Capturing Pseudocritical Property change of Steam in a Spiral Steam Pipe of a Boiler Through Numerical Technique

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Abstract

Heat transfer characteristics of fluids is rather peculiar when the bulk fluid temperature approaches pseudocritical point. In the present paper, computational fluid dynamics (CFD) methodology has been used to predict the attainment of pseudocritical temperature of steam in a typical spiral pipe. Abrupt changes in fluid properties near pseudocritical point are captured using commercially available CFD tool Ansys Fluent. The CFD methodology is first validated with experimental results available in literature for the specific type of problems. Then attainment of pseudocritical point in a steam pipe of an industrial boiler is predicted. For a specific mass velocity and heat flux condition, the axial location is identified where bulk fluid temperature attains pseudocritical point. Density, dynamic viscosity, and thermal conductivity of steam take sudden dips when bulk fluid temperature attains a value of 382.9 °C. Isobaric specific heat of steam attains its peak at the same bulk temperature. The attainment of pseudocritical point by steam in spiral tube is captured accurately with the numerical model.

Keywords: *Industrial boilers*; *pseudocritical temperature; spiral pipe; large specific heat; bulk fluid temperature.*

1.0 Introduction:

Due to the enhanced thermal efficiency of supercritical fluids over subcritical fluids, power plants are increasingly using supercritical steam as the working fluid. However, the transfer of heat to supercritical fluids is a complex phenomenon. All the properties of fluid behave erratically in the vicinity of critical point. Isobaric specific heat of the fluid attains a peak just before the bulk fluid temperature crosses the critical stage. The temperature at which the isobaric specific heat attains its peak is known as the pseudocritical temperature. Several researchers have studied the peculiar behaviour of supercritical fluids in the vicinity of pseudocritical point, both experimentally and numerically. The experiments carried out by Yamagata et al. [1] in early 70s are still considered to be the basis for studies of heat transfer to supercritical fluids. They studied and established the heat transfer enhancement and heat transfer deterioration phenomena in a test tube using super critical fluid, over a varied range of flow parameters. Based on the variation in specific heat with respect to bulk fluid temperature, Chen et al. [2] defined a large specific heat region for supercritical water, where the specific heat at constant pressure is greater than 8.4 kJ/kgK. Jianguo et al. [3] carried out comparative studies on the heat transfer characteristics to supercritical and subcritical water. They postulated various regions of heat transfer process based on the inside wall temperature of the pipe. Qing et al. [4] and Jianguo et al. [5] carried out similar kind of studies on heat transfer to supercritical water in ribbed tubes.

Koshizuka et al. [6] are among the early researchers who have studied the heat transfer of supercritical fluids using numerical techniques. They investigated the heat transfer deterioration in a vertical pipe. Kao et al. [7] numerically studied the effects of buoyancy and Prandtl number on heat transfer deterioration in circular channels. Sharabi et al. [8] studied the turbulent heat transfer to supercritical water in non-circular channels using CFD tools. He et al. [9] and Kim et al. [10] carried out numerical studies on heat transfer to supercritical water and evaluated the accuracies of various turbulence models. Kanungo et al. [11,12] used CFD technique to propose novel heat transfer coefficient (HTC)correlations for supercritical steam flowing inside spiral tubes.

All the studies performed on heat transfer to supercritical fluids are specific to certain geometries and flow conditions. In the present work, we have numerically studied the change in steam properties near critical point in a spiral steam pipe of an industrial boiler. Firstly, the computational methodology is validated with the experimental results of Yamagata et al. [1].

In the second part of the study, the variation of steam properties with respect to bulk fluid temperature, in the spiral steam pipe is predicted. The stiff changes in steam properties near pseudocritical point is captured in present study. The axial location in the pipe where the isobaric specific heat attains its peak, is identified.

2.0 Methodology:

Commercially available CFD software Ansys Fluent 19.1 is used in the present study. Variation in density, specific heat, dynamic viscosity, and thermal conductivity of steam with respect to bulk fluid temperature is captured. After successful validation of the present methodology against Yamagata et al. [1], the numerical study is extended to a geometry (henceforth referred as real geometry) which is a representative of steam pipe of an industrial boiler. The axial location of peak isobaric specific heat in the steam pipe is identified.

2.1 Geometrical details

The geometrical details of the test case and the real geometry is depicted in Table-1. ID stands for internal diameter and L stands for length.

Table-1: Geometrical details

Case	Type	Dimensions	Mass flux	Heat flux
Test	Straight pipe	ID 7.5 mm	1830 kg/m^{2}s	698 kW/m^2
		L 1500 mm		
Real geometry	Helical pipe	ID 7.5 mm	1830 kg/m^{2}s	533 kW/m^2
		L 17500 mm		
		Spiralling angle 20.7 °		
		Helix diameter 1000 mm		

The flow models for the straight tube and the spiral tube are shown in Fig.1 and Fig.2 respectively.

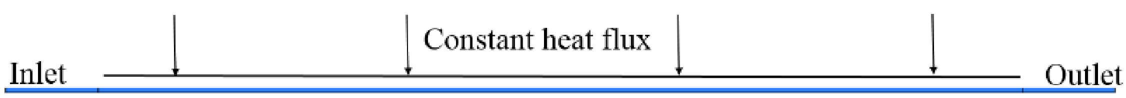

Figure 1: 3D model of test case

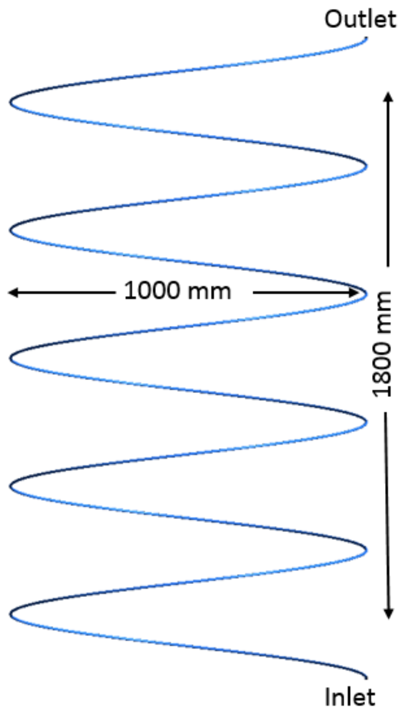

Figure 2: 3D model of real geometry

2.2 Numerical details:

In both test case (Fig. 1) and real geometry (Fig. 2), at inlet of pipe total pressure value of 245 bar is prescribed. At outlet, the mass flow boundary condition is prescribed. To make sure that attainment of pseudocritical point happens before steam leaves the pipe, the inlet temperature of steam is maintained at 379 °C. A constant wall heat flux of 698 kW/m^2 for test case and 533 kW/m^2 for real geometry are prescribed as the heat source. Shear stress transport (SST) turbulence model along with high resolution advection scheme are used in both the cases. Convergence criteria for flow and energy simulations is selected as the root mean square value of residuals, which should fall below the value of 1E-05. Sufficient growth layer from the pipe wall to centre is maintained to accurately resolve the near wall effects. The governing equations solved by the CFD solver are the continuity equation, momentum equations, equations for turbulence and the energy equation. Effect of gravity is also accounted for in the present study.

3.0 Results and discussion:

As described in section 2.0, the CFD methodology is first validated by comparing the predictions with experimental results of Yamagata et al. [1]. At a pressure value of 245 bar, the pseudocritical temperature of steam is 382.9 °C. The properties of steam change erratically in the vicinity of the pseudocritical point. The predicted values of steam property variation at 245 bar pressure is compared with the same reported by Yamagata et al. [1] in Fig.3. Since the focus of the present study is the attainment of pseudocritical point of steam, which is 382.9 °C for the present case, the range of simulated data is just around 382.9 °C. This is to be noted that capturing the steam property variation for the entire tube length will deflect the focus from pseudocritical point.

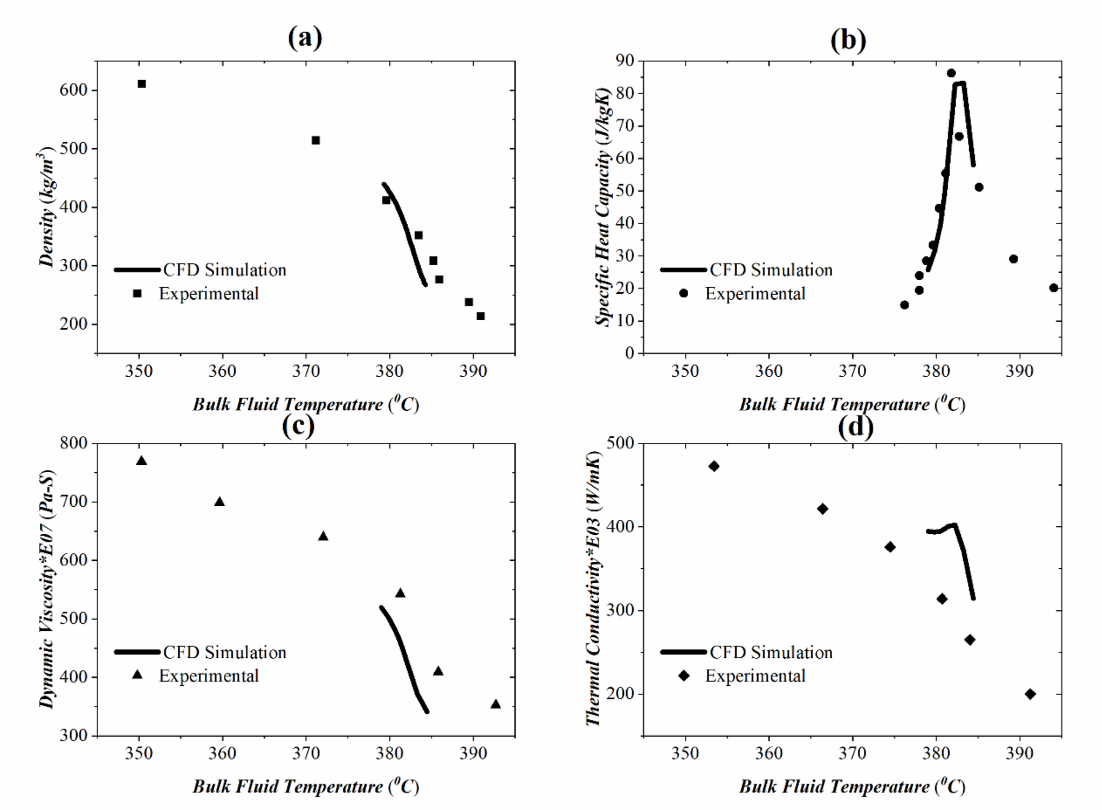

Figure 3: Comparison of thermophysical property variation of steam near pseudocritical point, as predicted by simulation with experimental values (a) Density (b) Specific Heat Capacity (c) Dynamic Viscosity (d) Thermal Conductivity.

As it can be seen in Fig.3, all the properties predicted by simulation is matching very closely with experimental values. The peak specific heat capacity value as predicted by CFD simulation for the test case is around 84 kJ/kg K, against the value of around 85 kJ/kg K reported in Yamagata et al [1]. For both experimental as well as simulation cases, as the bulk fluid temperature approaches 382.9 °C, density, dynamic viscosity, and thermal conductivity of steam take sudden dips and the specific heat capacity attains its peak. It is to be noted that the plots in Fig.3 are created by manually extracting data points from the plots of Yamagata et al. [1] for comparison purpose. Any discrepancy between the plots of Yamagata et al. [1] and those of Fig.3 are attributed to manual error in data extraction.

The variation in steam properties in the real geometry (Fig. 2) with respect to bulk fluid temperature, as predicted by our CFD model is presented in Fig.4. In this case also, as the bulk fluid temperature approaches the pseudocritical value, all the properties change drastically. The density, dynamic viscosity and thermal conductivity of steam undergo a sudden dip. The specific heat also attains its peak near the pseudocritical point. The peak value of isobaric specific heat observed here is 83 kJ/kg K. For this particular heat flux and mass velocity, the length of steam pipe where the isobaric specific heat attains its peak is between 10500 mm to 12250 mm.

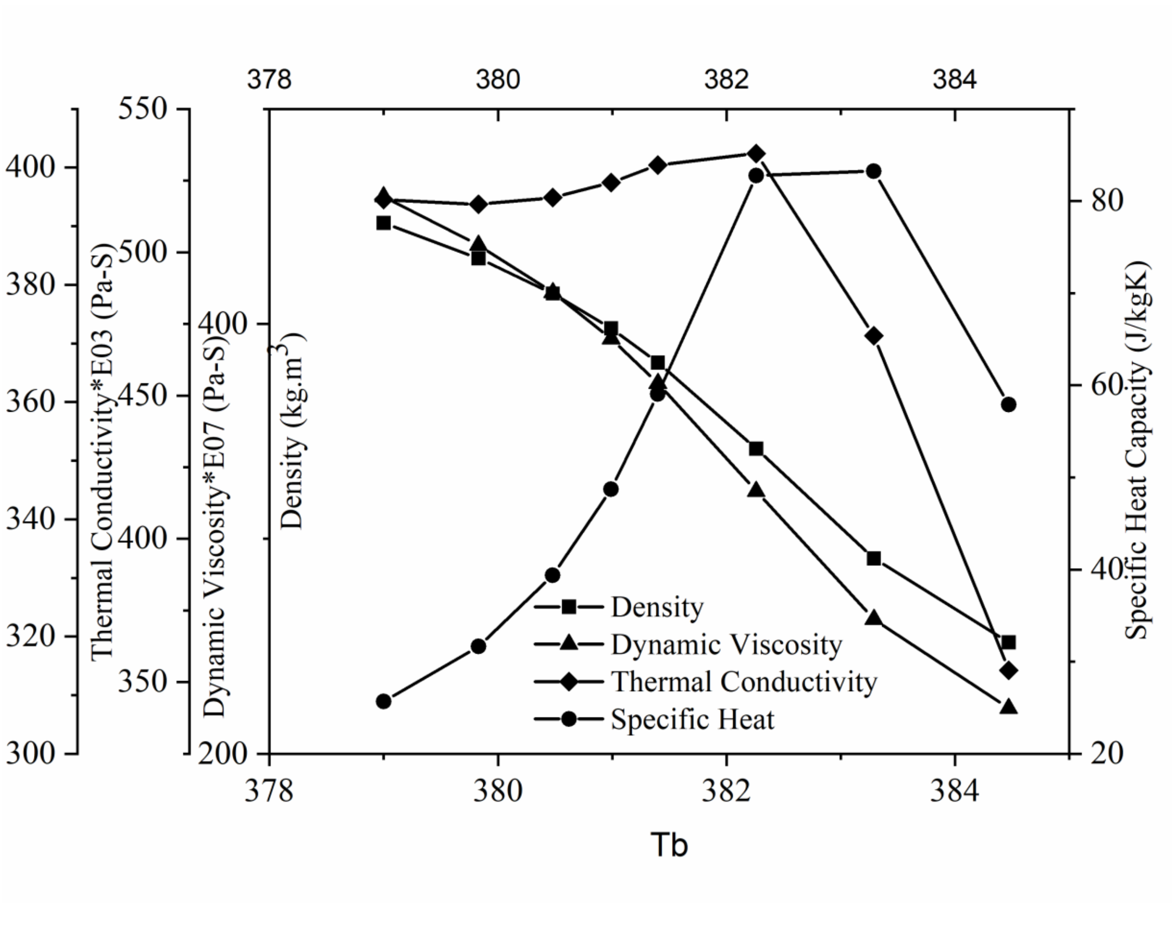

Figure 4: Variation in thermophysical properties of steam in the vicinity of the pseudocritical point for real geometry, as predicted by our CFD model.

4.0 Conclusions:

Properties of steam behave erratically when the bulk fluid temperature approaches the pseudocritical point. We conducted CFD simulations using Ansys Fluent 19.1 and predicted the behaviour of steam at the pseudocritical point in line with Yamagata et al. [1], which is considered as a test case in the present study. Our results agree very well with those of [1]. Then we used the present CFD solver to study the properties of steam in a geometry, which is a representative of steam pipe of an industrial boiler. In case of real geometry, as the bulk fluid temperature approaches the pseudocritical value of 382.9 °C, the fluid density, dynamic viscosity and thermal conductivity take sudden dips. The isobaric specific heat attains it peak exactly at 382.9 °C and the peak value of isobaric specific heat near pseudocritical point, as predicted by CFD model is 83 kJ/kg K for the specific geometry and boundary condition. The length of pipe at which the isobaric specific heat attains its peak for the given heat flux and mass velocity is somewhere in between 10500 mm and 12250 mm.

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