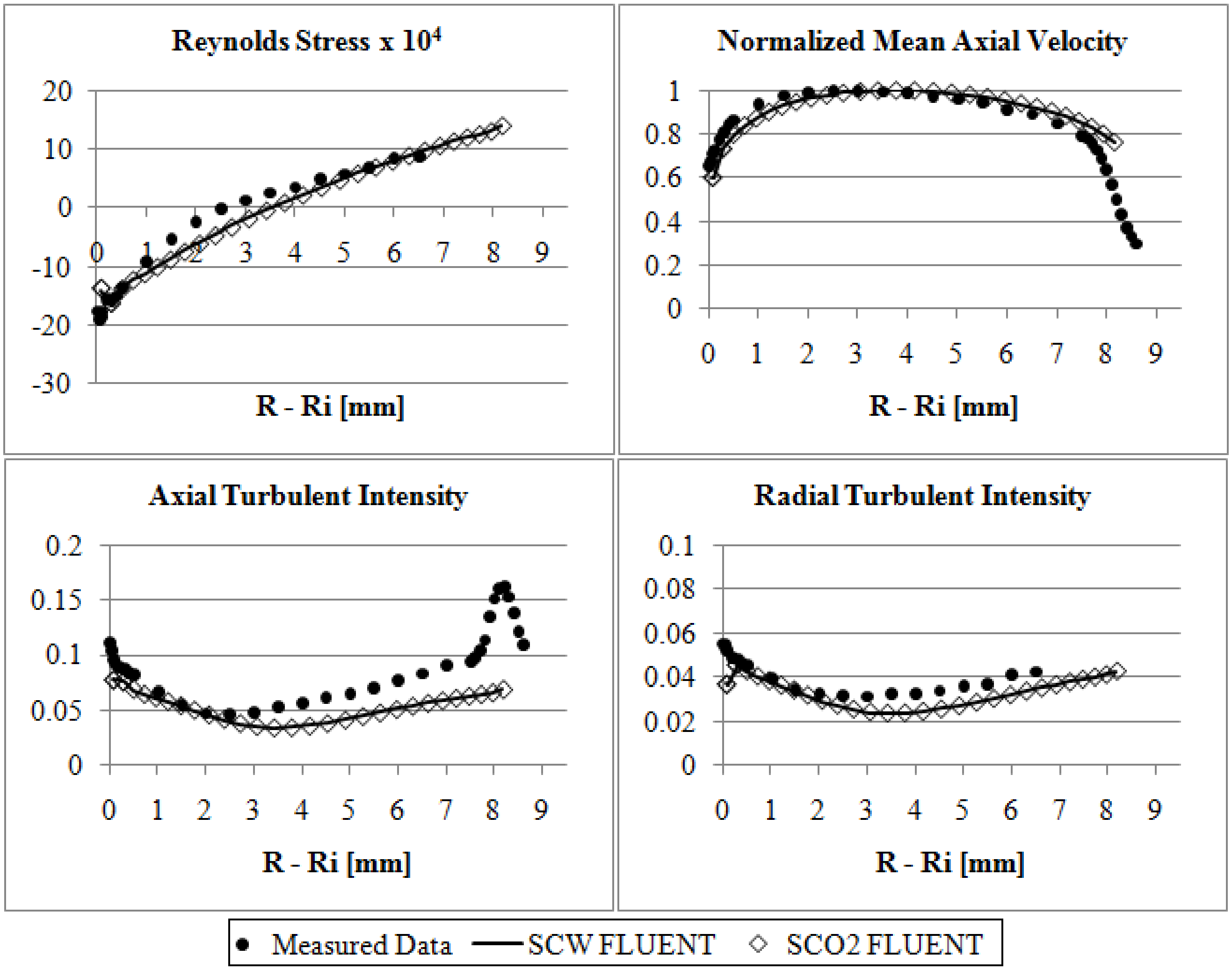



Figure 4. Case Number 2 – high mass flux, moderate heat flux

Also of interest are the average wall- and bulk- temperatures, normalized with respect to the pseudo-critical temperature. A comparison, again for Case 2 of Table 1, is given in Figure 5 below. Here, axial position refers to the height along the heated length of the test section. As was the case with the turbulence parameters, good agreement with the magnitude and trend of the measured data is generally observed; however, exact agreement between the FLUENT model predictions is no longer seen. The difference between the predictions for the SCW and $SCO_2$ wall temperatures is approximately 10%.

The discrepancy between the temperature predictions is presumably due, at least in part, to imperfect similarity in Prandtl number between the two fluids. Specifically, the behaviour of the specific heat is not explicitly addressed in the scaling, though constraints on the temperature and pressure defining this property are imposed. It has been suggested [13] that careful choice of pressure scaling can allow greater similarity between the Prandtl number for dissimilar fluids; however, this would manifest as a distortion in the scaling of temperature and, by extension, heat flux, due to the sensitivity of the pseudo-critical temperature to pressure.

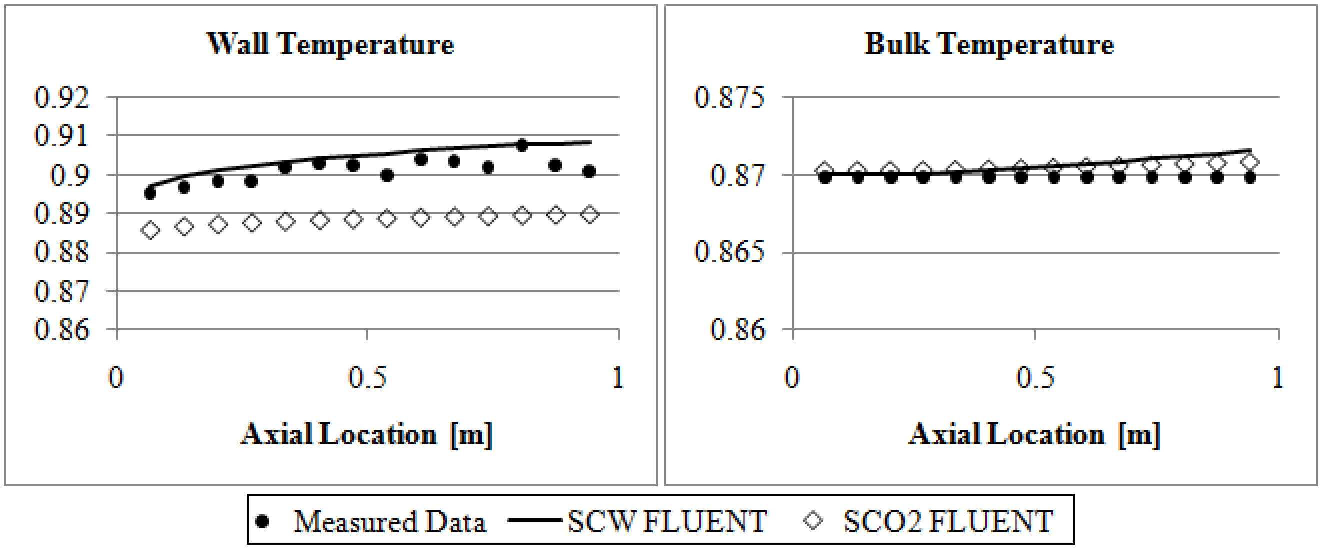



Figure 5. Temperature Variation for Case Number 2 – high mass flux, moderate heat flux

Use of the pressure-based solver in conjunction with the enhanced wall treatment for the low mass flux case did not alter the agreement between the SCW and $SCO_2$ predictions.

Overall, these results lend encouraging support to the viability of the scaling laws. The remarkable agreement between the simulation results for SCW and $SCO_2$, given the vastly different mass flow, heat flux, and temperature conditions applied, implies that the key physical parameters governing the flow behaviour have been correctly accounted for in the scaling.

## 4. Conclusions

An extensive set of experiments in supercritical water conducted at the University of Wisconsin have been scaled in preparation for conducting similar experiments in supercritical carbon dioxide. The planned experiments will use the same test section geometry and much of the same measurement equipment and techniques used in the SCW tests to allow for direct comparison of the heat transfer results, which will be used as a primary indicator of scaling law performance. As a secondary indicator, the computational fluid dynamics software FLUENT was used to compare agreement between fluid flow behaviour in select representative scaled SCW – $SCO_2$ case pairs. The excellent agreement seen between the predictions for the two fluids, coupled with the previously seen agreement with measured data in SCW, lend credibility to the scaling law. If the same good agreement with experimental data in $SCO_2$ is later found, as is expected, then the scaling law will be soundly verified. $SCO_2$ could then be used as a substitute fluid in experiments relating to the SCWR, which would greatly broaden the scope of possible experiments by reducing both the technical challenge and overall cost of such experiments.

## 5. References

[1] Bilbao y León, Sama, and Aksan, Nusret. "Improving the understanding of thermal-hydraulics and heat transfer in super critical water cooled reactors," Proceedings of the International Congress on Advances in Nuclear Power Plants, San Diego, California, USA, 2010 June 13-17.

[2] Yamagata, K., Nishikawa, K., Hasegawa, S., and Fuji, T. “Forced convective heat transfer to supercritical water flowing in tubes,” International Journal of Heat and Mass Transfer 15, 12, pp.2575-2593. (1971)

[3] Shitsman, M. E. “Impairment of the heat transfer at supercritical pressures,” High Temperatures (Teplofzika Vysokikh Temperaur ctp. 267-275) 1, 2, pp. 237-244. (1963)

[4] Pioro, I. L. and Duffey, R. B. “Heat transfer and hydraulic resistance at supercritical pressures in power-engineering applications,” ASME Press. (2007)

[5] Jackson, J. D. and Hall, W. B. “Influence of buoyancy on heat transfer to fluids flowing in vertical tubes under turbulent conditions.” *Turbulent Forced Convection in Channels and Bundles*, Vol. 2, Hemisphere, New York, pp. 613-640. (1979)

[6] Jackson, J. D. “A semi-empirical model of turbulent convective heat transfer to fluids at supercritical pressure,” Proceedings of the 16th International Conference on Nuclear Engineering, Orlando, Florida, USA, 2008 May 11-15.

[7] Cheng, X., Liu, X.J., and Gu, H.Y. “Fluid-to-fluid scaling of heat transfer in supercritical fluids,” The 2nd Canada-China Joint Workshop on Supercritical Water-Cooled Reactors, Toronto, Ontario, Canada, 2010 April 25-28.

[8] Licht, J.R., Anderson, M., and Corradini, M. “Heat transfer and fluid flow characteristics in supercritical pressure water,” ASME Journal of Heat Transfer, Vol. 131. (2009)

[9] Licht, J.R. “Heat transfer and fluid flow characteristics in supercritical water,” Ph. D. Thesis, University of Wisconsin-Madison, Madison. (2008)

[10] Kiss, A., and Aszódi A. “Summary for three different validation cases of coolant flow in supercritical water test sections with the CFD code ANSYS CFX 11.0,” Nuclear Technology, Vol. 170. (2010)

[11] Herkenrath, H. Mörk-Mörkenstein, P., Jung, U., and Weckermann, F.J. “Wärmübergang an wasser bei erzwungener strömung im druckbereich von 140 bis 250 bar,” Euratom report EUR 3658 d, European Atomic Energy Community. (1967)

[12] Swenson, H.S., Carver, J.R., and Kakarala, C.R. “Heat transfer to supercritical water in smooth-bore tubes,” Journal of Heat Transfer, 87, 477. (1965)

[13] Rhode, M., and van der Hagen, T.H.J., “Downscaling the HPLWR to an Experimental Facility by Using a Scaling Fluid,” 4th International Symposium on Supercritical Water-Cooled Reactors, March 8-11, Heidelberg, Germany.