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Time dependent start-up thermal analysis of a Super Fast Reactor

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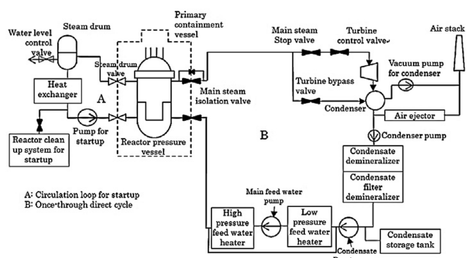
HIGHLIGHTS

- Time dependent startup thermal analysis of a Super Fast Reactor is performed.
- A recirculation system is used for pressurization and for generating supercritical steam.
- MCST satisfies the criterion both during subcritical pressure and during power-raising.
- MCST is not sensitive to the change of inlet temperature, gap volume and flow rate because of high flow to power ratio.
- CHF is not limiting the MCST during subcritical pressure due to large margin of heat flux.

GRAPHICAL ABSTRACT



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ABSTRACT

The startup system of a supercritical pressure light water cooled fast reactor (Super FR) is studied by time dependent thermal-hydraulic analysis. The plant analysis code is developed based on an innovative upward flow pattern in all the assemblies of the Super FR. A recirculation system consisting of a steam drum, a circulation pump, and a heat exchanger is used for the startup. Detailed procedures are performed and the maximum cladding surface temperature (MCST) at rated power, 640 °C, is used as the criterion. Firstly a small constant nuclear power is used for rising the core feed water temperature to be 280 °C through the recirculation system. Secondly, pressurization is done in the recirculation system from atmospheric to operating pressure, 25 MPa, by raising the power. Thirdly, line-switching from recirculation mode to once-through direct-cycle is performed while turbines are started by supercritical steam at supercritical pressure. Finally the power is raised to be 100% of power followed by raising the flow rate. During pressurization the heat flux margin is large due to low power used for pressurization and the MCST is much lower than the criterion. The MCST is not sensitive to the inlet temperature, the flow rate, and the gap volume of the core because of high flow to power ratio. Smaller dimension of steam drum can be used for pressurization stably. The MCST satisfies the criterion both during subcritical pressure and during power-raising.

1. Introduction

A supercritical water-cooled fast reactor (Super FR) is one of the supercritical water cooled reactors (SCWRs) which have been developed over than two decades (Oka et al., 1992; Oka and Koshizuka, 2001; Oka et al., 2010, 2013). It is a Generation IV reactor concept and designed to find a way of competitive plutonium

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utilization. This reactor is functioning with relatively higher neutron energy spectrum which requires less amount of moderation to make the core design compact in size with distinguishing high power density. It is continuously developed to improve economy of fast reactors over thermal reactors. The Super FR has good potential in this regard (Oka and Koshizuka, 2001).

Thermal behavior during startup is one of the important issues in developing SCWRs. The startup characteristics of a Super FR are different from these of a conventional light water reactor (LWR) because these involve transition of the coolant from subcritical pressure to supercritical pressure (Yi et al., 2004). There will be a large change in the thermodynamic properties and transport properties of the coolant. Cooling ability of the coolant, a startup scheme and the required components for the startup must be investigated.

The past investigation of startup of a low-temperature Super FR was done by referring to the startup schemes of supercritical fossil fired power plants (FPPs) (Nakatsuka et al., 2001). The plant also used similar turbines to the turbines of FPPs. A bypass system was used to keep the flow rate during subcritical pressure. The feasibilities of both constant pressure startup system and sliding pressure startup system were investigated from the view point of thermal consideration.

Startup systems of a high-temperature supercritical-pressure light water-cooled thermal reactor Super LWR (SCLWR-H) were also investigated by using the same schemes as these of FPPs (Yi et al., 2004, 2005). More detailed thermal-hydraulic analyses of various startup phases of the sliding pressure startup system were carried out by single channel model. Phases such as pressurization phase and temperature-raising phase were investigated and analyzed. The study assumed that the system pressure could be raised independently from the power. The supercritical turbines were started by using saturated steam at subcritical pressure while the turbines of FPPs were started by using superheated steam at subcritical pressure.

Thermal analysis during power-raising of a Super FR with downward-upward two-pass coolant flow was also studied (Cai et al., 2009). Maximum cladding surface temperature at rated power became the criterion. Flow distribution between the part of seed assemblies and blanket assemblies in the first path was calculated to find the region satisfying the criterion. The allowable region in the second path was also analyzed. MCST for some regions in each part of assemblies may exceed the criterion.

A new design of sliding pressure startup scheme for SCWRs was proposed to provide a pressurization system and to meet the requirement of supercritical steam for starting supercritical turbines (Yamada and Ishiwatari, 2009). It solved the previous assumption of pressurization which was raised independently from the power. This scheme was proposed by introducing a recirculation system instead of a bypass system. It was a different scheme from the sliding pressure startup scheme of FPPs where superheated steam was generated in the boiler. The startup procedures of a Super FR which all blanket fuel assemblies and part of the seed fuel assemblies were cooled by downward flow were studied by using the new startup scheme.

Currently, a Super FR is developed to achieve better performance (Liu and Oka, 2013; Oka et al., 2013). The core characteristics of the Super FR are shown in Table 1. Core 1 and core 2 in the table are similar and these are the same concept due to progress during the design. An innovative flow pattern with all-upward two-pass flow is introduced in the cores for simplifying upper core structure as shown in Fig. 1. There are two flow paths in the cores. In the first path are part of the seed assemblies (seed 1) and all blanket assemblies. In the second path is the other part of seed assemblies (seed 2). Firstly the coolant flows to the lower dome through the feed water line. Then it is divided into two parts flowing upward through the first path (seed 1 and blanket assemblies). From the first path the coolants flow downward through the gap and these are mixed in the mixing plenum. The mixed coolant flows upward through the second path (seed 2) and finally is delivered to the main steam line through the upper plenum. This flow pattern simplifies the upper core structure. Compact size core with tight pin design is also adopted to maintain the high power density. The amount of solid moderator (ZrH) in the blanket is adjusted for the negative void reactivity. The startup behavior of the Super FR is studied due to these innovations.

Table 1
Characteristics of Super FR.

Parameters	Core 1	Core 2
Thermal/electrical power (MWt/MWe)	2325/1000	2325/1000
Active core height (m)	1.8	3.6
Power density (MW/m^3)	171	238
Number of assemblies for Seed1/Seed2/Blanket	72/126/97	72/90/73
Number of fuel rods per assembly for Seed1/Seed2/Blanket	378/378/61	271/252/61
Fuel rod diameter (mm)	5.5	5.5
Inlet and outlet temperature (°C)	280/500	280/500
Total flow rate (kg/s)	1200	1200
Flow distribution between Seed1 and Blanket (%)	80/20	91/9
Working pressure (MPa)	25.0	25.0
MCST (°C)	640	640
Cladding material	Stainless steel	Stainless steel

In the present study a time dependent startup thermal analysis of the Super FR is conducted. Startup system based on a recirculation system is used for the Super FR (Core 1). In the previous study, detailed thermal analyses of the startup system were not carried out. These thermal analyses of the startup system are necessary to clarify the characteristics from thermal point of view. This study is performed with the following purposes:

1. to investigate the startup procedures of a Super FR,
2. to perform the detailed time dependent startup thermal analysis of a Super FR:
   a. heat flux margin analysis during subcritical pressure,
   b. startup sensitivity analysis during pressurization,

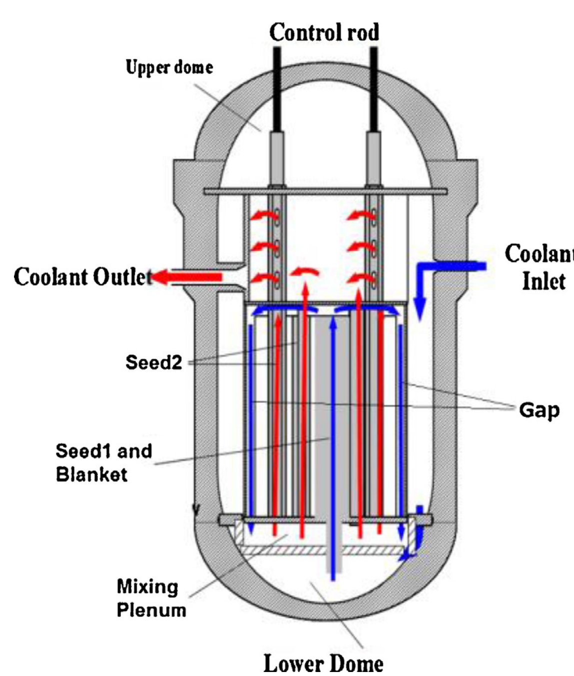

Fig. 1. Coolant flow path in RPV of Super FR.