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Core and sub-channel analysis of SCWR with mixed spectrum core

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ABSTRACT

The SCWR core concept SCWR-M is proposed based on a mixed spectrum and consists of a thermal zone and a fast zone. This core design combines the merits of both thermal and fast SCWR cores, and minimizes their shortcomings. In the thermal zone co-current flow mode is applied with an exit temperature slightly over the pseudo-critical point. The downward flow in the thermal fuel assembly will provide an effective cooling of the fuel rods. In the forthcoming fast zone, a sufficiently large negative coolant void reactivity coefficient and high conversion ratio can be achieved by the axial multi-layer arrangement of fuel rods. Due to the high coolant inlet temperature over the pseudo-critical point, the heat transfer deterioration phenomenon will be eliminated in this fast spectrum zone. And the low water density in the fast zone enables a hard neutron spectrum, also with a wide lattice structure, which minimizes the effect of non-uniformity of the circumferential heat transfer and reduces the cladding peak temperature.

The performance of the proposed core, including the neutron-physical and thermal-hydraulic behavior in sub-channel scale, is investigated with coupled neutron-physical/thermal-hydraulic simulation tools, which at the same time enables multi-scale analysis. During the coupling procedure, the thermal-hydraulic behavior is analyzed using a multi-channel code and the neutron-physical performance is computed with a 3-D diffusion code. Based on the core results, the pin-power reconstruction is carried out for each fuel assembly to predict the local pin-power distribution. Moreover, the sub-channel calculation is performed to obtain the thermal-hydraulic parameters for each sub-channel and fuel rod. Based on the coupled analysis, measures to improve the performance of the SCWR-M core design are proposed and evaluated in this paper.

The results achieved in this paper have shown that the mixed spectrum SCWR core concept (SCWR-M) is feasible and promising. One reference SCWR-M design is proposed for future analysis.

1. Introduction

The super-critical water-cooled reactor (SCWR) offers high thermal efficiencies and considerable plant simplification and is considered as a logical extension of the existing water-cooled reactors (Oka and Koshizuka, 2001). In the last years, extensive R&D activities have been carried out covering various aspects of the SCWR development. Pre-conceptual core design is an important task among the R&D activities. For the time being, a large number of pre-conceptual designs of SCWR reactor cores have been proposed in the open literature. Most of the concepts are based on thermal spectrum (Yamaji et al., 2005a; Schulenberg et al., 2008). Efforts were also made to design SCWR reactor cores with fast neutron spectrum (Yoo et al., 2006).

Fast spectrum reactor cores proposed by Yoo et al. (2006) and Yang et al. (2007) consist of seed and blanket fuel. Fuel pins are tightly arranged inside fuel assemblies in a hexagonal lattice. The fast spectrum reactor enables higher fuel utilization and higher power density. However, the tight lattice will cause a strong non-uniformity of the circumferential distribution of heat transfer, and subsequently, the cladding surface temperature (Cheng et al., 2007; Yang et al., 2007). Compared to the fast core design, the fuel assembly structure of a thermal reactor core is much more complicated (Yamaji et al., 2005a; Schulenberg et al., 2008), mainly due to the introduction of additional moderator into the core or into the fuel assemblies. At the same time, the hot-channel factor is another concern which should be taken into consideration in the thermal SCWR (Cheng et al., 2008).

To avoid the serious problems in both mechanical design and safety features, and on the other hand to achieve a high temperature at the reactor exit, a mixed core design with multi-layer fuel assembly has been proposed by Cheng et al. (2008). The core consists of two zones with different neutron spectrums, one with thermal and the other with fast spectrum. In the thermal zone co-current flow mode is applied with an exit temperature over the pseudo-critical point. The downward flow in the thermal fuel assembly will provide an effective cooling of the fuel rods. As a re-

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sult, the cladding temperature will be kept at a low value. In the forthcoming fast zone a high exit temperature is achieved. Due to the high coolant inlet temperature over the pseudo-critical point, the heat transfer deterioration phenomenon will be eliminated in this upward flowing area. And the low density in the fast zone can provide a hard neutron spectrum with a wide lattice structure, which can mitigate the non-uniformity of the circumferential heat transfer at the cladding surface and ensure a big inventory of water in the core. Consequently, with a hard neutron spectrum and the multi-layer fuel assembly, a conversion ratio over 1.0 can be achieved in the fast fuel assemblies.

Investigations are also carried out to perform core and sub-channel analysis. Recently, Waata (2005) developed a coupled simulation approach with MCNP and the sub-channel code STAFAS for a fuel assembly analysis (2005). Although this gives detailed local characteristics of the fuel rods and sub-channels, application of the coupling procedure is restricted to one fuel assembly and requires extremely large computational efforts. The non-uniformity of the power and mass flow rate distribution over the reactor core is beyond its consideration. This would lead to an underestimation of power generation in the hottest fuel assembly. Yamaji et al. (2005b) performed a pin-wise power reconstruction within fuel assemblies. Based on the pin-wise power distribution, sub-channel calculation is performed to obtain the detailed coolant and cladding temperature of the sub-channels and the fuel rods. This approach requires a large amount of neutronic calculations to derive an accurate pin-wise power distribution in the assembly. Liu and Cheng (2009a) evaluated the cladding peak temperature by a 3-D core coupling calculation. In the first step, each fuel assembly is homogenized for the coupled core analysis of neutronics and thermal-hydraulics. Based on the fuel assembly averaged parameters, several fuel assemblies with critical parameters, e.g. highest coolant temperature, are selected for further detailed investigations. In the second step, a coupled analysis of thermal-hydraulics in the sub-channel scale and neutron-physics in the pin-wise scale is then carried out for the selected critical fuel assemblies, in order to determine parameter distribution inside the fuel assembly. The fuel assembly averaged values, such as fuel assembly power, mass flux, and moderator flow rate, are taken from the coupling core calculation. However, in the second step, the reflective boundary condition is applied to the selected fuel assembly neutronic calculation, which will eliminate the effect of the neighboring assemblies.

This paper will investigate the main features, including the sub-channel behavior, of the proposed core with 3-D coupled neutron-physical and thermal-hydraulic calculations. A detail discussion of the analysis code system will also be presented in this paper. According to the results obtained, it shows that the mixed spectrum SCWR concept (SCWR-M) is feasible and promising. One SCWR-M design will be recommended for the future study due to its better characters.

2. The mixed core design

Fig. 1 shows schematically the geometrical arrangement of the proposed mixed core. There are totally 284 fuel assemblies in the core. To simplify the calculation process and to investigate the preliminary character of the mixed core, only the case with fresh fuels is considered in this study. The basic idea is to divide the core into two parts with different neutron spectrums. In the outer zone with 164 fuel assemblies, the neutron energy spectrum is similar to that of a thermal reactor. The inner zone with 120 fuel assemblies has fast neutron spectrum. The average linear power rate is 18 kW/m for both the thermal zone and the fast zone. The active height is 4.5 m for the thermal zone and 2.0 m for the fast zone. The average power density is 90.26 MW/m^3 including blanket fuel and the equivalent core diameter is 3.4 m.

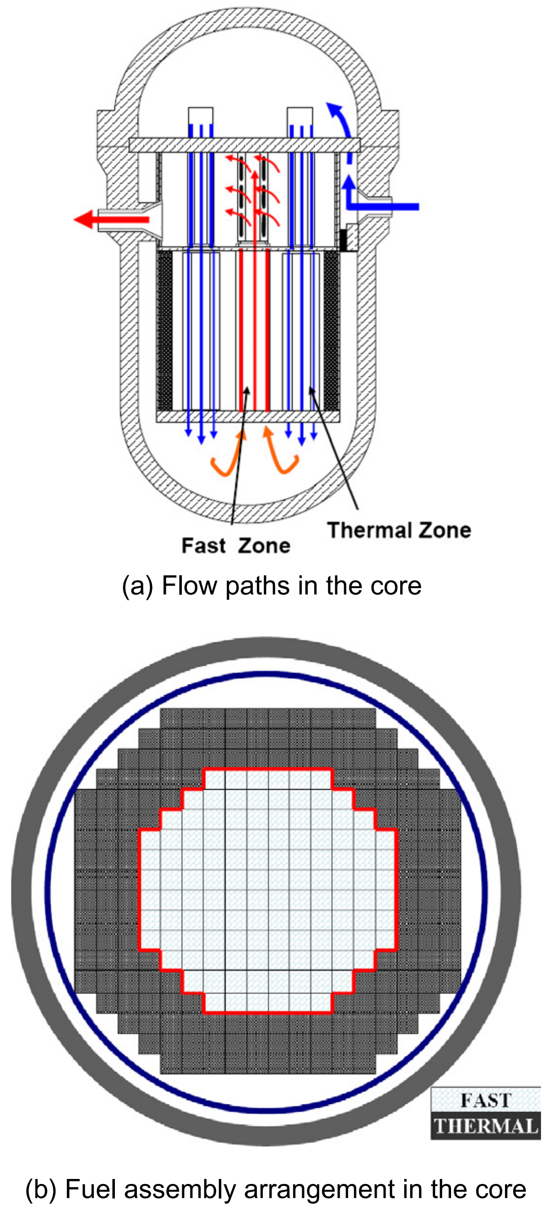

Fig. 1. Scheme of the SCWR-M core.

The selection of the fuel assembly design is derived from an optimization work, which is performed by Yang et al. (2010). For the thermal zone, the basic idea of the multi-layer concept is axially to divide the active length into several layers with different enrichment, schematically illustrated in Fig. 2a. For the fast zone, in order to achieve negative void reactivity coefficients, the seed core is designed to be short to increase neutron leakage as schematically shown in Fig. 2b. Axial blankets with depleted uranium are also introduced to increase the conversion ratio and to reduce the void reactivity coefficient. The seed and blanket materials are axially divided into 11 layers (Yang et al., 2010).

In the thermal zone, the co-current flow mode is applied to the fuel assembly. The cold water entering the pressure vessel goes upward to the upper dome and into both the moderator channels and the cooling channels of the thermal zone. In the thermal zone, 25% of the mass flow rate goes through the moderator channels. It exits the thermal zone in the lower plenum, from where it enters the