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Numerical study on flow and heat transfer characteristics in the rod bundle channels under super critical pressure condition

Xingbo Yang, G.H. Su *, Wenxi Tian, Jiayun Wang, Suizheng Qiu

State Key Laboratory of Multiphase Flow in Power Engineering, Department of Nuclear Science and Technology, Xi'an Jiaotong University, Xi'an 710049, PR China

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ABSTRACT

In this study, the 3D flow and heat transfer characteristics in rod bundle channels of the super critical water-cooled reactor were numerically investigated using CFX codes. Different turbulent models were evaluated and the flow and heat transfer characteristics in different typical channels were obtained. The effect of pitch-to-diameter ratio (P/D) on the distributions of surface temperature and heat transfer coefficient (HTC) was analysed. For typical quadrilateral channel, it was found that HTC increases with P/D first and then decreases significantly when P/D is <1.4. There exists a "flat region" at the maximum value when P/D is 1.4. If P/D is larger than 1.4, heat transfer deterioration (HTD) occurs as main stream enthalpy is quite small. Furthermore, the HTD under low mass flow rate and the non-uniformity of circumferential temperature were also discussed.

1. Introduction

The super critical water-cooled reactor (SCWR) is considered as one of the most promising Generation IV candidate reactors due to its simplified system, high thermal efficiency and sufficient operation experiences of the thermal power stations with super critical water-cooled cycle.

Several conceptual designs of SCWRs have been proposed: (a) super critical water-cooled thermal neutron reactor; (b) super critical water-cooled fast neutron reactor; (c) super critical water-cooled mixed neutron spectrum reactor; (d) super critical water-cooled pebble bed reactor; and (e) super critical heavy water-cooled reactor. Table 1 shows the detailed design parameters of present typical SCWRs around the world.

Although no boiling crisis occurs for the super critical coolant in the core, heat transfer deterioration occurring in the SCWR may lead to severe consequence. Therefore, the study of flow and heat transfer characteristics in the rod bundle channels in the super critical water-cooled reactor is of significant importance for its design and development.

The research on thermal hydraulic behavior of super critical fluids dates back to 1950s. Experimental and theoretical research on heat transfer under super critical pressure conditions was performed and was also conducted in the past decades (Jackson and Hall, 1979; Polyakov, 1991; Cheng and Schulenberg, 2001; Pioro and Duffey, 2005). In recent years, numerical simulation has been successfully adopted in the studies of heat transfer characteristics of the super critical water (Kim et al., 2004; Roelof and Komen, 2005; Oka et al., 2007; Cai et al., 2009). Compared with experimental investigation, numerical simulation costs much less and the results are also very instructive. Koshizuka et al. (1995) numerically analysed the deterioration in heat transfer at super critical water cooling in a vertical pipe. The results agreed with the experimental data of Yamagata et al. (1972). It was found that heat transfer deterioration is caused by two mechanisms depending on the mass flow rate. Yang et al. (2007) numerically investigated the heat transfer in upward flows of super critical water in circular tubes and in tight fuel rod bundles using the commercial CFD code. Some turbulence models were compared in the numerical simulations. The results were compared with experimental data and other heat transfer correlations in the super critical condition. It was found that there was a strong non-uniformity of the circumferential distribution of the cladding surface temperature in the square lattice bundle with a small pitch-to-diameter ratio (P/D), which did not occur in the triangular lattice bundle with a small P/D. This was caused by the large non-uniformity of the flow area in the cross section of sub-channels. Some improved suggestions were proposed to avoid the large circumferential temperature gradient at the cladding surface. Cheng et al. (2007) investigated the heat transfer of super critical water in various flow channels using the commercial CFD code software. Three different flow channels were selected and the impact of mesh structures, turbulence models, and flow channel configurations were analysed. The applicability of different turbulence models had been evaluated under super critical condition and a new definition for the onset of heat transfer deterioration was proposed. Shang et al. (2008) studied the system pressure effect on heat transfer of super critical water in

* Corresponding author. Tel./fax: +86 29 82663401.
E-mail address: ghsu@mail.xjtu.edu.cn (G.H. Su).

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Table 1
Typical SCWRs around the world (Li and Wang, 2006).

Name	Proposed by	Design concept	Moderate	Rated power (MW)	Outlet temperature (°C)	Pressure (MPa)	Net efficiency (%)	Reference
W21	Tokyo university	Thermal neutron spectrum SCWR	H_2O	1570	508	25	44	Dobashi et al. (1997, 1998) and Oka and Koshizuka (2000)
TWG1	Water TWG (Japan)	Fast neutron spectrum SCWR	H_2O	1728	Alternative	Alternative	38–45	Sakurai et al. (2003)
W6–1	AECL (Canada)	CANDU-X-MARK1	D_2O	910	430	25	41	Torgerson et al. (2006)
W6–2		CANDU-XNC		370	400	25	41	
W6–3		CANDU-ALX1		950	450	25	40.6	
W6–4		CANDU-ALX2		1143	650	25	45	
–	Europe	HPLWR	H_2O	1000	500	25	44	Heusener et al. (2000) and Squarer et al. (2003)
–	INEL (USA)	Thermal neutron spectrum SCWR	H_2O	1600	500	25	44	Jacopo (2003)
B500SKD1	Russia	Integrative SCWR	H_2O	515	381	23.6	38	Kurchatov Institute (1992)

a horizontal round tube using CFD technique. It was found that when the buoyancy effect was negligible, the system pressure change had significant effects on the heat transfer. However, when the buoyancy effect was considerably strong, it had less effect due to the strong influences of the buoyancy force. Gu et al. (2008) numerically studied the thermal-hydraulic behavior of super critical water flows in two typical types of sub-channels in SCWR, i.e. square and triangular lattices. The results showed that the circumferential temperature distribution was non-uniform, especially when pitch-to-diameter ratio is small.

As described above, many numerical studies on the heat transfer characteristics of super critical fluids have been carried out. However, they were mostly limited to simple flow channel geometries. For the basic understanding of thermal-hydraulic behavior in SCWRs, in this study different turbulent models were evaluated, and the flow and heat transfer characteristics in different rod bundle channels were numerically investigated by using CFX codes.

2. Mathematical and physical models

The reactor considered in this study is one of the SCWRs proposed in China (Cheng, 2007) which is thermal and fast neutron mixed type. There are 100 fuel assemblies (FA) in the fast neutron region and 184 in the thermal neutron region.

Fig. 1 shows the detailed FA arrangement in the fast neutron region. The diameter of the fuel rod (D) is 8 mm. The gap between two rods (P) is 10.2 mm. Each fuel assembly consists of 289 fuel rods (17×17). The width of the FA is 177.2 mm. As shown in Fig. 1b,[1] the red and blue regions are fuel and blanket layers, respectively. Each layer is 50 cm high and therefore the total height is 4.5 m. The fuel rod average linear power density is 16 kW/m.

Fig. 2 shows the cross section of the thermal neutron region. The diameter of the fuel rod (D) is 8 mm while the rod spacing (P) is 9.6 mm. The length of the rod bundle channel is 4 m, with 250 mm reflectors on both ends. Therefore its total length is 4.5 m. There are 180 fuel rods, including 24 burnable poison rods (yellow rods). The average wall heat flux is 600 kW/m^2.

The detailed parameters of the SCWR in China are given in Table 2.

2.1. Geometric structure and computational domain

Only a quarter of the fast and thermal FA is calculated taking symmetry into consideration. According to the geometric structures, the fast neutron channels are divided into three different kinds as shown in Fig. 3, i.e. the typical quadrilateral, the wall and the corner channels. The thermal neutron channels also include wall and corner channels but there are two different kinds of wall channels, as shown in Fig. 4. Only the shadow regions are calculated for symmetry. Furthermore, as the shadow regions are symmetric along the dashed lines, only half needs to be calculated.

2.2. Selection of turbulent models

The proper choice of the turbulent models is important for scientific calculation and can lead to satisfactory simulation results. Therefore, lots of research has been done on this field. Kim et al. (2004) applied more than 10 first order closure turbulence models as shown in Table 3 and found that the low-Reynolds number models were not able to estimate the wall temperature correctly. The RNG $k-\varepsilon$ model with the enhanced near-wall treatment obtained the most satisfactory prediction. Other researchers (Cheng et al., 2007; Gu et al., 2007) investigated the heat transfer characteristics of SCWR in different flow channels and found that the second order turbulence models, i.e. the Reynolds stress model of Speziale (SSG) and the Reynolds stress model of Launder (LRR) give excellent prediction. Yang et al. (2007) found that the two-layer model is more accurate to predict the heat transfer at super critical pressure than other models using STAR-CD. However, due to the limitations of computational capabilities, they adopted standard high Reynolds number (Re) $k-\varepsilon$ model with standard wall function to perform the CFD analyses. Gou et al. (2010) numerically investigated the heat transfer in sub-channels of a super fast reactor and found that the non-linear Speziale quadratic high Re $k-\varepsilon$ model with two-layer near-wall treatment and the $y+$ value <1 give the acceptable results using STAR-CD.

Based on the review of the open literature on the turbulence models adopted under super critical pressure condition, different researchers have different conclusions. As there were no experimental data of bundle rod channels, most results were compared with the data of circular tubes and it's hard to tell which model can simulate the turbulence flow best.

The RNG method has been employed in the turbulent flow field since 1970s. In late 1980s, Yakhot and Orazag (1986) theoretically deduced RNG $k-\varepsilon$ turbulent model. They believed that turbulent flow in the inertia sub-region can be described by the N–S equations with random forces. Therefore, the N–S equations restricted by the boundary and initial conditions turn into the unrestricted Fourier transforming (Kandikar, 2002) so as to get rid of the high frequency and small size turbulent terms. Smith and Reynolds (1992) discovered the error in RNG $k-\varepsilon$ turbulent model and deduced a modified one. Table 4 presents the comparison between the three models. Speziale et al. (1991) calculated the distribution of turbulent kinetic energy by using the original RNG $k-\varepsilon$ model

[1] For interpretation of color in Figs. 1–2 and 5–24, the reader is referred to the web version of this article.