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Thermo hydraulic analysis of narrow channel effect in supercritical-pressure light water reactor

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ABSTRACT

The size of the gap between fuel rods has important effects on flow and heat transfer in a supercritical-pressure light water reactor. Based on thermal analysis at different coolant flow rates, the reasonable value range of gap size between fuel rods is obtained, for which the maximum cladding temperature safety limits and installation technology are comprehensively considered. Firstly, for a given design flow rate of coolant, thermal hydraulic analysis of supercritical pressure light water reactor with different gap sizes is provided by changing the fuel rod pitch only. The results show that, by means of reducing the gap size between fuel rods, the heat transfer coefficients between coolant and fuel rod, as well as the heat transfer coefficient between coolant and water rod, would both increase noticeably. Furthermore, the maximum cladding temperature will significantly decrease when the moderator temperature is decreased but coolant temperature remains essentially constant. Meanwhile, the reduction in the maximum cladding temperature in the inner assemblies is much larger than that in the outer assemblies. In addition, the maximum cladding temperature could be further reduced by means of increasing coolant flow rate for each gap size. Finally, the characteristics of narrow channels effect are proposed, and the maximum allowable gap between fuel rods is obtained by making full use of the enhancing narrow channels effect on heat transfer, and concurrently considering installation. This could provide a theoretical reference for supercritical-pressure light water reactor design optimization, in which the effects of gap size and flow rate on heat transfer are both considered.

1. Introduction

Along with the development of nuclear technology, the advanced reactor structures become more and more compact. In which, narrow channel is always used for the design of gaps between fuel rods to strengthen the heat transfer with the increase of flow velocity. For supercritical water reactor, even more little size is adopted than that for other advanced PWR s such as China Advanced Research Reactor. This is mainly because of the low flow rate, which is required high flow velocity to transfer heat out of the core effectively (Oka et al., 2010). According to the concepts of reactor design developed in Japan, Europe, America and China (Yamaji et al., 2005; Yoo et al., 2006; Mukohara et al., 2000; Squarer et al., 2003; Kamei et al., 2006), core design parameters of the supercritical-pressure light water reactors are presented in Table 1. Meanwhile, the design parameters of PWR and BWR are also given. Taking SCLWR-H for example, the gaps between fuel rods is only 1.0 mm. This shows that the narrow channel design has become an important part for the design of advanced reactors with supercritical water reactor included. In the narrow channel, heat transfer will be enhanced with the degree of superheat decreased due to the size effect of the slit. Thereby, narrow channel effect is becoming an important research topic for supercritical reactor research. In the past studies of the supercritical pressure light water reactors, the works mainly focused on its thermal characteristic analysis and it pays little attention to the gap changing (Hu, 2008; Yang et al., 2011; Yang et al., 2010). Recently, although few researches on narrow gap heat transfer have been developed, but much more are concentrated on the analysis in sub-critical pressure (Cheng et al., 2011; Wen et al., 2010; Liu et al., 2011; Zhang et al., 2011). Thus, more detailed research on the narrow heat transfer performance should be further presented to supercritical-pressure light water reactors, especially considering the influence of size changing of gaps between fuel rods. Based on the concept of super LWR proposed in Japan, thermal hydraulic analysis of supercritical-pressure light water reactors on narrow channel effect is carried out, in which the water's serious physical property change in pseudo-critical area is considered. And the maximum allowable gap between fuel rods is calculated for different coolant flow rate design, in which the narrow channels effect on heat transfer enhancing is analyzed and considered. It could be used to provide a certain theory reference for design optimization of supercritical-pressure light water reactor.

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Table 1
Core characteristics of supercritical-pressure light water reactors and comparison with PWR.

	SCLWR-H	SCFR-H	Super LWR	HPLWR	SCWR-M	LWR	BWR
Main coolant flow rate (kg/s)	1342	1700	1420	1160	1976	1938	1778[b]
Average inlet and outlet coolant temperature (°C)	280/530	280/537	280/500	280/500	280/510	226/283.6	62.8/399
P/D	1.098	1.15	1.098	1.19	1.20/1.275[a]	1.34	1.39
Fuel rod pitch (mm)	11.2	10.1	11.2	9.5	9.6/10.2[a]	12.50	16.20
Fuel rod diameter (mm)	10.2	8.8	10.2	8.0	8.0	9.33	11.65
Gaps between fuel rods (mm)	1.0	1.3	1.0	1.5	1.6/2.2[a]	3.17	4.55

[a] Represents design value in the fast zone.
[b] Recirculation flow rate of BWR is 13417 kg/s.

2. Study object

In present work, the super LWR core design is selected as the study object, which has been proposed by Tokyo university of Japan since 2006 (Kamei et al., 2006). It is designed with division arrangement for fuel assemblies, in which 48 fuel assemblies in interior zone and 73 fuel assemblies in peripheral zone. But all fuel assemblies have the same structure for fuel rods arrangement. Fig. 1 shows the horizontal cross-section of a single square fuel assembly. In the right side, partial enlarged view is given with fuel rod pitch, fuel rod diameter and gaps between fuel rods shown clearly.

As shown in Fig. 1 that, the gaps between fuel rods is 1.0 mm with fuel rod diameter of 10.2 mm and fuel rods pitch of 11.2 mm. During the following studies, narrow channel effect analysis on different gaps is derived by the assumption that only fuel rods pitch changes. Besides, the edge length of water rods wall would be changed accordingly even when keeping the arrangement of fuel assemblies and the diameter of fuel rods unchanged.

For supercritical pressure water reactor, it adopts supercritical water (374 °C, 22.1 MPa) as the coolant, which has the special physical property as simple substance that different from that of super-cooled water or superheated steam. Considering the special properties of supercritical water and the particular core design, the descending-flow is adopted for fuel channels in the inner fuel assemblies and the upwelling-flow is designed for fuel channels in the outer fuel assemblies. The flow chart is shown in Fig. 2.

It can be seen from Fig. 2 that, after flowing upward to the top dome of reactor through the main feed water pipes, water flows down into three different flow channels, which including fuel channels in the outer fuel assemblies, moderator channels in the outer fuel assemblies, and moderator channels in the inner fuel assemblies. The distribution proportions are 42.2%, 19.7%, 30% respectively. Then together with the rest part from down comer, all of the water enters into fuel channels in the inner fuel assemblies and finally flows out of reactor from the upper plenum.

3. Calculation model

3.1. Neutronic calculations model

A simplified distribution cosine functions to axial power is used for modeling of one-dimensional static/steady state single channel neutronic calculation. Then, the calculation model is given in the following formula:

$$Q_{reactor} = mn_{fuel}\sum_{i=0}^{n}(q_{\max}f(i)) \tag{1}$$

In which, $Q_{reactor}$ is reactor power, W; $q_{\max}$ is the maximum linear power of fuel rod, W/m; m, n_{fuel} are respectively the number of fuel assemblies, and the number of fuel rods in each fuel assembly; and $f(i)$ is the power distribution factor of the node i, which satisfies the cosine functions.

3.2. Flow model

For either fuel channels or moderator channels, the steady-state flow distribution calculation model consists of three governing equations. It contains mass continuity equation, axial momentum conservation equation, and energy conservation equation (Yoo et al., 2007), which are shown from the following equations:

$$\Delta(\rho v) = 0 \tag{2}$$

$$\rho v \Delta v = -\Delta P_f + \Delta P_{el} + \Delta P_a \tag{3}$$

$$\rho v \Delta h = q_2 - q_1 \tag{4}$$

In which, ρ is the density of coolant or moderator, kg/m^3; v is the velocity of coolant or moderator, m/s; ΔP_f, ΔP_{el}, ΔP_a is friction pressure drop, elevation pressure drop and acceleration pressure drop respectively, MPa; Δh is the enthalpy value change of coolant or moderator between inlet to outlet of channels, J/kg; q_1 is the

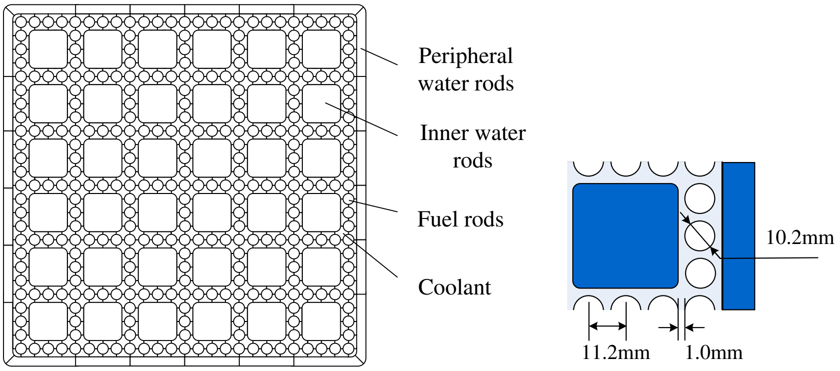

Fig. 1. The horizontal cross-section of the single square fuel assembly.