Unprotected Transient Analyses of Natural Circulation LBE-Cooled Accelerator Driven Sub-critical System

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Abstract:

Accelerator Driven sub-critical System (ADS) is used for nuclear fuel breeding and transmutation, which is one of the most hopeful ways for nuclear energy research and development (R&D) work. A 10 MW_{th} natural circulation LBE-cooled ADS research reactor conceptual design is developed by FDS Team, Institute of Nuclear Energy Safety Technology (INEST), Chinese Academy of Sciences (CAS). In this paper, to investigate the transient and natural circulation characteristics of this LBE-cooled reactor, three typical unprotected transient accidents were simulated by the Neutronics and Thermal-hydraulics Coupled Simulation Program (NTC) developed by FDS Team. The transients simulated were unprotected loss of heat sink (ULOHS), unprotected beam overpower (UBOP) and unprotected transient overpower (UTOP) respectively. The analyses results of ULOHS showed that the fuel interior temperature was about 1103 K at 1600 s due to the big coolant mass flow rate decrease. For a UBOP transient with 100% beam current increase, the coolant mass flow rate increased due to the natural circulation characteristics and the final stable power increase was about 93%. During a UTOP transient with 0.5 $ reactivity insertion, the simulation results showed that the increase of the core power was only 0.6 MW and the fuel, cladding temperature and coolant mass flow rate all had very small increases. Due to the natural circulation characteristics, the reactor was safe for all the three unprotected transients simulated in this contribution.

Keywords: LBE; ADS; neutronics and thermal-hydraulics coupling; natural circulation
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1. Introduction

The accelerator driven sub-critical system (ADS) is a device for Minor Actinide (MA) transmutation and is composed by a high-energy proton accelerator, a spallation target and a sub-critical core. It is considered to be one of the most hopeful development directions for nuclear energy sustainable development. The study on ADS has been carried out in several countries of the world. In Europe, in the 5th Framework Programmes (FP) of the European Atomic Energy Community (EURATOM), the PDS-XADS was developed [1]. The ADS studies were continued in the 6th FP EURATOM project [2], in which a small scale 50 MW LBE-cooled eXperimenTal-ADS (XT-ADS) and a full scale ADS named EFIT were developed. During the 7th FP, a new collaborative project called Central Design Team (CDT) for a FAst Spectrum Transmutation Experimental Facility (FASTEF) was launched, in which a preliminary design of the Multi-purpose hYbrid Research Reactor for High-tech Applications (MYRRHA) had been underway at the Belgian Nuclear Research Centre SCK•CEN [3-4]. In Japan, within the framework of the J-PARC project, Japan Atomic Energy Agency (JAEA) promoted to construct the Transmutation Experimental Facility (TEF) to study the minor actinide (MA) transmutation by not only the ADS but also the fast reactor [5]. For the United States and Korea, the ADS researches are underway within the ATM project [6] and HYPER project [7-8] respectively. In China, the Strategic Priority Research Program of ADS transmutation was launched in 2011 by the Chinese Academy of Sciences [9-12]. A 10 MW_{th} natural circulation LBE-cooled research reactor has been proposed and developed by FDS Team [13-22] for the R & D work of ADS technologies.

The Neutronics and Thermal-hydraulics Coupled simulation program (NTC) is developed by FDS Team, which is a code used for transient analysis of advanced reactors, such as Fusion-Driven Subcritical System and lead- or LBE-cooled fast reactor. Recently NTC code was extended by FDS Team to be used on the research of LBE-cooled ADS. And NTC-2D used in this paper is a two-dimensional version of NTC.

In this paper, to investigate the safety and natural circulation characteristics, the steady state and three typical unprotected transient accidents of the 10 MWth natural circulation LBE-cooled ADS were simulated with NTC-2D, which were unprotected loss of heat sink (ULOHS), unprotected beam overpower (UBOP) and unprotected transient overpower (UTOP).

2. NTC code

The computational code employed in the following simulations was NTC-2D, which is a neutronics and thermal-hydraulics coupled code developed for reactor transient analysis. The code structure is presented in Figure 1.

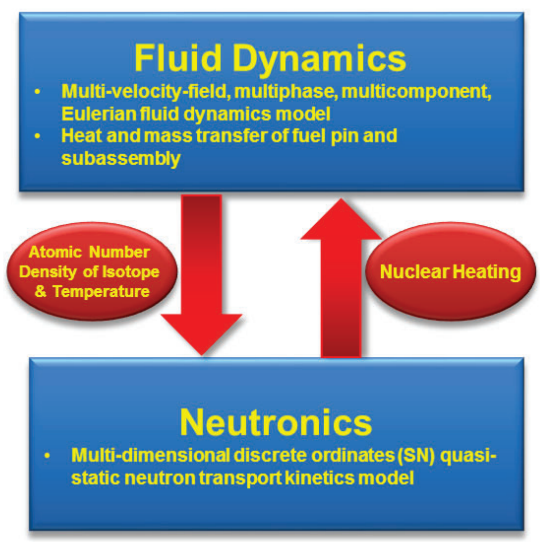

Fig. 1 The code and function structure of NTC

The neutronics module of NTC-2D employs a space- and energy-dependent neutron transport model and the thermal-hydraulics module is a two-dimensional, multi-phase, multi-component fluid-dynamics model coupled with a heat and mass transfer model of fuel pin and assembly structure. Those make NTC-2D very applicable for the accurate simulation of the transient accidents of many kinds of reactor, especially for ADSs in which the neutron flux distributions are anisotropic and non-uniform.

3. Calculation model

3.1 Natural Circulation LBE-cooled ADS concept

The natural circulation LBE-cooled ADS reactor is designed to be pool type reactor. The core thermal power is removed by 850 tons of liquid LBE of which the operation temperature is between 533 K and 663 K. The natural circulation is a kind of passive safety and prevents loss of flow accident (LOFA). The operation range of secondary coolant (488 K-503 K) is much higher than the melting point (398 K) of the primary coolant LBE, so there is no possibility of the solidification of the primary coolant LBE at relatively low temperature caused by the emergency over cooling accident. There are four primary heat exchangers in the main vessel. The secondary loop coolant is water and the final heat sink is air cooling. A Reactor Vessel Air Cooling System (RVACS) is used to remove the decay heat during accidents. The core assembly distribution is presented in Figure 2. There are four functional regions of the reactor core from the center to the external part, which are target region, active region, reflector and shielding. The fuel is UO_2 with 19.75% enrichment and the cladding material is 316Ti stainless steel. k_{eff} is designed to be 0.98.

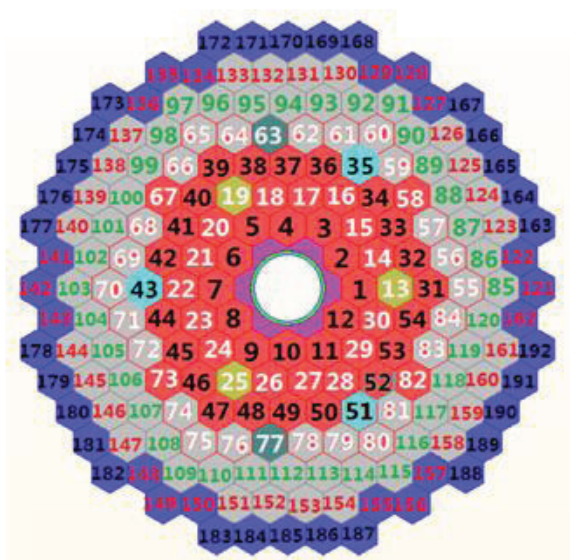

Fig. 2 Core Assembly Distribution of the 10 MW_{th} ADS

3.2 Calculation model for NTC-2D

As NTC-2D is a two-dimensional code, radial and axial directions of the ADS reactor should be considered. The calculation model for NTC-2D is presented in Figure 3.

We can see from Figure 3 that the axial and radial directions of the model were divided to many cells and regions were composed by some neighboring cells. All the assemblies were put in active, reflector or shielding regions according to different similarities. The upper and lower regions of the reactor were hot and cold pools respectively. And the heat exchangers were considered to be ideal.

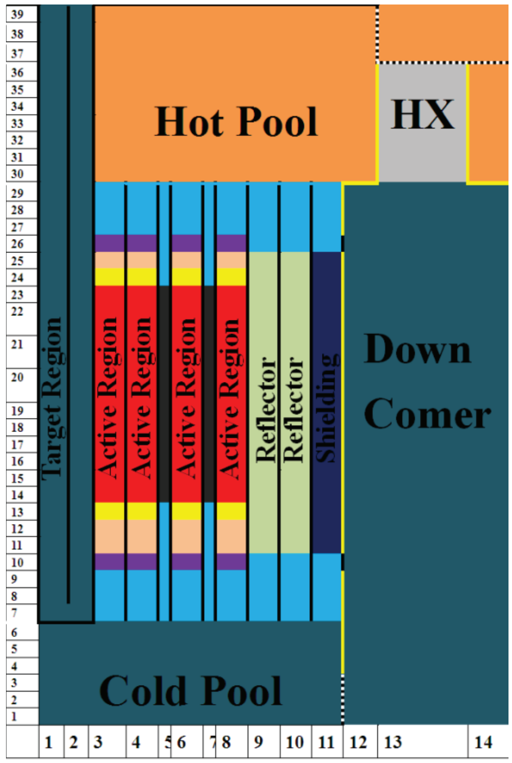

Fig. 3 Calculation model of the 10 MW_{th} ADS

4. Simulation and analyses

4.1 Steady state

The steady operation state was simulated by NTC-2D, of which the results can be used as the base of the transient simulations. The calculation results of the steady states are presented in Table 1.

Table 1 Calculation results of steady state

Parameters	Unit	Design value	Calculation value	Relative difference
Core power	MW_{th}	10	10.3	3%
K_{eff}	--	0.98	0.975	0.5%
Average coolant temperature of core inlet	K	533	533.2	0.03%
Average coolant temperature of core outlet	K	663	670	1%

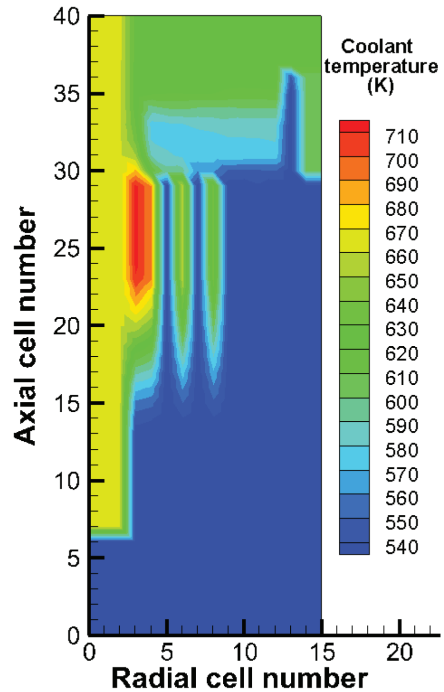

Fig. 4 Temperature distribution of steady state

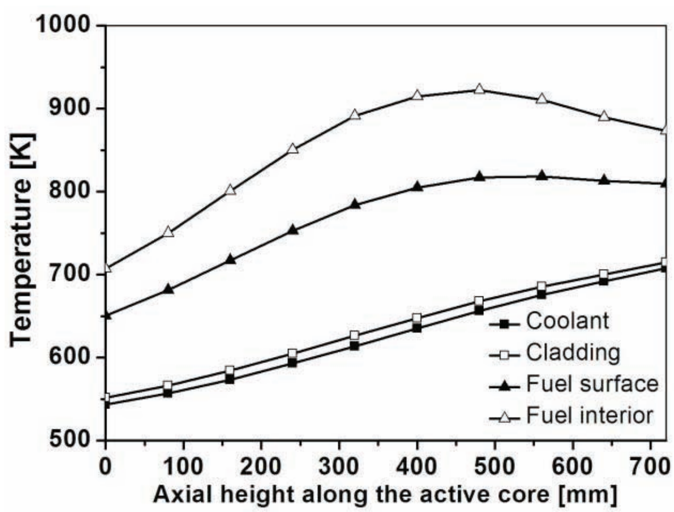

Fig. 5 Axial temperature distributions in the hottest channel of steady state

As shown in Table 1, the calculation results of the main neutronics and thermal-hydraulics parameters were very close to the design values, between which the differences were all smaller than 3%. The coolant temperature distribution of the steady state simulation is presented in Figure 4 and the temperature distributions in the hottest channel are presented in Figure 5. All the results in Figure 4 and 5 showed that the natural circulation can be established in this ADS reactor.

4.2 Unprotected loss of heat sink

The loss of heat sink simulated in this paper was assumed to be caused by the loss of secondary loop, which was a complete loss of heat sink accident at the initial time. There was no reactor shutdown during this transient. The unprotected simulation results are shown in Figures 6-8.

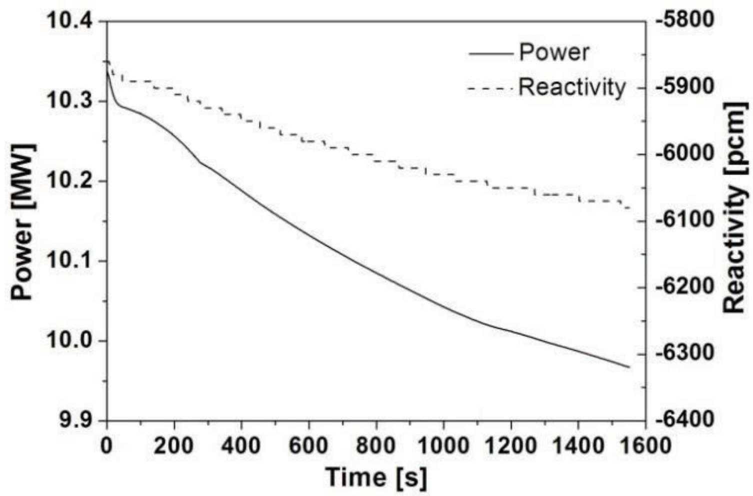

Fig. 6 Core power and reactivity in ULOHS

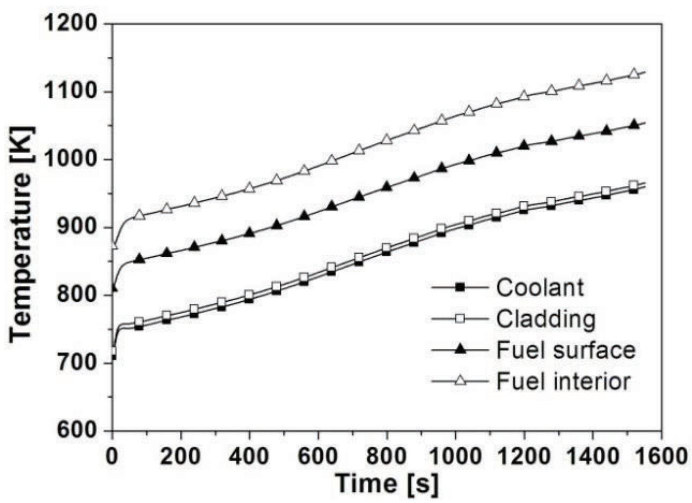

Fig. 7 Temperatures in the hottest channel in ULOHS

For the ADS reactor, in which the Doppler effect and coolant reactivity feedback were not so important, the core power decrease was only 0.35 MW. As the heat sink was lost, the driven force of natural circulation decreased sharply, which led to the decrease of coolant mass flow rate. So all temperatures in the hottest channel increased and the fuel interior temperature was about 1103 K at 1600 s. In the same ULOHS condition, as the driven force of a forced circulation ADS was a pump, the coolant mass flow rate would never change.

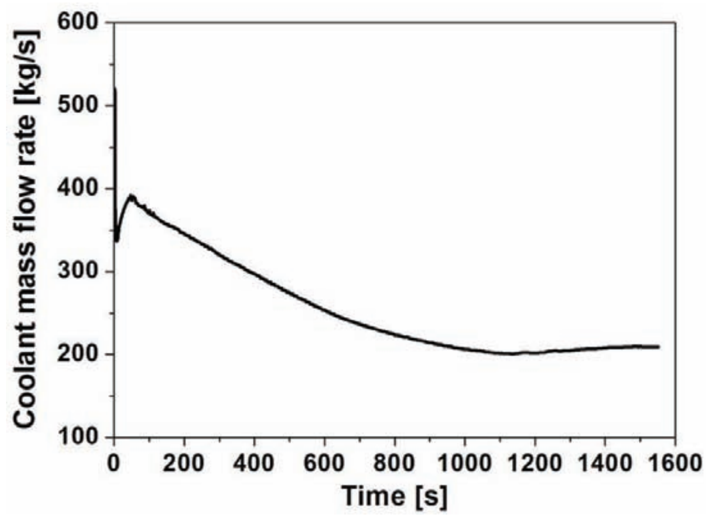

Fig. 8 Coolant mass flow rate in ULOHS

4.3 Unprotected beam overpower

The simulation of unprotected beam overpower transient was performed in this section. This accident is usually caused by the sudden increase of the beam current. In this paper, the accident was assumed to happen at the beginning of cycle (BOC) condition and the beam power had a 100% increase. The reactor would not scram during this accident. The simulation results of UBOP are presented in Figure 9-11.

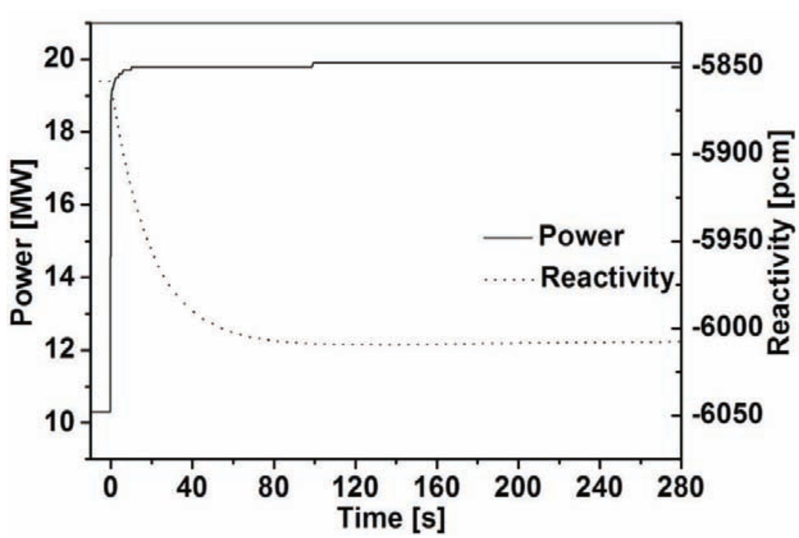

Fig. 9 Core power and reactivity in UBOP

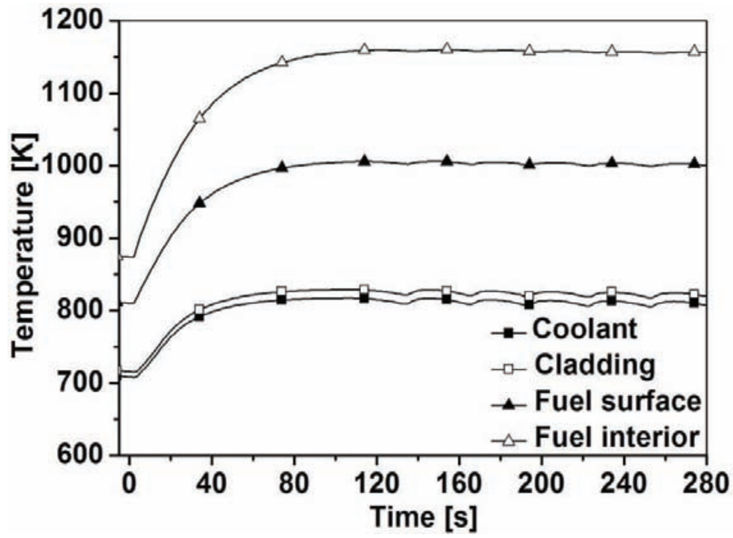

Fig. 10 Temperatures in the hottest channel in UBOP

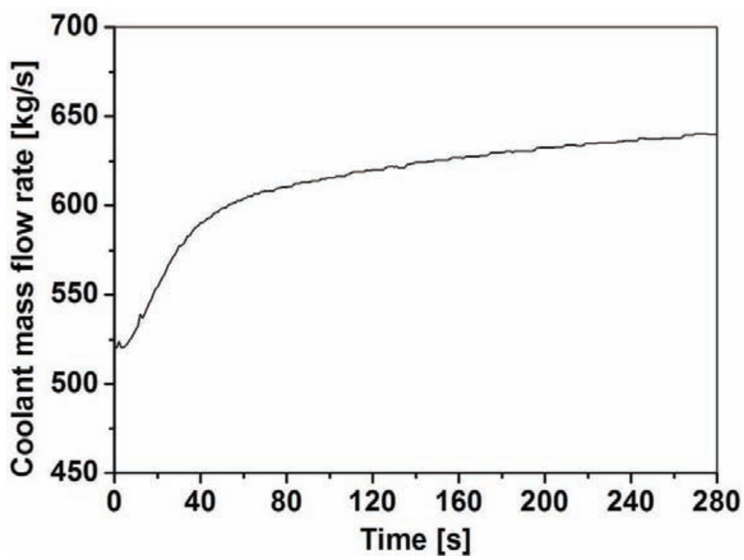

Fig. 11 Coolant mass flow rate in UBOP

As shown in Figure 9, the power increase was about 93% at 120 s, which was caused by the Doppler effect and coolant reactivity feedback. The maximum fuel and cladding temperatures were 1156 K and 824 K respectively, which were both smaller than the safety limits. Due to the natural circulation characteristics, the coolant mass flow rate increased. For a forced circulation ADS with the same power, the coolant mass flow rate would not change and the temperature increases would be bigger than the natural circulation reactor.

4.4 Unprotected transient overpower

In this study, the transient overpower accident was assumed to be caused by the control rod withdraw. The total reactivity insertion of UTOP was assumed to be 0.5 $ (358 pcm) in 1 s. There was no reactor shutdown during the whole transient process. The simulation results are presented in Figure 12-13.

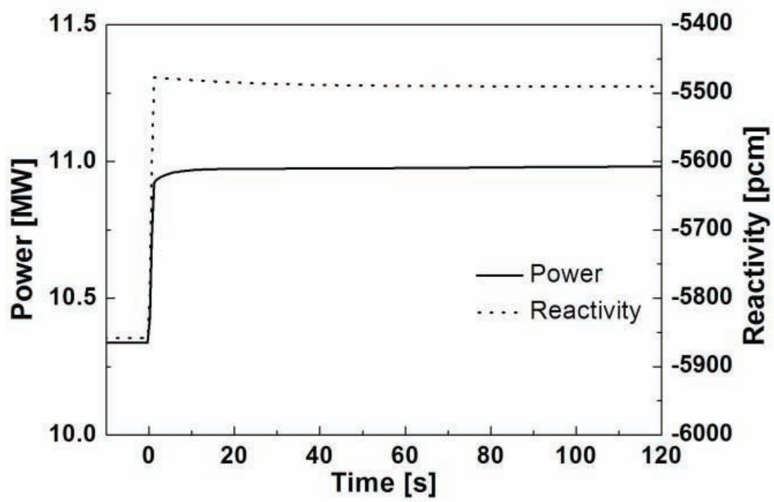

Fig. 12 Core power and reactivity in UTOP

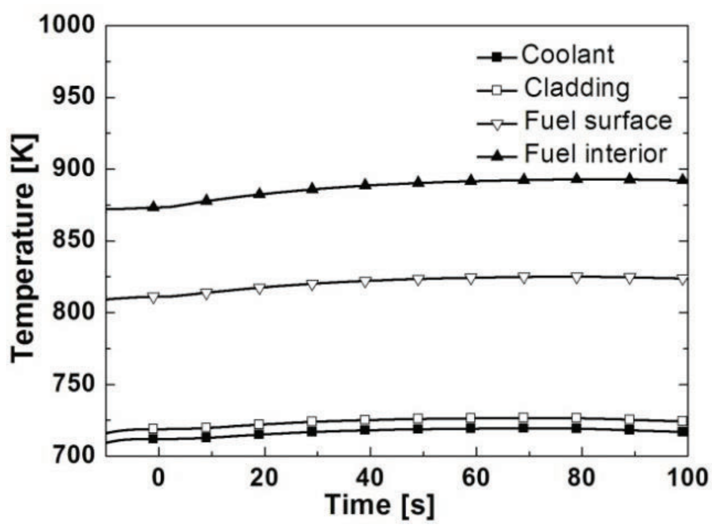

Fig. 13 Temperatures in the hottest channel in UTOP

As shown in the two figures, the core power increase was only about 0.6 MW, all the temperature increases in the hottest channel were small and the fuel interior temperature increase was just 19 K. As the core power increase was unobvious, a very small change of the coolant mass flow rate could remove the more heat caused by the power increase. All those showed good safety characteristics of this natural circulation ADS reactor.

5. Conclusions

The steady operation state and three typical unprotected transient accidents of the 10 MWth natural circulation LBE-cooled accelerator driven system were simulated by NTC-2D, which aimed at the investigation of the safety and natural circulation characteristics of this reactor. The analyses results reveal following:

In steady state simulation, the differences between the calculated and design values were all very small, the natural circulation was successfully established.

The simulation results of ULOHS showed that the core power decrease was only 0.35 MW and the fuel interior temperature was about 1103 K at 1600 s as the coolant mass flow rate decreased heavily caused by the loss of heat sink. The reactor was safe during a short term. The temperatures would increase and exceed the safety limits for a long term.

For UBOP accident with 100% beam current increase, the final core power increase was about 93%. The maximum fuel and cladding temperatures were 1156 K and 824 K respectively. The coolant mass flow rate increased due to the natural circulation characteristics, which could remove the more heat generated by the power increase.

For UTOP transient with 0.5 $ total reactivity insertion in 1 s, the simulation results showed that the increase of the core power was only 0.6 MW. The fuel, cladding temperature and coolant mass flow rate increases were all small, which showed good safety characteristics of this natural circulation ADS reactor.

Acknowledgements

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