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Effect of turbulence models on predicting convective heat transfer to hydrocarbon fuel at supercritical pressure

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Abstract A variety of turbulence models were used to perform numerical simulations of heat transfer for hydrocarbon fuel flowing upward and downward through uniformly heated vertical pipes at supercritical pressure. Inlet temperatures varied from 373 K to 663 K, with heat flux ranging from 300 kW/m^2 to 550 kW/m^2. Comparative analyses between predicted and experimental results were used to evaluate the ability of turbulence models to respond to variable thermophysical properties of hydrocarbon fuel at supercritical pressure. It was found that the prediction performance of turbulence models is mainly determined by the damping function, which enables them to respond differently to local flow conditions. Although prediction accuracy for experimental results varied from condition to condition, the shear stress transport (SST) and launder and sharma models performed better than all other models used in the study. For very small buoyancy-influenced runs, the thermal-induced acceleration due to variations in density lead to the impairment of heat transfer occurring in the vicinity of pseudo-critical points, and heat transfer was enhanced at higher temperatures through the combined action of four thermophysical properties: density, viscosity, thermal conductivity and specific heat. For very large buoyancy-influenced runs, the thermal-induced acceleration effect was over predicted by the LS and AB models.

1. Introduction

Supercritical fluids have been used in many fields since critical phenomena was observed by Thomas Andrews in 1869.[1] Regular fossil fuel power plants operated by using supercritical water to drive steam turbines in the 1960s and 1970s. In the brief period of time since then, the development of emerging nuclear power stations such as supercritical water reactor

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(SCWR),[2] air-conditioners[3] and cooled cooling air (CCA) technology for advanced aircraft engines[4] has stimulated a renewed interest in the flow and heat transfer of supercritical fluids.

Particular focus has been placed upon its use in regenerative cooling technology to deal with heat management problems that occur due to aerodynamic heating of scramjet engines.[5,6] This cooling operates by the heat of the combustor first being absorbed by endothermic hydrocarbon fuel flowing through a cooling channel at supercritical pressure and then released as the fuel is injected from nozzles into the combustor.[7] The most striking feature of supercritical fluids is that they have no phase change under supercritical pressure conditions but undergo a dramatic alteration of physical properties at temperatures in the vicinity of critical point. The nonlinear relationship between thermal-physical properties and temperature leads to strong coupling between velocity fields and scalar functions. This may arouse distinct distortions of velocity fields, especially under the influence of buoyancy force and thermal-induced acceleration. Hence very significant phenomena, different from heat transfer under subcritical conditions, can be seen in supercritical heat transfer.

There is a wide variety of reviews about experimental studies and numerical analysis on heat transfer at supercritical pressure.[8–11] Moreover, there are some surveys on hydraulic resistance of fluids at supercritical pressure.[12–15] It should be noted that experimental data obtained in literature have mainly been limited to that related to heat transfer, such as wall temperature. With detailed predictive information lacking, numerical simulation might provide for what cannot be obtained from experimentation and help to give a better understanding of heat transfer mechanisms. Turbulence modeling has played an important role in the mathematical modeling for supercritical heat transfer using computational fluid dynamics (CFD) methods. Early studies usually used mixed length models to consider variations in physical properties.[16] Afterwards, more complicated models including one-equation and two-equation models were used.[17–21] In recent years, in order to evaluate the performance of a range of turbulence models in terms of simulating heat transfer to fluids at supercritical pressure, studies comparing turbulence models adopted by CFD tools for numerical simulation have been performed.[22–28] It has been found that low-Reynolds number turbulence models can reproduce experimental data qualitatively in the heat transfer enhanced and deterioration regimes though vary obviously in terms of quantitative prediction.

Many comparison studies of turbulence models assisting in simulated heat transfer at supercritical pressure have been performed with water and CO_2 as working fluids, but very few have been done that study hydrocarbon fuels as working fluids. Compared to pure substances, hydrocarbon fuels show more complicated behaviors that result from their being composed of thousands of components that may undergo cracking and coking reactions as temperature increases.[29,30] Zhu et al.[31] have applied the SST $k-\omega$ two-equation turbulence model with enhanced wall treatment to the numerical simulation for the thermal cracking of *n*-decane flowing at supercritical pressure, while Goel and Boehman[32] used the laminar model in simulation of jet fuel degradation in flow reactors. To this author's knowledge, there is no detailed study on turbulence modelling of hydrocarbon fuels under supercritical pressure.

Numerical computations with commercial software (Fluent) have been performed that simulate the flow and heat transfer of hydrocarbon fuel at supercritical pressure, and a comparison study of computational results using a range of turbulence models with experimental data is presented in this paper. This is done in order to assess the ability of turbulence models to predict supercritical heat transfer of hydrocarbon fuel with a special focus on the response to variable thermophysical properties under supercritical pressure.

2. Simulated experiment

This study simulated and investigated the experiments by Zhang[33] where the characteristics of local convection heat transfer of a supercritical hydrocarbon fuel called RP-3 flowed downward through a vertical mini-tube. The test section was made of stainless steel with an inner diameter of 1.8 mm and wall thickness of 0.2 mm, comprising a 90 mm long adiabatic entrance section, and a uniformly-heated section length of 300 mm followed by an adiabatic exit section 60 mm long. The temperature, pressure and mass flow rate were measured by a K-type thermocouple welded onto the test tube; the pressure sensor mounted downstream of the test tube and mass flowmeter installed upstream of the test tube, respectively. Detailed information about the experiment can be found in Zhang.[33] Due to there being no obvious heat transfer deterioration data on RP-3, the experimental results of Liu[34] are selected, which study the heat transfer deterioration of *n*-decane at supercritical pressures flowing upward and downward in small vertical tubes. The test section, with an inner tube diameter of 2 mm and the wall thickness of 0.5 mm, was a 959 mm vertical tube including two 100 mm adiabatic sections before and after the heated section.

Table 1 shows the experimental conditions considered in present paper. At $P = 5$ MPa and $T_{in} = 373$ K, the deterioration of heat transfer could be found at the beginning of the heating section. At $P = 4$ MPa, as T_{in} increased, the process of heat transfer has four experimental regimes: the initial heating section, normal heat transfer, heat transfer enhancement, and heat transfer deterioration. At $P = 3$ MPa, the buoyancy effect is very strong when flowing upward, but very weak when flowing downward. When computing all dimensionless numbers, the characteristic length and characteristic temperature are the inner diameter of tube and the average temperature of fluids in across section of the tube, respectively. The calculation of thermal physical properties of hydrocarbon fuel is described in Section 3.6.

3. Numerical modelling

The commercial CFD software, ANSYS Fluent 14.5, was adopted for numerical simulation in this paper. The following sections introduce the governing equations, turbulence modelling, boundary conditions, solution methods and the fluid properties to model supercritical convection heat transfer in a vertical tube, in sequence.

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