Thermal-Fluid Analysis of the PMR 200MW$_{th}$ Reactor System at the Steady State and Transient Conditions

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1. Introduction

This paper describes the thermal-fluid analysis of the PMR 200MW$_{th}$ reactor system [1] at the steady state and the transient conditions such as LPCC (Low Pressure Conduction Cooling) and HPCC (High Pressure Conduction Cooling) events.

As one of the candidate reactor types for a nuclear hydrogen production demonstration plant [2], the PMR 200MW$_{th}$ reactor is pre-conceptually designed to have a 200 MW thermal power, a prismatic annular core, 6 layers of fuel block, the air-cooled RCCS (Reactor Cavity Cooling System) and the VCS (Vessel Cooling System).

The GAMMA+ code [3] is used for the analysis. The calculation uses the detailed core flow network model including the flows through the coolant channels, the bypass gaps and the cross flow gaps. The steady state RCS (Reactor Cooling System) operates at the total helium flow rate of 82.79 kg/s, the inlet temperature of 490 ^{o}C, the outlet temperature of 950 ^{o}C, and the outlet pressure of 7.0 MPa. The inlet temperature and the flow rate of the VCS are 140 ^{o}C and 2.0 kg/s, respectively. The inlet air temperature of the RCCS is 43 ^{o}C.

LPCC event assumes the scenario that the outlet pressure decreases from 7.0 to 0.1 MPa in 12 seconds, and then the reactor trip signal occurs when the pressure is less than 6.24 MPa. HPCC event assumes the scenario that the RCS flow decreases from 82.79 to 0.0 kg/s in 60 seconds, and then the reactor trip signal occurs when the flow is less than 75.0 kg/s. The power trip and the VCS flow isolation start after 1 second on the reactor trip signal.

The analysis provides the maximum temperatures of the main components and the detailed core flow distribution at the steady state. The transient calculations examine the peak temperature behavior of the main components during the LPCC and the HPCC events.

2. PMR 200MW$_{th}$ Reactor System

Fig. 1 shows the system configuration of the PMR 200MW$_{th}$ reactor. The VCS flow goes through the gap between the core barrel and the RPV (Reactor Pressure Vessel). The VCS is designed to use the conventional SA533/SA508 material for the RPV. The main RCS flow goes through the inlet plenum, the bottom plenum, the riser holes in the permanent reflector, the top plenum, the core coolant channels and the outlet plenum.

The prismatic annular core is composed of total 66 fuel block assemblies (FA) in 3 radial rings (18 in inner ring, 24 in mid- & outer ring) and 6 axial layers of fuel block. The core is surrounded by the central reflector, the top/bottom reflectors, and the side reflector. All core components are surrounded by the RPV which is cooled by the VCS and the RCCS. The decay heat during the transient is only removed by the natural circulation through 250 RCCS tubes in the reactor cavity.

As shown in Fig.1, the core cross section has a 1/6 symmetry with 11 fuel block assemblies in 3 radial rings. The GAMMA+ code is able to simulate 11 fuel block assemblies. But, this calculation uses the model of 3 ring fuel block assemblies to reduce the number of flow path. The average ring power is based on the specific power data of MASTER code results [4].

The detailed core flow model uses 3 coolant channels, 8 gap bypass, 4 RSC/CR holes and cross flow. The cross flow is considered by the junctions between the adjacent FA gaps, between coolant channel and FA gap, and between RSC/CR hole and FA gap. The areas of the gap bypass flow and the cross flow are based on the horizontal FA gap size of 2 mm and the vertical gap size of 1.5 mm.

3. Results of the Steady State

The axial core temperature profiles show a flat distribution in the active core because the power peaking factor at the top is higher than that at the bottom.

The peak fuel compact centerline temperature is 1138 ^{o}C at BOC as shown in Fig. 2, and is 1171 ^{o}C at MOC and EOC. These are less than the steady state fuel design limit of 1250 ^{o}C. The peak temperature occurs at top core in inner ring at BOC and MOC, but occurs at middle core in outer ring at EOC due to the power distribution. The maximum temperature of the RPV is 295 ^{o}C, which is much less than the design limit of 371 ^{o}C for SA508 material.

The flow rates in the coolant channels change at the axial locations due to the effects of the cross flow and the bypass flow. The detailed core flow results show that the maximum bypass flow occurs at the middle core, where the coolant flow rates at inner ring, mid ring and outer ring are 23%, 32% and 32% of RCS flow, respectively. Thus, the minimum coolant channel flow is 87% and the maximum bypass flow is 13% of RCS flow.

The cross flow between the adjacent FA gaps is less than 0.2 kg/s except that the cross flow between the side reflector gap and the outer ring gap shows 0.8 kg/s at the bottom core. The cross flow between the coolant channel/RSC/CR hole and the FA gap is less than 1.5 kg/s, and the direction of the cross flow changes at the middle core.

4. Results of LPCC and HPCC

For LPCC event, the reactor trip signal occurred at 1.1 seconds after the decrease of the outlet pressure started, and then the power trip and the VCS flow isolation started at 2.1 seconds.

Fig. 3 shows the peak temperature behavior of the main components during LPCC event at BOC. The peak fuel centerline temperature is 1383 °C at 38 hours, which is much less than the transient fuel design limit of 1600 °C. The peak temperature of the RPV is 452 °C at 72 hours. The peak temperatures of the main components at MOC are slightly higher than those at BOC due to the power distribution.

For HPCC event, the reactor trip signal occurred at 5.7 seconds after the decrease of the RCS flow started.

Due to the decrease of the RCS flow, the increase of the peak fuel centerline temperature of HPCC is less than 1 °C in 6 seconds. After then, the peak fuel centerline temperature decreases to 1002 °C until 0.2 hours and increases again to 1125 °C until 25 hours. The peak temperature of the RPV is 380 °C at 48 hours. The peak temperature of the top reflector of HPCC event is higher than that of LPCC event due to the natural convection. The peak temperatures of other components of HPCC event are less than those of LPCC event.

5. Conclusions

The results of the steady state and transient analysis for the PMR 200MW$_{th}$ reactor show that the peak temperatures of the main components are less than the design limits. The peak temperatures of the main components are passively decreased by the air-cooled RCCS during the LPCC and HPCC events.

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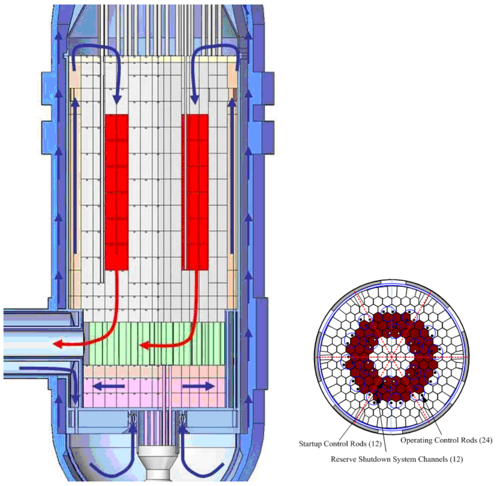

Fig.1 System Configuration of the PMR 200MW$_{th}$ Reactor

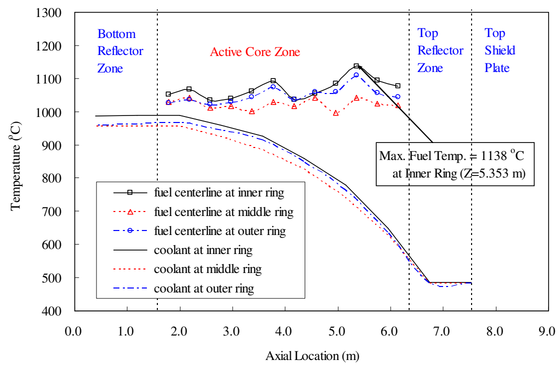

Fig.2 Peak Fuel Compact Centerline Temperature

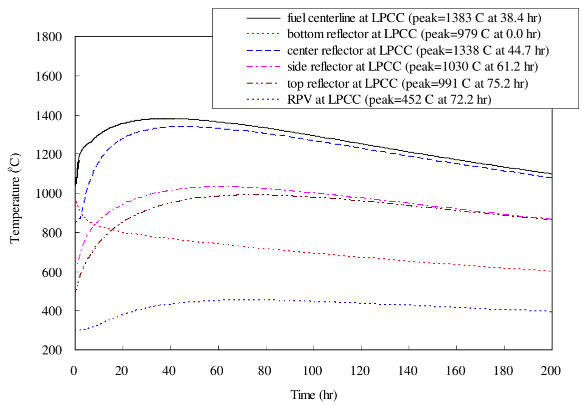

Fig.3 Peak Temperature Transients during LPCC