Prediction of Heat Transfer in a Vertical Bare Tube Upward Flow

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Summary

A vertical bare tube was used to study the behavior of water as a supercritical fluid. The tube was designed with similar properties to the pressure tube of a Supercritical Water-Cooled type reactor. The experiment was repeated with low and high mass flux and the outcomes were compared. A full Computational Fluid Dynamics (CFD) model was prepared to confirm the experimental data. The CFD model helped in predicting the behavior of flow and heat transfer inside the tube which was difficult to achieve by the experimental data.

1. Introduction

The energy demand has increased which has caused the interest to shift into different types of energy. Nuclear power plays an important role in filling the needs of energy. Generation IV type reactors are becoming the centre of nuclear study. This is due to their high thermal efficiency compared to the current nuclear power plants [1]. Generation IV type reactors operate on supercritical fluids instead of subcritical fluids. Operating on supercritical fluids had created several concerns on whether the fuel channel materials are able to withstand the high operating conditions.

This paper provides a brief study on predicting the heat transfer in water as a supercritical fluid. A simple fuel channel presented by a vertical bare tube with an upward flow is used to predict the behaviour of heat transfer. This will be achieved by generating a CFD model using PHOENICS software [2]. The results from the CFD model are further compared to the experimental data, which was provided by the Institute for Physics and Power Engineering (Obninsk, Russia).

2. Experimental Setup

The experimental setup was performed on a vertical tube with an upward flow. The tube has a length (L) of 4 m, an outer diameter (D_{out}) of 12 mm, and an inner diameter (D_{in}) of 10 mm. The tube's wall material was set as standard stainless steel with an inner wall roughness height (ε) of 0.65 μm. De-ionized water was used as the working fluid. The experiment was repeated with a mass flux (G) of 500 kg/m^2·s and 200 kg/m^2·s to study the behavior of water as a supercritical fluid at higher and lower mass fluxes. Electrical heaters along the tube's wall were used to heat the fluid. These heaters operate on an AC power supply of 600 kW.

The properties of the test tube were set similar to the fuel channel in supercritical type reactors. The inlet temperature (T_{in}) of the tube was set to 350°C for both experiments (500 and 200 kg/m^2·s). An average applied pressure (P) was set to 24 MPa. A heat flux of 141 kW/m^2 was used for experiment 1 (G = 500 kg/m^2·s) while a heat flux (q_{avg}) of 129 kW/m^2 was used for the second experiment (G = 200 kg/m^2·s). Table 1 shows a summary of the tube specification in experiments 1 and 2.

Table 1. Test Tube's Properties in Experiment 1 and 2

	Experiment 1	Experiment 2
L, m	4	
D_{in}, mm	10	
D_{out}, mm	12	
ε, μm	0.63 – 0.80	
G, kg/m^2·s	500	200
T_{in}, °C	350	
P, MPa	24	
q_{avg}, kW/m^2	141	129

3. Stress and Deformation Analysis

Due to the high operating temperature and pressure, a series of stress and deformation analysis was performed to test the ability of the tube's materials to withstand these high operation conditions. The analysis was performed using Siemens NX software [3].

The analysis was conducted on 1 m length tube with a specification similar to the test tube. The properties of stainless steel was taken at a temperature of 550°C (maximum temperature in the test tube). Table 2 shows the properties of stainless steel at 550°C which was imported into the simulation to test the ability of stainless steel to withstand the high operating conditions.

Table 2. Materials Properties of Stainless Steel at 550°C [4]

Properties	Standard Stainless Steel
Density, kg/m^3	8030
Young's Modulus, GPa	158
Poisson's Ratio	0.28
Yield Strength, MPa	290
Thermal Expansion Coefficient, 1/C	$10.2 \cdot 10^{-6}$
Thermal Conductivity, W/m·K	21.4
Specific Heat, J/kg·K	500

The tube was meshed using 3D tetrahedral. The solution was set to NX NASTRAN structural type solver. The applied loads were a pressure of 24 MPa and a temperature of 550°C. Figure 1 shows the outcome of the deformation analysis. It was shown that the maximum deformation was only 2% of the total thickness of the tube's wall. Therefore, it can be concluded that this material has the ability to withstand the high operating conditions, which was confirmed through the experimental outcomes.

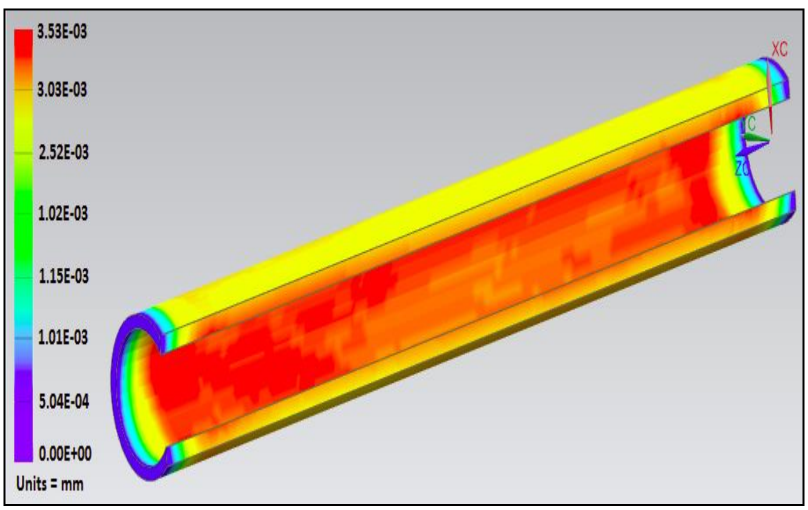

Figure 1. Deformation Analysis on a Vertical Tube Using Siemens NX software

4. Experimental Data and CFD Outcome

A double-precision solver of PHOENICS software was used to perform the CFD analysis. An axisymmetric 2D model was used as a domain with the Y-axis as the radial distance and the Z-axis as the axial distance. The Y-axis was set to 5 mm and the Z-axis was set to 5 m. The main reason for setting the Z-axis to 5 m instead of 4 m was to allow the turbulent velocity to develop fully when it reaches the tube's inlet. The applied pressure and temperature were similar to the experimental setup. A two-layer low-Reynolds-number k-ε turbulence model was used with a turbulent Prandtl number of 0.86. A non-uniform mesh was applied with a finer mesh near the tube's wall.

The supercritical properties of water were imported into the CFD simulation using REFPROP software from the National Institute of Standards and Technology (NIST) [5].

The main focus of the study was on predicting the inside tube wall temperature, the bulk fluid temperature and the heat transfer coefficient since these properties can give a better understanding of the heat transfer behavior along the vertical test tube.

Figure 2 shows the experimental data vs. the CFD outcome (solid lines) for experiment 1 (mass flux of 500 kg/m^2·s). Figure 2 shows a good agreement between the experimental and the CFD outcome. However, the reading of wall temperature at 1.4 and 2.3 m are outside the experimental data fit that could be due to a reading or device error. Similar case can be seen in the heat transfer coefficient outcome at these two points.

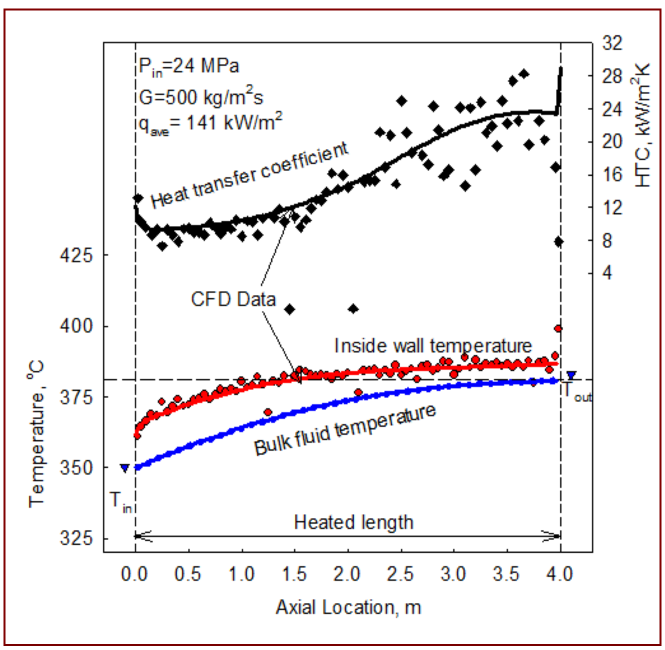

Figure 2. Experimental Data vs. CFD results for Experiment 1

Figure 3 shows the experimental data vs. the CFD outcome for experiment 2 (mass flux of 200 kg/m^2·s). Figure 3 shows a good correlation between the experimental data and the CFD results. Given that the CFD setup for experiment 2 was similar to experiment 1, the outcome in experiment 2 was expected to be similar to experiment 1. However, the experimental data between 0.5 to 3.5 m do not match quantitatively well the CFD results. The peak in the experimental data (Figure 3) due to the Deteriorated Heat Transfer (DHT) regime in these areas at low mass flux was not predicted. DHT process can lead to the formation of bubbles in the fluid and near the tube's wall [6]. This can further lead to a significant increase in the wall temperature and thus decreases the heat transfer coefficient as shown in Figure 3. A possible reason for the disagreement between the experimental data and the CFD results in this case could be because the current turbulent model used in the CFD runs does not allow to predict the DHT regime accurately.

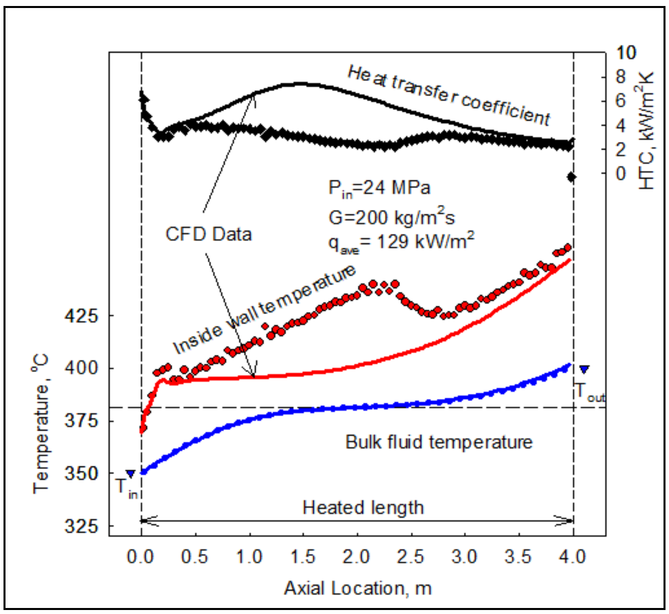

Figure 3. Experimental Data vs. CFD results for Experiment 2

5. Conclusions

A vertical test tube was used to test the water as a supercritical material. The tube was set up with specification similar to those in supercritical type reactors. The main focus of the study was on predicting the heat transfer. This was achieved by generating a CFD model and by comparing the outcome to the experimental data. Due to the high operating conditions a deformation analysis was conducted. Through this analysis, it was proven the ability of the wall's material to withstand these high operating conditions.

The experiment was repeated at two different mass fluxes (500 and 200 $kg/m^2 \cdot s$) to test the heat transfer at higher and lower mass flux. The experimental data showed a good agreement with the CFD results and no DHT regime was generated in this case. However, the DHT regime was clearly recognized at lower mass flux.

6. References

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