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Comparative study of turbulence model predictions of upward supercritical fluid flow in vertical rod bundle subchannels

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HIGHLIGHTS

- 3D CFD analysis of steady turbulent upward flow of supercritical water and carbon-dioxide in vertical subchannels.
- Conjugate heat transfer analysis including heating rods using commercial code ANSYS CFX and ANYS Fluent.
- Six two-equation RANS turbulence models applied to six experimental cases; compared with axial wall temperature variation.
- Some cases of significant over-prediction of wall temperature.
- Best overall agreement found with k-epsilon model.

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ABSTRACT

Computations of three-dimensional turbulent vertical up-flow of supercritical fluid in the subchannel of a heated rod bundle were made using the Computational Fluid Dynamics codes ANSYS CFX and ANSYS Fluent. Results for a total of six cases from three different sets of experiments are presented. For all six cases, steady-state predictions of fluid velocity, pressure, and temperature were made using six versions of the two-equation Reynolds-averaged Navier-Stokes turbulence models with accompanying wall treatments. A conjugate heat transfer model was used that also predicted the temperature distribution in an adjacent solid region representing a heater. In the model of one experiment, the solid region also included cladding and insulation.

The k-epsilon turbulence model, implemented using CFX and Scalable Wall Functions, provided the numerical results that have the smallest overall deviation from experimental results for three of the six cases, and predicted the experimental data of the remaining four cases reasonably well, unlike other turbulence models that sometimes severely over-predict the experimental data for wall surface temperature.

1. Introduction

A Supercritical Water Cooled Reactor (SCWR) is one of the six proposed Generation IV nuclear reactor designs proposed by the Generation IV International Forum (GIF) for development in commercial applications. The sudden changes in the thermophysical properties of fluids near the critical point and the pseudocritical point, however, contribute to a heat transfer phenomenon known as heat transfer deterioration (HTD). HTD is associated with sudden spikes in wall surface temperature and has been observed in many heated tube, annuli, and rod bundle experiments with supercritical flow. A reliable numerical model of supercritical flow in rod bundles could help to avoid HTD in new SCWR designs. Such a model could use an area-averaged approach or a 3D Computational Fluid Dynamics (CFD) approach. The focus of this work is related to CFD studies.

Many experiments have been performed since the 1950s that were focused on studying the heat transfer behaviour of supercritical fluids in heated tubes and annuli. They have been reviewed well (e.g., Duffey and Pioro, 2005; Groeneveld et al., 2008; Pioro and Duffey, 2005). Many of those experiments were modelled using CFD. An indication of which turbulence models are recommended was sought by examining the modelling studies that compared at least three turbulence models. Table 1 summarizes those studies. The summary shows that there is no clear consensus among researchers about which turbulence model provides the best numerical predictions for the tube and annulus geometries.

Experiments using rod bundles are currently the closest representation of real SCWR conditions because of the more complex flow pattern and heat transfer phenomena that occur in the subchannels of the rod bundles. Because of the relatively higher

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Nomenclature

C_p	specific heat capacity at constant pressure (J kg^{-1} K^{-1})
G	mass flux (kg m^{-2} s^{-1})
h_b	bulk enthalpy (kJ kg^{-1} K^{-1})
k	turbulence kinetic energy (m^2 s^{-2})
$\dot{m}$	mass flow rate (kg s^{-1})
N	total number of surface temperature data points in experiment
P	pressure (MPa)
$\dot{Q}'''$	volumetric heat rate (W m^{-3})
T	temperature (K)
$T_{exp,i}$	surface temperature of experiment at location i (K)
T_i	surface temperature of numerical result at location i (K)
W	mean velocity in z-direction (m s^{-1})
x, y, z	position in a Cartesian coordinate system (m)
y^+	non-dimensional wall-normal distance

Greek Letters

ε	turbulence dissipation rate (m^2 s^{-3})
λ	thermal conductivity (W m^{-1} K^{-1})
λ_t	turbulent thermal conductivity (W m^{-1} K^{-1})
μ	dynamic viscosity (Pa s)
μ_t	eddy viscosity (Pa s)
ρ	density (kg m^{-3})
ω	specific turbulence dissipation (s^{-1})

Acronyms

AWT	Automatic Wall Treatment (in CFX)
BSL	Menter Baseline
CFD	Computational Fluid Dynamics
DNS	Direct Numerical Simulation
EWT	Enhanced Wall Treatment (in Fluent)
GIF	Generation IV International Forum
HTD	Heat Transfer Deterioration
JAEA	Japan Atomic Energy Agency
LB	Lam-Bremhorst
LES	Large Eddy Simulation
LR k-ε	Low Reynolds k-ε
RANS	Reynolds-Averaged Navier–Stokes
SMC	Second Moment Closure (Reynolds Stress)
ω-SMC	omega-Second Moment Closure
$RMS_{RN,T}$	Range-normalized root mean square of temperature differences
SCWR	Supercritical Water-Cooled Reactor
SSG	Speziale-Sarkar-Gatski
SST	Shear Stress Transport
SWF	Scalable Wall Function
WF	Standard Wall Function
YS	Yang-Shih

cost and difficulty to operate, there are fewer experiments on supercritical flow in rod bundle subchannels than for heated tubes and annuli. A summary of pertinent experimental work on supercritical flow in a vertical rod bundle is given in Table 2. It should be noted that Richards presented the seven-rod bundle experimental results of Kirillov et al. (2006) and Rohde et al. (2015) presented water-cooled seven-rod bundle experiments that were performed by the Japan Atomic Energy Agency (JAEA) for a benchmark exercise organized by the GIF Project Management board.

For modelling supercritical flow in rod bundles, Zhang et al. (2014) recommended the SST turbulence model. They also used the ω-SMC turbulence model and were able to capture the HTD seen in the Richards (2012) seven-rod R12 bundle experiments. Huang et al. (2014) also simulated the experiments found in Richards and noted that HTD was captured best when the Enhanced Wall Treatment (EWT) was used instead of a standard wall function. The heater rod surface temperatures of one of the cases were predicted better using the SMC turbulence model compared to the SST turbulence model. For the remaining cases, the SMC turbulence model gave the best heater rod surface temperature predictions. Xiong et al. (2015) simulated the four-rod bundle water experiments of Zhao et al. (2013). They found that the ω-SMC and BSL-SMC turbulence models over-predicted heater rod surface temperatures, whereas the SSG-SMC turbulence model under-predicted heater rod surface temperatures. Chang and Tavoularis (2015) simulated the seven-rod bundle water experiments of Rohde et al. (2015) and found that the v^2-f turbulence model predicted wall surface temperatures better than the other turbulence models that were used. Table 3 summarizes these numerical studies. There is also no clear consensus on the turbulence model to be used to obtain consistently good predictions in supercritical flow in rod bundle subchannels.

This work focuses on rod bundle subchannels and the CFD approach in the context that, to be of practical use in industry, the model should not require excessive computational effort and should be easily accessible. Therefore, consideration is restricted to RANS two-equation turbulence models that are readily available in commercial CFD software. The present study aims to further the understanding of HTD in numerical predictions of heated rod bundles. The present study also extends the number of two-equation RANS models applied to supercritical flow in rod bundle. Finally, new results are presented for a variety of rod numbers and two fluids: a four-rod bundle with water, a seven-rod bundle with water, and a seven-rod bundle with R12; there are six experimental cases in total. Six instances of turbulence models were used for each of the six cases.

Cases from the sets of experiments presented in Rohde et al. (2015), Richards (2012), and Wang et al. (2014) were selected for the present study because they provide a range of fluids and geometries and because sufficient information was given to enable numerical modelling and comparisons with the experimental results. Results are presented from simulations of two cases from each of the Rohde et al. Richards, and Wang et al. experimental data sets. To the best of the authors' knowledge there are no previous studies that compare numerical predictions with the experimental data of Wang et al. (2014).

The six turbulence models used are (1) SST in CFX, (2) SST in Fluent, (3) k-ε in CFX, (4) RNG k-ε in Fluent, (5) Yang-Shih LR k-ε in Fluent, and (6) Lam-Bremhorst LR k-ε in Fluent. Fluent used Enhanced Wall Treatment (EWT) in the SST and RNG k-ε models. CFX used Automatic Wall Treatment (AWT) in the SST model and Scalable Wall Functions (SWF) in the k-ε turbulence model. The SST model was chosen for both codes in order to compare the results of using the same turbulence model with two wall treatments. Additional details on the turbulence models are given in the next section.

2. Numerical models

Commercial CFD programs ANSYS CFX (v14.5 to v16.2) and Fluent (v15.0 to v16.2) were used to generate steady-state numerical solutions to the experimental cases under consideration. Both CFX and Fluent solve the governing equations of continuity, momen-