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Simulation of Thermal-hydraulic Process in Reactor of HTR-PM

ZHOU Ke-feng[1], *ZHOU Yang-ping*[2], *SUI Zhe*[2], *MA Yuanle*[2]
1.Nuclear and Radiation Safety Center, MEP
Beijing 100082，China
2.Institute of Nuclear and New Energy Technology, Tsinghua University
Beijing, 100084, China
phone: +86-010-82205807, zhoukefeng@chinansc.cn

Abstract–This paper provides the physical process in the reactor of High Temperature Gas-cooled Reactor Pebble-bed Module (HTR-PM) and introduces the standard operation conditions. The FORTRAN code developed for the thermal hydraulic module of Full-Scale Simulator (FSS) of HTR-PM is used to simulate two typical operation transients including cold startup process and cold shutdown process. And the results were compared to the safety analysis code, namely TINTE. The good agreement indicates that the code is applicable for simulating the thermal-hydraulic process in reactor of HTR-PM. And for long time transient process, the code shows good stability and convergence.

Key words: thermal-hydraulic code, cold startup, cold shutdown, simulator

I. INTRODUCTION

High Temperature Gas-cooled Reactor Pebble-bed Module (HTR-PM) is one of the major science and technology projects, which are listed in China's national medium and long-term project for scientific and technological development. As the first commercial modular pebble-bed High Temperature gas-cooled Reactor (HTR) project, HTR-PM project, which is designed by Institute of Nuclear and New Energy Technology (INET), Tsinghua University, will be constructed cooperatively by INET, China Huaneng Group and China Nuclear Engineering & Construction Corporation. Based on the technology and experience of the HTR-10[1], the preparation work of HTR-PM had already been started in the end of 2006 in Shandong province, China.

An operator training plant simulator is required for operating a nuclear power plant [2]. Operators should be licensed on the simulator prior to operating the nuclear power plant. The development of Full Scale Simulator (FSS), as an indispensable part of the project of HTR-PM, has been carried out. The simulation of the reactor is one of the key elements in FSS.

For the simulation of thermal hydraulic process in the reactor of HTR-PM, a FORTRAN code is developed based on the thermal fluid network and SIMPLE algorithm. The code is applied to simulate several cases of HTR-PM, such as the steady states (100%FP and 50%FP) and the accident of Control Rod Withdrawal Error (CRWE). The results agree with those from THERMIX code which indicate that the thermal-hydraulic model and its solving method are reasonable and applicable [3-4].

According to the related standard [5] about the development of FSS, the simulator needs to be able to simulate the change between work conditions which include cold shutdown to power rating condition and power rating to cold shutdown condition. In this paper, the code is used to simulate the above transient processes by input reactor power, coolant inlet temperature and mass flow rate. The results of important parameters show that the code can reflect the characteristic of transient process.

Section 2 of this paper, briefly introduces the thermal hydraulic process in the reactor of HTR-PM. and physical process in thermal hydraulic model. Section 3 gives the simulation results of transient processes. Finally, Section 4 gives conclusions of this paper.

II. INTRODUCTION OF HTR-PM

The HTR-PM deploys two units of pebble-bed modular HTRs each with 250 MW thermal power.

Two reactor modules are coupled with two steam generators which are connected to one steam turbine-generator with 210 MW electric power. The reactor and the steam generator are installed in two separate pressure vessels. The pressure vessels are assembled in a staggered, side-by-side arrangement and are connected by a horizontal coaxial hot gas duct. The primary pressure boundary consists of the Reactor Pressure Vessel (RPV), the Steam Generator Pressure Vessel (SGPV) and the Hot gas Duct Pressure Vessel (HDPV), which all are housed in a concrete shielding cavity as shown in Fig. 1[8]. The main design parameters are listed in Table 1.

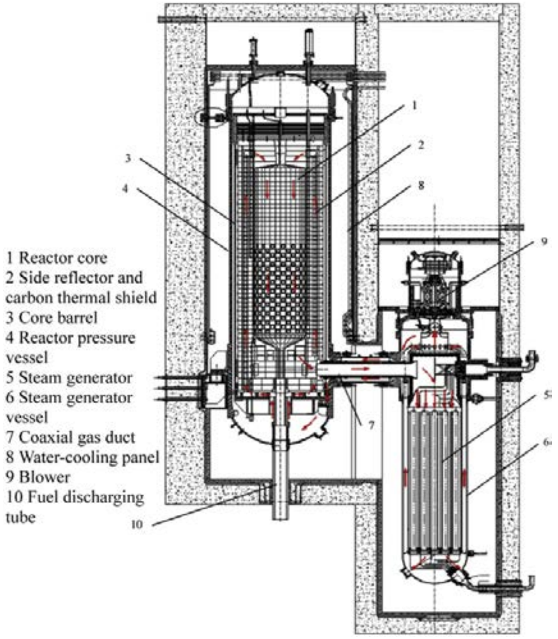

Fig.1. Primary loop of HTR-PM.

Table 1 Major design parameters of HTR-PM

Item	Value
Thermal power (MW)	2 × 250
Electric power (MW)	210
Active core diameter (cm)	300
Equivalent active core height (cm)	1100
Primary helium pressure (MPa)	7.0
Average helium temperature at reactor inlet/outlet (℃)	250/750
Helium mass flow rate at full power (kg・s^{-1})	96
Type of steam generator	Once-through helical
Main steam flow rate at the inlet of turbine ((kg・s^{-1})	98
Main steam pressure (MPa)	14.3
Main steam temperature (℃)	566
Main feed-water temperature (℃)	205

As shown in Fig. 1, the thermal-hydraulic process related with the reactor and the primary loop of HTR-PM can be mainly explained as following:

Before entering the reactor vessel, the helium gas pressure is approximate 7 MPa and the temperature of the inlet helium gas is around 250 ℃. After the helium flows through the hot fuel pebble in the reactor core, the outlet helium temperature reaches to 750 ℃. The hot helium exits the reactors and flows through the hot gas duct. The hot helium releases its thermal power to the water in the steam generator where it is cooled down to around 250 ℃. Then, the helium blower blows the cold helium through the outer coaxial pipes of the hot gas duct. Finally, the cold helium flows into the RPV where it is heated again. In this way, a circulation of the helium flow is established in the primary loop. At the side of the secondary loop of HTR-PM plant, the water at a temperature of 205 ℃ in the steam generator is heated to 566 ℃ by the hot helium and becomes superheated steam. Then the superheated steam with a pressure of 14.3 MPa will drive the steam turbine and its conjoined generator in order to generate electrical power.

II.B. Physical process in the thermal hydraulic model

The simulation of thermal-hydraulic process in the reactor consists primarily of the following two main parts:

(1) Core thermal-hydraulic simulation: The reactor core includes primary and by-pass cooling flows, and leakage flows through graphite gaps. All these flows would need to be simulated correctly and all the heat transfer mechanisms need to be simulated.

(2) Material and thermal conductivity simulation: The thermal conductivity of graphite as a function of fast neutron dose and temperature is required for calculating the temperature distribution in the reactor core. This applies for fuel element graphite as well as structural graphite.

Table.2 shows the most physical processes in the thermal hydraulic model in detail. Based on the physical process mentioned above, heat transfer network and thermal-hydraulic network are adopted to simulate the thermal-hydraulic process of reactor of HTR-PM.

III SIMULATION OF OPERATION CONDITION

III.A. Operation Condition in HTR-PM

According to the reactivity, power level, temperature of coolant and pressure of RCS, 8 standard operation conditions is defined in HTR-PM. And conditions transition requirements and processes are also specified, which make the reactor to stay in a standard operation state.

Table.2 Physical process in the Thermal-Hydraulic model

No.	**Physical processes**	**Core regions**	**Key functions**	**Model origins**
1	Helium thermodynamic properties	The entire HTR-PM fluid area	Function of pressure and Temperature	KTA 3102.1
2	Thermal conductivity and heat capacity	Pebble bed, graphite reflectors, carbon bricks, reactor internals and RPV	Function of neutron dose and temperature	THERMIX correlations
3	Effective thermal conductivity	Pebble bed	Include contract conduction, convection and radiation	Zehner－Schlunder correlation
4	Heat transfer coefficient of the surface of spherical fuel elements	Pebble bed	Function of pebble packing density	KTA 3102.2
5	Loss of Pressure through Friction in Pebble Bed Cores	Pebble bed	Function of pebble packing density	KTA 3102.3
6	Heat conduction within the fuel sphere	Pebble bed	Radial temperature distribution in a sphere from the centre to the wall	1D conduction in spherical coordinate
7	Multidimensional heat conduction in the structural area	graphite reflectors, carbon bricks, reactor internals and RPV	2D temperature profile	2D conduction model in Cartesian coordinate
8	Heat loss to residual heat removal system	Reactor Pressure Vessel	Heat sink due to loss of heat	radiation heat loss to water wall

The standard operation conditions include unload cold shutdown, maintain cold shutdown, normal cold shutdown, hot shutdown, cold startup, hot startup, low power operation and high power operation. Fig. 2 gives the transition of these operation conditions.

Unload cold shutdown and maintain cold shutdown are the states after the reactor cold shutdown. In these two states, change of model and initial condition and discontinuous simulation are allowed [4]. So the thermal hydraulic simulation will mainly focus on the other condition. In this paper, cold shutdown to power rating process and power rating to cold shutdown process are simulated.

III.B. Simulation of cold startup process

At the beginning of cold startup process, the reactor stays in cold shutdown state. Along with the power lifting, start and shutdown loop system will be cut off. And the power will stay at 30% and above level finally. The features of cold startup process are as follows,

- Time scale is large,
- Power is linear raised in different sloop,
- The coolant inlet temperature increases continually,
- Mass flow rate change sharply between the low power level to high power level.

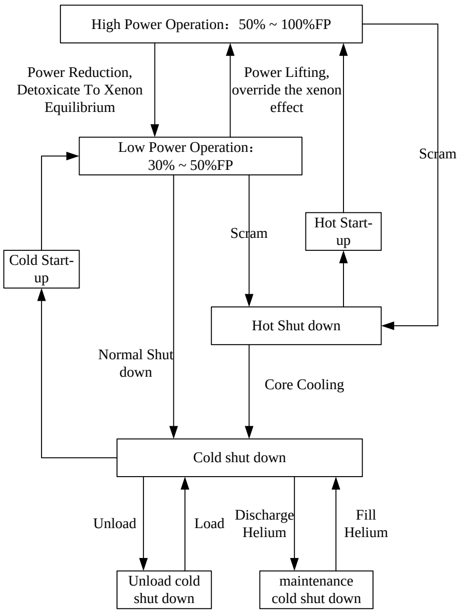

Fig.2 The transition of 8 standard operation state

Fig.3 shows the inputs of cold startup simulation which includes reactor power, coolant inlet temperature and mass flow rate. All these inputs are the same with TINTE code. Fig.4 ~ Fig.6 show the results of outlet temperature of coolant, pressure drop and heat removal by coolant. Fig.7 gives the temperature distribution of solid zones in reactor during the cold startup process.

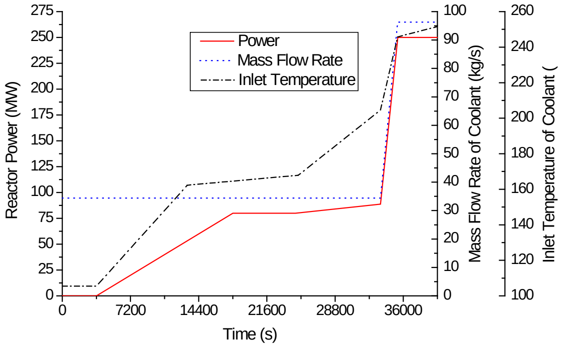

Fig.3 the inputs of cold startup simulation

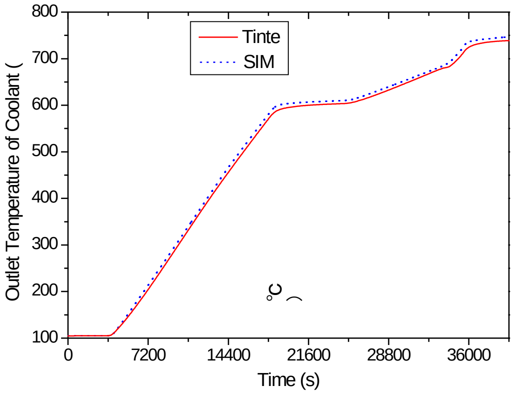

Fig.4 coolant outlet temperature of cold startup process

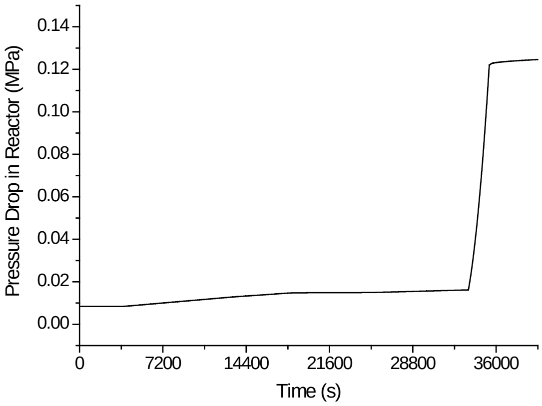

Fig.5 the pressure drop in cold startup process

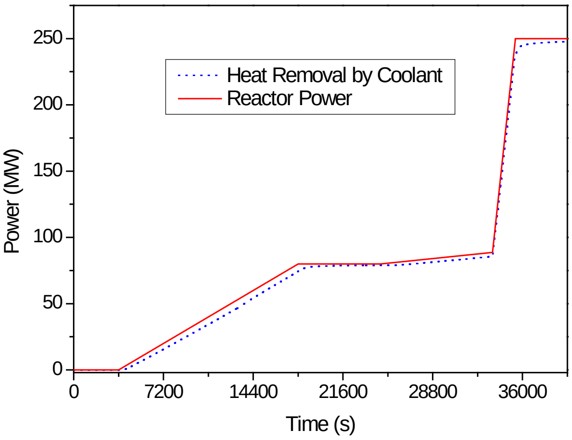

Fig.6 heat removal by coolant in cold startup process

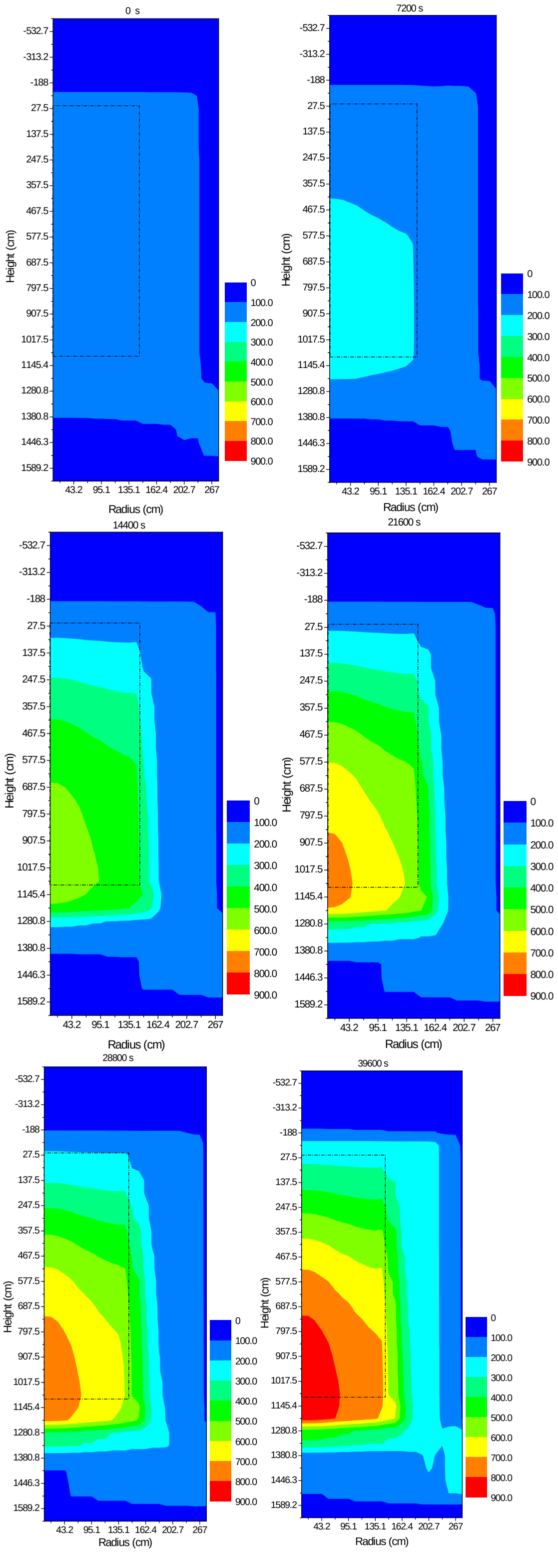

Fig.7 distribution of temperature in solid zone in reactor in cold startup process

0~3600s, the reactor stays in cold shutdown state. In this stage, the reactor is heat up by main helium fan and the coolant temperature keeps in 105℃. So the heat removal by the coolant is negative. 3600~18000s, the reactor power is raised from zero power to 31.6% linearly. The temperature of solid zone increases along with power. Because of the large heat capacity, the temperature of solid zone legs behind the power. So the heat removal by coolant also legs behind the power. Due to the increasing of coolant temperature, the viscosity of helium increase correspondingly which make the pressure drop increase too. 18000~24600s, the reactor power keeps at 31.6%FP and the flow rate of coolant keeps at 33.88kg/s. In this stage, the heat removal by coolant increases gradually, and equals to the power soon. 24600~33000s, the flow rate of coolant keeps at 33.88kg/s, and the power raise up to 35.2%. In this stage, the temperature of solid zone and the outlet temperature of coolant go up. Because of the change of coolant viscosity, the pressure drop increase. The heat removal increases with a little delay. From 33000s, system keeps at a steady state for a short time. And from 33600s to 35400s, the power will raise up to full power. And the flow rate of coolant increases to rated flow rate correspondingly. In this stage, because of the increase of flow rate, the pressure drop raises up obviously.

In the simulation of cold startup, the code can reflect the change of main parameters correctly which satisfy the requirement of precision in FSS. And it also shows that the code has good stability and convergence in power raising process.

III.C. Simulation of cold shutdown process

Shutdown process means the state of NPP change from power operation to zero power. There are two type of shutdown, normal shutdown and scram. For the normal shutdown, all the control rods and absorption balls will drop to keep enough shutdown depth. The decay heat will be removed by the main fan, steam generator and start and shutdown loop system. The features of cold startup process are as follows,

- Time scale is large,
- Power is linear reduced in different sloop,
- The coolant inlet temperature decreases continually,
- Mass flow rate change sharply between the high power level to low power level.

Fig.8 shows the inputs of cold startup simulation which includes reactor power, coolant inlet temperature and mass flow rate. All these inputs are the same with TINTE code. Fig.9 ~ Fig.11 show the results of outlet temperature of coolant, pressure drop and heat removal by coolant. Fig.12 gives the temperature distribution of solid zones in reactor during the cold shutdown process.

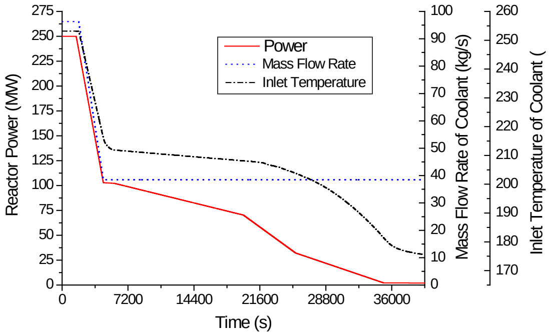

Fig.8 the inputs of cold shutdown simulation

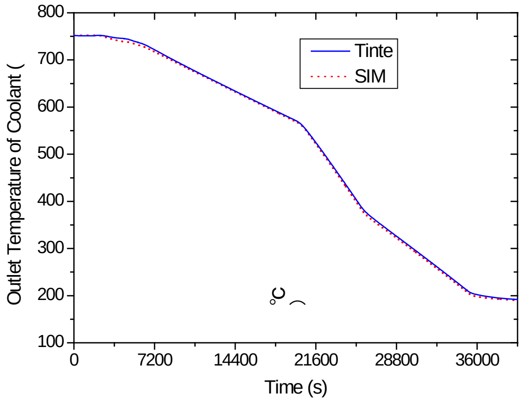

Fig.9 coolant outlet temperature of cold startup process

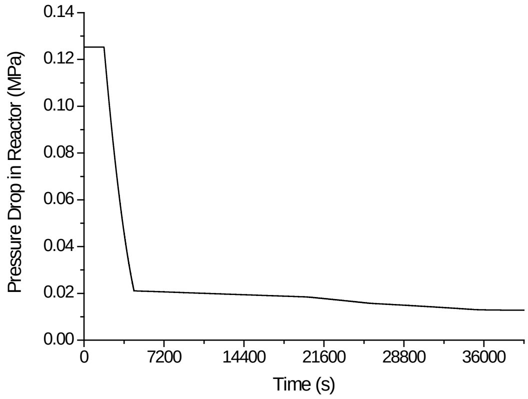

Fig.10 the pressure drop in cold shutdown process

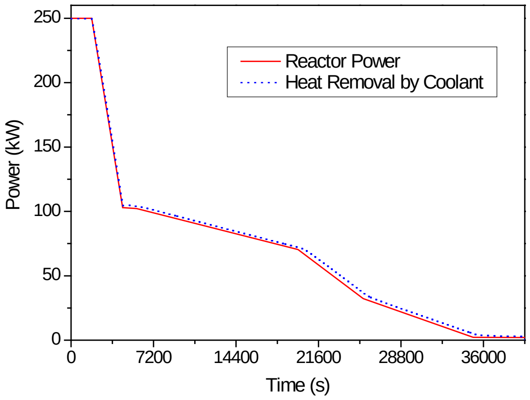

Fig.11 heat removal by coolant in cold shutdown process

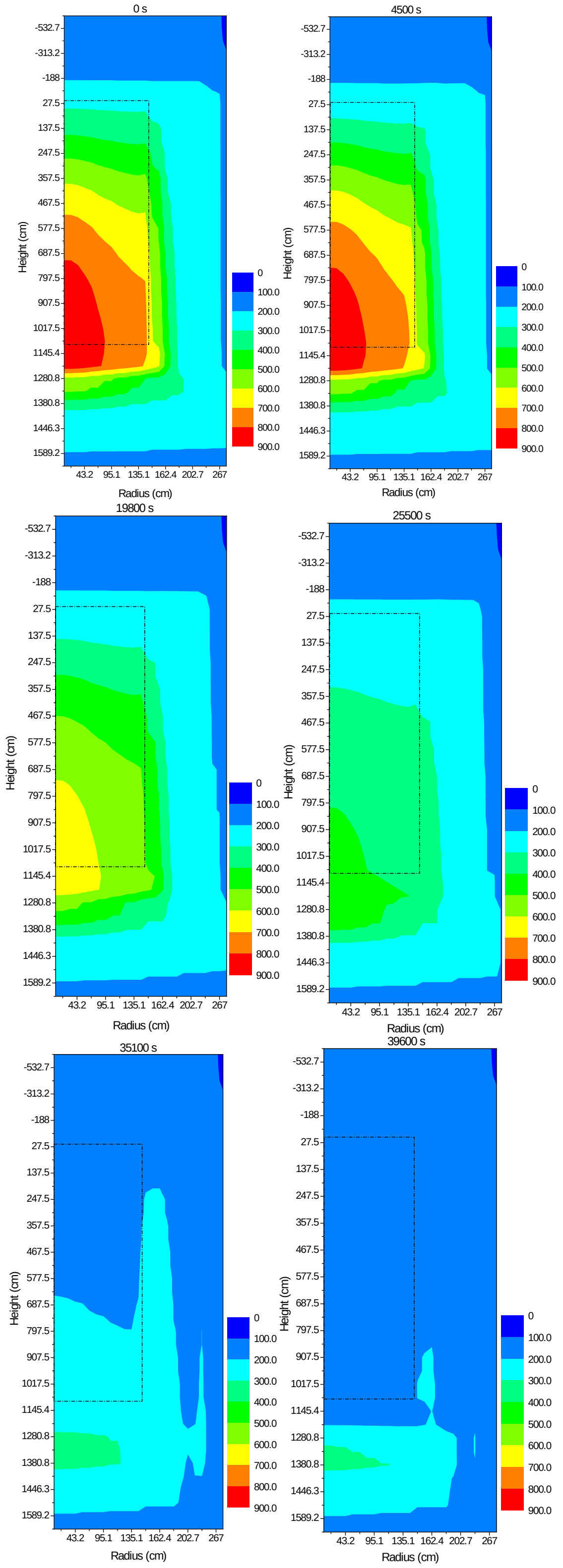

Fig.12 distribution of temperature in solid zone in reactor in cold shutdown process

0~1800s, the reactor stays in full power operation state. From 1800s to 4500s, the power and coolant mass flow rate decrease to 40% linearly. Because of the heat capacity of solid zone, in the earlier stage, the outlet temperature increases slightly. From 4500s to 5700s, the steam is switched from main stream loop to start and shutdown loop system. From 5700s, the flow rate of coolant keeps at 38.508kg/s and the power decrease gradually by using control rods and absorption balls. In this stage, the coolant outlet temperature, the pressure drop and the heat removal by coolant decrease gradually. Compared to the power, because of heat capacity, the heat removal by coolant is bigger which is opposite to the cold startup process. From 35100s, all the control rods drop down, and the reactor becomes subcritical. The start and shutdown loop system continue working to discharge the residual heat actively.

In the simulation of cold shutdown, the code can reflect the change of main parameters correctly which satisfy the requirement of precision in FSS. And it also shows that the code has good stability and convergence in power decreasing process.

IV CONCLUSIONS

In this paper, the code which is designed for thermal hydraulic module of FSS is used to simulate two transient processes. One is from cold shutdown to full power; the other is from rating power to cold shutdown. With the same inputs, the outlet temperature shows good agreement with TINTE code. And the other results reflect the characteristic of HTR-PM. For the long time transient process, the code shows good stability and convergence which are very important for the simulator.

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