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Numerical study on heat transfer of SCW near the pseudo-critical temperature in a hexagon sub-channel

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ABSTRACT

A numerical study was carried out to study the local heat transfer performance of supercritical water (SCW) within a hexagon bare inner sub-channel by using the commercial CFD code CFX. The main objective was to focus on the special thermal–hydraulic characteristics near the pseudo-critical temperature (PCT) at different working conditions. The results show that the secondary flow induced in the inner sub-channel is weak in comparison with the axial main flow, and becomes weaker near the PCT. A stagnation point of the secondary flow is created right at the narrow gap, which can partially explain the weak heat transfer near the narrow gap region. The nonuniform geometry of the sub-channel dominates the creation of a secondary flow in the sub-channel near the PCT. The fluid temperature very close to the cladding surface dominates the heat transfer enhancement of SCW within the sub-channel. The maximum values of the local heat transfer coefficient appear when the PCT is within the buffer layer of that angular position, indicating that the buffer layer is directly related to the heat transfer enhancement. The system parameters evidently affect the heat transfer performance, and the corresponding local heat transfer performance varies differently in the circumferential direction.

1. Introduction

The conceptual design of supercritical water cooled reactor (SCWR) has been conducted for over thirty years by many scholars to develop the fourth generation reactor technology (Oka et al., 2010; Pioro et al., 2004). Excellent works have been done in several aspects, such as the flow and heat transfer (Jackson,2002; Wu et al., 2011; Zhu et al., 2014; Zhu et al., 2014), fuel material (Hughes et al., 2017; Mandapaka et al., 2017), thermal hydraulic (Rahimi et al., 2017; Ruzickova et al., 2014) and reactor system (Zareer et al., 2017; Su et al., 2014; Maitri et al., 2017). Among all findings presented in open literatures, the flow and heat transfer of supercritical water within sub-channel has been of significant concern. Both experimental and numerical methods are applied to this very field. Licht et al. (2008) used an annular channel to simulate an inner sub-channel of reactor core and conducted experiment research on heat transfer of supercritical water. They found that the empirical correlation obtained by Jackson (2002) can well predict the supercritical heat transfer in an annular channel. A series of experiments in annular channels with 2, 4, and 6 mm gap were performed by Wu et al. (2011)) and Yang et al. (2013). The heat transfer performances of supercritical water were comprehensively studied and multiple factors, e.g. flow direction, flow enhancing device and system parameters, were discussed. Wang et al. (2015) experimentally studied the flow and heat transfer performance of SCW in a sub-channel of the 2×2 rod bundle and explored the system parameter effects on the heat transfer. A fitted correlation with an accuracy of $\pm$ 10% was finally proposed to predict the heat transfer coefficient of SCW in the range of pressure from 23 to 28 MPa, mass fluxes from 700 to 1300 kg/m^{2}s and inner heat fluxes from 200 to 1000 kW/m^2. Eter et al. (2016) obtained the heat transfer measurements in a three-rod bundle equipped with wire-wrap and grid spacers by using supercritical pressure carbon dioxide as working medium. The one set of deteriorated heat transfer, as well as the effects of wire wrap and grid spacer were presented. Cheng et al. (2007) conducted numerical research on the heat transfer of supercritical water in various flow channels. Recommendations were made on the application of turbulence models and the non-uniformity heat transfer within sub-channel were suggested to be taken into account in the design of fuel assemblies of SCWR. Oka et al. (Yang et al., 2007; Guo and Oka, 2015; Guo and Oka, 2015) thoroughly studied the heat transfer performance of supercritical water flowing in a fuel rod bundle using CFD method. It was found that strong non-uniformity of the circumferential distribution of the cladding temperature exists in a square lattice bundle with a small pitch-to-diameter ratio, and this phenomenon is caused by the large non-uniformity of the flow area in the cross-section of sub-channels. Podila and Rao (2015) tested a bare-rod bundle geometry for a new conceptual design of the Canadian

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Nomenclature

c	Specific heat ($kJ\,kg^{-1}\,K^{-1}$)
g	gravity acceleration ($m\,s^{-2}$)
G	mass flow rate ($kg\,m^{-2}\,s^{-1}$)
h	heat transfer coefficient ($kW\,m^{-2}\,K^{-1}$)
H	enthalpy ($kJ\,kg^{-1}$)
HTC	Heat transfer coefficient ($kW\,m^{-2}\,K^{-1}$)
P	pressure (MPa)
PCT	Pseudo Critical Temperature
Pr	Prandtl number
q	heat flux ($kW\,m^{-2}$)
Re	Reynolds number
SCW	Supercritical Water
SCWR	Supercritical Water Cooled Reactor
T	temperature (K)
y^+	non-dimensional distance from the wall
z	flow direction (m)

Subscript

b	bulk
ng	narrow gap
sc	sub-channel center
pc	pseudo-critical
w	wall

SCWR by using STAR-CCM + CFD code. It was found that the increase of inlet temperature and operational pressure is effective in reducing the occurrence of heat transfer deterioration of SCW.

The SCWR can be considered as a kind of Boiling Water Reactor (BWR), but, with higher efficiency and without phase change of coolant during the heating process. From the lower mixing plenum to the outlet of PRV, the pseudo critical point of supercritical water cannot be avoided. It means the most attractive features of SCW—the sharp property changes near the pseudo-critical temperature (PCT) —must be involved in the mechanism analysis of the flow and heat transfer in the sub-channel of SCWR. However, corresponding researches to explore the heat transfer performances near the PCT of SCWR are insufficient and need to be further conducted. Can the circumferential difference of the heat transfer be reduced in this region? Can the intensity of the secondary flow be changed? These questions should be taken into account during the concept design of an SCWR.

In this paper, the turbulence mode used to predict the heat transfer performance is first verified, and the heat transfer performance of SCW within a bare inner sub-channel is then studied. The results achieved will be adopted as a baseline to further evaluate the effects of grid spacer on the local heat transfer performance near the PCT. The main objective focuses on the special features brought about by sharp property changes, and the corresponding mechanisms are discussed in detail.

2. Numerical approach

2.1. Analysis geometry and physical conditions

The configuration employed and the computational domain selected for the inner sub-channel are schematically shown in Fig. 1. A tight, typical hexagon rod bundle is used. The length of the sub-channel is about 1500 mm to ensure that the entrance effect can be avoided. The methods used to select the computational domain for the inner sub-channels, and set the boundary conditions, were introduced in our previous studies (Zhu et al., 2014; Zhu et al., 2014); therefore, they are not repeated herein. The dimensions of the rod bundle and the corresponding physical conditions for the present study are shown in Table 1.

2.2. Turbulence model

In our previous studies (Zhu et al., 2014; Zhu et al., 2014); commercial CFD software STAR CCM + was used as the working platform, and the standard two-layer k-ε model by Wolfstein (1969) cooperating with all y + wall treatment ($y+ < 1$) was chosen as the turbulence model. To verify the usability of the turbulence model for the heat transfer prediction of SCW, the calculation results from two well-known empirical correlations for a vertical tube flow, described by Dittus and Bolter (1930) and Watts and Chou (1982) were used to test the simulation results in a high-bulk temperature region. This method must be improved because the flow condition involved in the present study is very different from the previous condition. The bulk temperature range in the present study includes the PCT (~384 °C at 25 MPa). The corresponding thermal properties completely vary in comparison with those in a high-bulk temperature region as the bulk temperature increases. Therefore, the usability of the turbulence model must be verified within the vicinity of the PCT. In addition, the Dittus and Bolter (1930) and Watts and Chou (1982) correlations were both obtained by correlating the experimental data of a vertical upward tube flow, which can be considered as a two-dimensional heat transfer problem, whereas the physical problem studied in this paper is three-dimensional and features a strong secondary flow in both the radial and circumferential directions. The turbulence model chosen should be able to accurately predict the heat transfer performance of an inner flow accompanied by a lateral secondary flow.

Owing to very high costs and several technical difficulties, e.g., the sealing problem at very high pressure and temperature, conducting experimental research on the heat transfer performance of SCW flowing in a rod bundle is very difficult, as is precisely measuring the flow and heat transfer features downstream from a grid spacer. Therefore, very little experimental data can be found in the open literature for testing a numerical computational method. To meet the key points mentioned above, in this study, two types of experimental data are used to test several turbulence models offered by CFX. The first one is the experimental data of a vertical round tube flow by Yamagata et al. (1972). These data are well known and have been adopted by many scholars to test the numerical method when SCW is studied. Therefore, the data by Yamagata et al. (1972) were first used in this study to test the usability

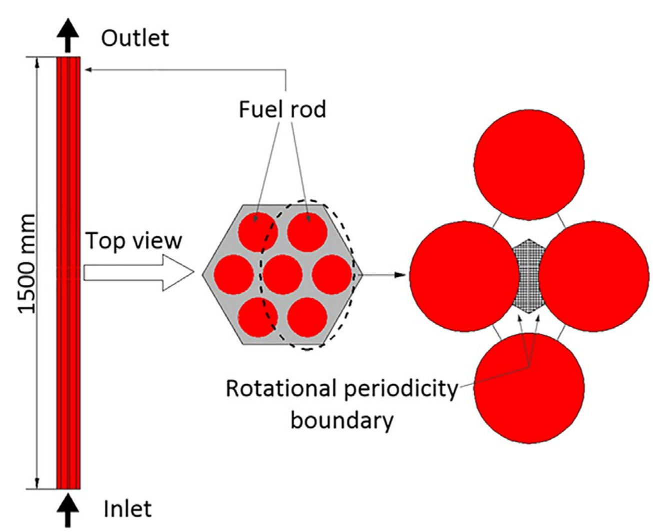

Fig. 1. Sketch of seven-rod bundle structure and the selected computational domain.