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Single pass core design for a Super Fast Reactor

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ABSTRACT

Single pass core design for Supercritical-pressure light water-cooled fast reactor (Super FR) is proposed. The whole core is cooled with upward coolant flow in one through flow pattern like PWR. Compared with the previous two pass core design; this new flow pattern significantly simplifies the core concept in terms of upper core structure, coolant flow scheme as well as refueling procedure. In single pass core design, supercritical-pressure water at approximately 25.0 MPa enters the core at 280 °C and heated up in one through upward flow to the average outlet temperature at 500 °C. Great coolant density change in vertical direction will cause significant axial power offset during the cycle. Meanwhile, Pu accumulated in the UO_2 also introduces great power increase in blanket assemblies during cycle, which requires large amount of flow for heat removal and makes the outlet temperature of blanket low at beginning of equilibrium cycle (BOEC). To deal with these issues, some MOX fuel is applied in the bottom region of blanket assemblies to mitigate the power change in blanket assembly and to increase the coolant outlet. With exclusive refueling and shuffling scheme as well as partial length control rod design, neutronics & TH coupled calculation shows satisfactory results that can fulfil the requirement of design for both 500 °C outlet temperature and negative coolant void reactivity.

1. Introduction

The concept of Supercritical-pressure light water-cooled fast reactor (Super FR) has been developed in the recent decades because of its favorable advantages such as high outlet coolant temperature, high thermal efficiency, high power density as well as potential for fuel breeding. Studies have been carried out progressively in Japan (Cao et al., 2008, 2009; Yoo et al., 2006; Oka et al., 2013).

In latest core design (Liu and Oka, 2013a), two pass flow pattern with all upward flow cooling is proposed and improved (Liu and Oka, 2014), CR guide tube design and in-core insertion scheme is taken into account. Despite that two pass flow core of Super FR is capable of delivering uniform vertical coolant density distribution; flattened radial power distribution etc. There are several drawbacks to overcome: complicated flow scheme requires complicated in-core structure to direct and re-direct the coolant flow, various penetrations and heat seal are necessary, complicated flow direction changes will pose flow stability issues etc. Moreover, control rod (CR) insertion strategy, refueling and fuel shuffling are also complicated due to upper core structure and its flow pattern.

Single pass core design for Super FR is therefore proposed and studied based on existing experience on two-pass core design, with assumed pin-power peaking profiles (Liu and Oka, 2013b). Safety analysis has also been conducted with satisfactory performance (Sutanto and Oka, 2014, 2015). The single pass core is cooled with upward flow in one through flow pattern like PWR (Fig. 1). Compared with the previous two pass core design; this new flow pattern can significantly simplify the in-core structure. It also enables the refueling, fuel shuffling schemes and control rod design from conventional PWR. However, the pin-power distribution in single pass core is much more complicated than two-pass core because of larger assembly size, reduced total assembly number and seed-blanket assembly coupling loading pattern. In addition, great coolant density change in vertical direction features extreme axial power profile and offset during cycle.

In the present study, single pass core design for Super FR is proposed and investigated in detail, additional aspects are considered in terms of pin-power peaking, fuel loading and shuffling scheme as well as control rod design and withdrawal scheme. By appropriate assembly design with MOX fuel loaded at bottom of blanket assemblies, adjusted fuel rod-duct wall gap clearance. Exclusive loading pattern are proposed. Partial length control rod design is

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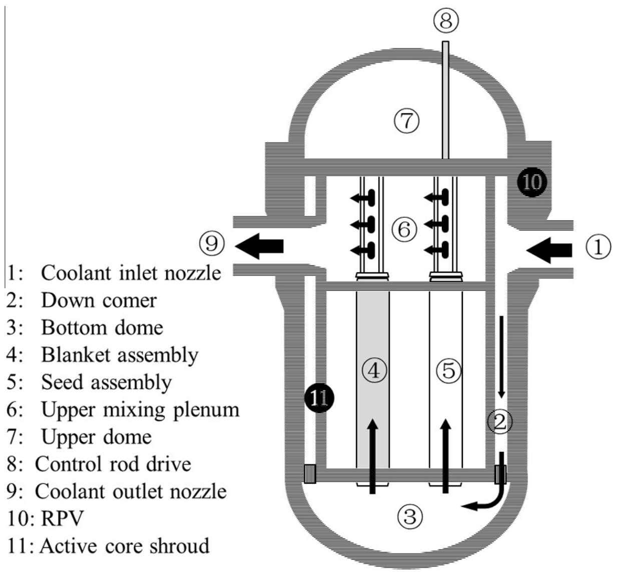

Fig. 1. Flow pattern of single pass Super FR.

also applied to mitigate the axial power offset during cycle, Results of neutronic & TH coupled calculation has shown that all design goals are fulfilled and design constrains are satisfied.

2. Design methodology

The design criteria and limitations are adopted from previous study (Oka et al., 2010) because of same fundamentals of the physics. They are listed as follow:

(1) The core should be at 1000 MWe class commercial scale.
(2) Core average outlet temperature should be over 500 °C, which ensures nearly 44% thermal efficiency of plant.
(3) Core overall volumetric power density should be greater than 100 kW/L (including gas plenum and radial reflector).
(4) Maximum linear heat generation rate (MLHGR) should be lower than 39 kW/m.
(5) Maximum cladding surface temperature (MCST) should be below 650 °C at normal operation.
(6) Negative void reactivity should be promised through cycle.
(7) Sufficient shutdown margin 1% for both equilibrium cycle and fresh core in cold, hot and operation state (when the maximum worth CR cluster is stuck).

Compared with previous two pass core design (Liu and Oka, 2014), additional considerations are taken into account from practical perspective as below:

(1) Larger assembly size with sufficient control rod guide tube positions, control rod dimension should be comparable with conventional PWR control rod dimension.
(2) Sufficient spacing between neighboring control rod drive mechanism (CRDM).
(3) Reduced total number of assemblies in core due to manufacturing and refueling cost (should be comparable with conventional PWR).

Code system used in this study is identical to the previous study, N/TH coupled code based on SRAC code system using evaluated nuclear library JENDL-3.3 (Okumura et al., 2007) for neutronic calculation and SPROD for single channel TH calculation. It applies 3D diffusion whole core neutronics and thermal–hydraulics coupled calculation. The flow chart of the code system is shown in Fig. 2.

3. Assembly design

Single pass core design raises new challenges firstly from neutronic aspect; great change of coolant density in vertical direction (inlet 280 °C, outlet 500 °C at 25.0 MPa, where average coolant density decreases over 8 times). Axial power distribution is much more non-flat type. Secondly, blanket assembly will be influential to the core outlet temperature because the coolant exiting blanket assembly goes directly to upper plenum and then core outlet. Pu is accumulated in the blanket assembly so that power generated in the blanket assemblies increase greatly during cycle. In order to sufficiently cool the blanket assemblies, higher flow rate is required based on the power of blanket assembly at the end of equilibrium cycle (EOEC). Therefore, the outlet temperature of blanket assembly at the beginning of equilibrium cycle (BOEC) will be very low which will also lower the core outlet temperature.

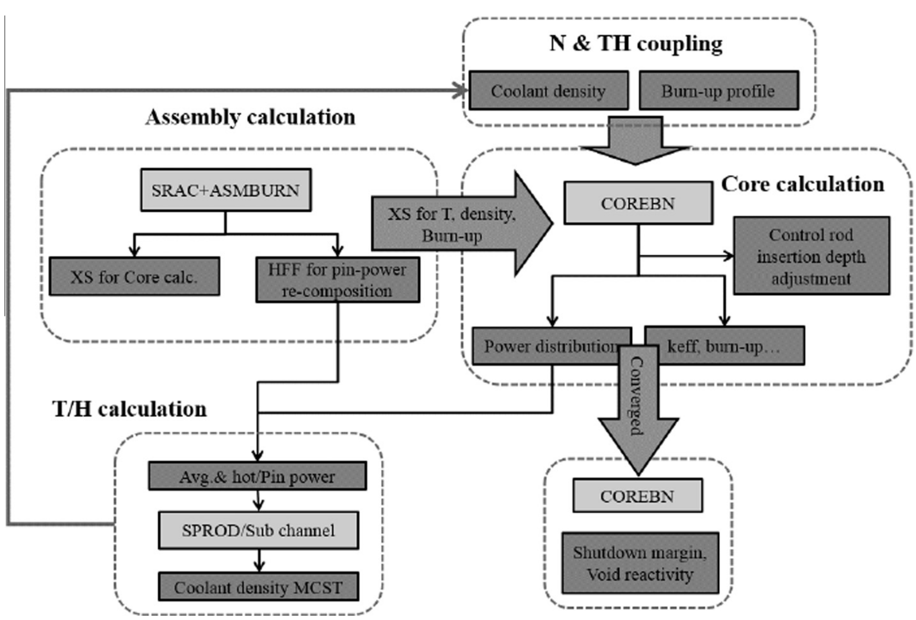

Fig. 2. Calculation flow chart of the code system.