DISTURBED TRANSIENT ANALYSIS WITH STABLE OPERATION MODE OF TMSR-SF1

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ABSTRACT

As an innovative reactor, Fluoride salt cooled High temperature Reactor (FHR) possesses many attractive features, such as high temperature, low pressure, dry-cooling. Thermal-hydraulic features of FHR are enormously different from other reactors, which dominate safety and operation characteristics of FHR. Disturbed transient analysis is helpful to fundamental comprehension of safety analysis and operation analysis. The first solid fuel thorium molten salt experimental reactor (TMSR-SF1) is a 10MWth FHR, which is projected by CAS-TMSR center. In this paper, disturbed transient analysis with stable operation mode is performed to refine characteristic parameters of TMSR-SF1. RELAP5/MOD4.0 code with modification is employed for this analysis. Disturbed variables include the followings: reactivity insertion, mass flow of primary loop, mass flow of secondary loop, mass flow in air radiator. Principal operating parameters are analyzed, such as power, temperature of core inlet and outlet, temperature of secondary loop inlet and outlet, characteristic time. These results may provide a basic understanding for safety limits, operating limits and definition of a power control strategy of TMSR-SF1.The final states of TMSR-SF1 under all kinds of disturbed transients tend to be steady, which is a straightforward and intuitive representation of its inherent stability properties. A recommendation of control means for power and temperatures of different loops are provided according to the variation of these variables under disturbance.

KEYWORDS
FHR, thermal-hydraulic, disturbed transient analysis, RELAP5

1. INTRODUCTION

Fluoride salt-cooled High-temperature Reactor (FHR) is an innovative reactor, which uses molten fluoride salt as reactor coolant whose outlet temperature can reach over 700 degrees, works at normal pressure (less than 10 atmospheres), can be dry-cooling. The concept of FHR was originally joint developed by Oak Ridge National Laboratory (ORNL), Sandia National Laboratories (SNL) and the University of California at Berkeley (UCB) during 2001-2003, which inherits the technical foundation and advantages of the six optional fourth-generation reactors, the second- and third-generation reactors, thermal power station. Because FHR has inherited many advantages and technical basis, it’s estimated that it has good economy, security, sustainability and non-proliferation of nuclear, and its commercialization has a very high feasibility in the current technology conditions [1,2]. In China, the Chinese Academy of Sciences (CAS) has initiated a large FHR development program to develop and refine future nuclear energy concepts that have the potential to provide significant safety and economic improvements over existing reactor concepts. The program is leading by Shanghai Institute of Applied Physics (SINAP), which will develop Thorium-based Molten Salt Reactor nuclear energy system (TMSR), and plans to construct a test reactor at first. The first solid fuel thorium molten salt experimental reactor (TMSR-SF1) will be a pebble bed 10MWth reactor, and the design is currently in progress.

Thermal-hydraulic features of FHR are enormously different from other reactors, such as the pebble bed should be considered as a porous media with a given porosity [2], coolant only exists in one phase under normal working condition. Disturbed transient analysis is intuitive and straightforward to comprehend its thermal-hydraulic features and is also important for safety analysis and operation analysis.

From the perspective of operational control, first of all it needs to give the main control quantity which can be adjusted by control system, i.e. control means. In order to select the appropriate main control quantity of the control system, the dynamic characteristics, namely the influence characteristics of the control quantity to the controlled quantity, should be studied before the designing of control scheme. From the perspective of the stability of the reactor, it needs to analyze possible variation of parameters during reactor operation, which also includes the control quantities. As a preliminary transient analysis, the disturbed variables are also the main control means for TMSR-SF1: reactivity insertion, mass flow of primary loop, mass flow of secondary loop, mass flow in air radiator.

As a new type reactor, no specific transient analysis software has been developed for FHR. The RELAP5 [3-5] code is originally designed for transient simulation of the light water cooled power reactors. Thermodynamic properties [6] such as FLIBE, FLINAK and air, were implemented into Relap5/MOD4.0. And a simple heat transfer correlation for forced convection through pebble beds [7] was implemented into Relap5/MOD4.0. In this research, the modified RELAP5 code is used to analyze disturbed transients of the pebble bed type FHR.

2. DESCRIPTION OF TMSR DESIGN

In the current design, the coolant in primary loop is a binary molten salt system of the 66.6%^{7}LiF-33.3%BeF_2 (mol) (flibe) originally used in the molten salt reactor [8], the coolant in secondary loop is FLINAK and the coolant in third loop is air. A schematic design of the reactor core is shown in Fig.1 and the cross sectional view of the reactor core is shown in Fig.2. The reactor is a graphite-moderated thermal reactor composed of the core and reflector, respectively consisting of fuel spheres and high-density graphite. The active region of TMSR is composed of fuel spheres. The active region is 180.0cm high, and the opposite side distances are 139.0cm and 134.6cm. The diameter of experiment and control channels is 13.0cm.

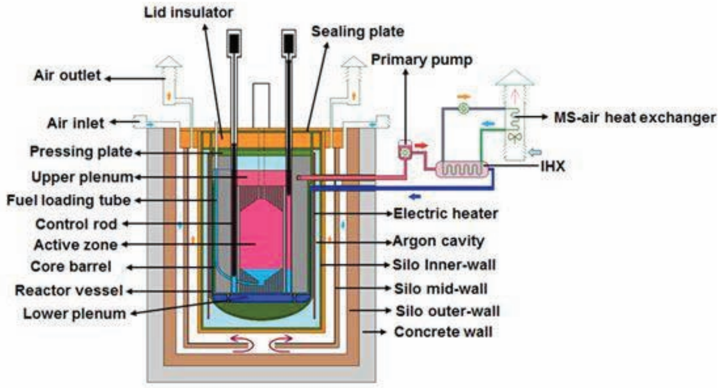


Figure 1. Schematic Diagram of TMSR-SF1.

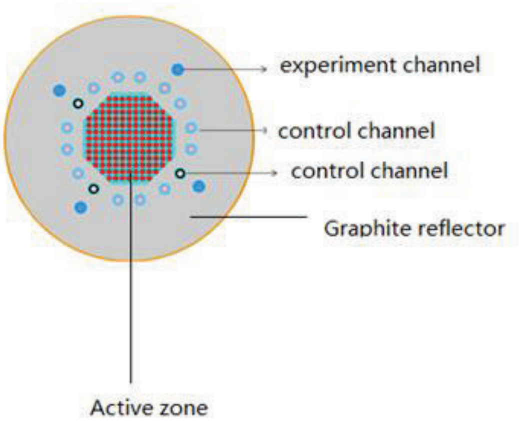


Figure 2. TMSR Cross Sectional View.

The fuel spheres in the fuel pebble zone are static and in ordered arrangement, and the packing fraction is 68.06%. The TMSR uses the spherical fuel elements with TRISO particles containing UO_2. The pebble diameter is 6.0cm and fuel zone diameter is 5.0cm with 0.5cm thickness graphite shell. The TRISO fuel particle consists of a UO_2 fuel kernel surrounded by a porous buffer layer, and successive isotropic layers of dense inner pyro carbon (IPyC), chemically vapor deposited silicon carbide (SiC), and dense outer pyro carbon (OPyC). Fig.3 presents the structure of the fuel pebble, and the geometric and material definitions are listed in Table I. The main design parameters of TMSR are shown in Table II.

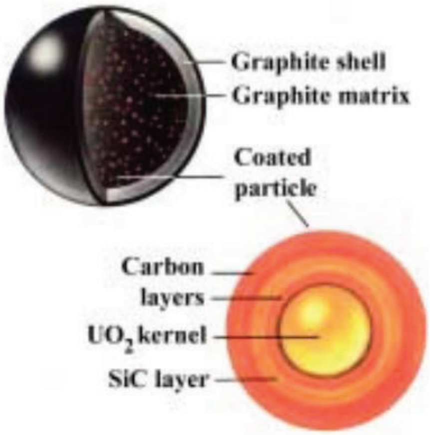


Figure 3. TMSR Fuel Sphere.

Table I. Geometry and composition of TMSR fuel sphere

Region	Parameters	Component Dimension	Value	Material	Density (g/cm3)
Pebble Fuel	Pebble fuel	Outside Radius	30mm		
	Pebble shell	Thickness	5 mm	graphite	1.75
	Active Region	Outer Radius	25 mm	TRISO/ Matrix	1.75
Triso	Fuel Kernel	Outer Radius	250μm	U02	10.40

Particle	Porous Pyrolytic Carbon	Thickness	95μm	Porous PyC	1.05
	Dense Inner Pyro carbon	Thickness	40μm	PyC	1.90
	Silicon Carbide	Thickness	35μm	SiC	3.18
	Dense Outer Pyro carbon	Thickness	40μm	PyC	1.90
	Triso Particle	Outside Particle	460μm		

Table II. Main design parameters of TMSR [8]

parameter	characteristic
fuel	Fuel sphere of 6.0cm
moderator	graphite
Coolant(primary, secondary, third)	FLIBE/FLINAK/Air
Power	10.0MW
Inlet temperature	873.0K
Mass flow of coolant(primary, secondary, third)	150.0,211.0,46.1kg/s
The number of fuel spheres	8317.0
Pressure of core cover gas	0.3Mpa
Fuel temperature coefficient of reactivity	
Active Region of fuel sphere	-0.00365$/K
Pebble shell of fuel sphere	-0.00505$/K
reflector	0.002183$/K
coolant	-0.00197$/K

3. DIDTURBED TRANSIENTS ANALYSIS

The transient analysis of the TMSR reactor is performed by the RELAP5/Mod4.0 code for full power reactor operating condition at the beginning of life. The components of a nuclear reactor are represented with a user-defined nodalization that contains hydrodynamic control volumes and junctions that represent flow paths between control volumes and heat structures. The mathematical models of Relap5/MOD4.0 were based on some fundamental conservation principles: the mass, momentum, and energy conservation equations. The detailed descriptions about these mutual coupled equations can be easily found in Relap5/MOD4.0 manual [3-5]. To model the reactor, Thermodynamic properties, such as FLIBE, FLINAK and air, were implemented into Relap5/MOD4.0. And a simple heat transfer correlation for forced convection through pebble beds was implemented into Relap5/MOD4.0, which was proposed by Wakao and described by Kavinany’s heat transfer handbook [7]. The thermal hydraulics correlations for an ordered pebble bed are obtained by considering the bed as a porous media with a given porosity [1]. Order pebble bed molten salt reactor differs from PWR, when Relap5/MOD4.0 code was used to model the reactor, and some important problems were solved in Ref.[9].

The friction pressure loss is computed using:

$$\Delta p_{fric} = K_e \frac{\rho v_{junc}^2}{2} \tag{1}$$

Where the equivalent value K_e is calculated based on the geometry of the junction between volumes. According to Ergun’s law [10], the friction factor is given by:

$$K_e = \frac{1-\varepsilon}{\varepsilon^3}\left(a\frac{1-\varepsilon}{\mathrm{Re}_d}+b\right) \qquad \mathrm{Re}_\mathrm{d} = \frac{m d_p}{\mu A_\mathrm{c}}$$

Where Re_d is the Reynolds number based on the pebble diameter, the total area Ac of the core, the fluid dynamic viscosity μ and the mass flow m, ε is the porosity. And the values for TMSR are a=180, b=1.95.

In order to model the reflector with the coolant channels, two heat structures have been defined, one on each side of the coolant channels (molten salt channel shown in Fig.4). Heat can then be transferred from the hotter to the colder heat structure, but solely by convection of the molten salt. This way of modeling is very important for transient calculations but that leads to a certain uncertainty.

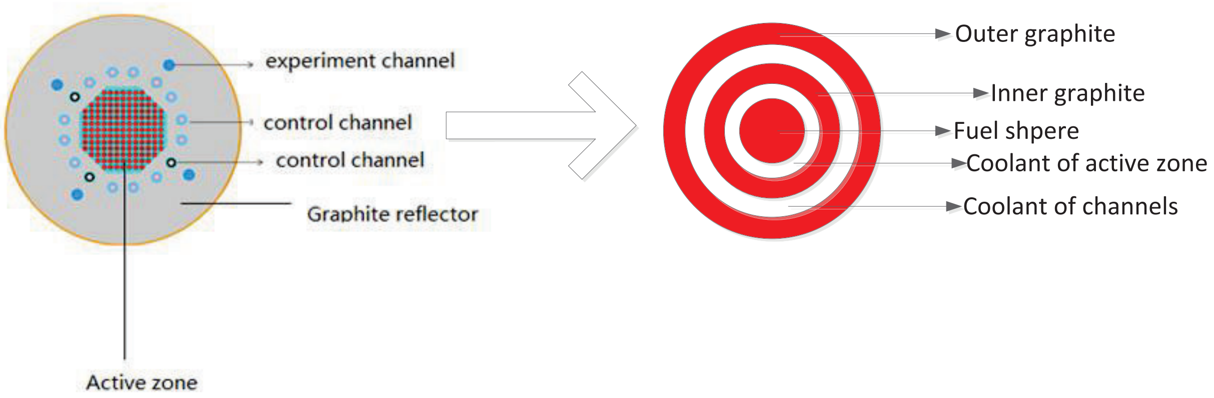


Figure 4. Heat Structure and Molten Channel of Reflector.

For the fuel pebble, it is assumed that the heat source is homogeneously distributed inside the solid fraction of each control volume. The solution of the energy equation with a homogeneous heat source assumption is the average temperature of the solid. During a steady state operation or for slow transient, the time of changing the power with changing reactivity is higher than the relaxation time for the temperature adjustment between fuel kernel and its surrounding graphite. For high temperature reactors, this relaxation time varies from 10^{-2} to 10^{-1} second [11] and the assumption of homogeneous heat source can be justified for steady state and slow transients. For fast transient, where the time of changing reactivity is very small compared to temperature relaxation time, large differences are observed between the results obtained from a homogeneous and a heterogeneous assumption, but the homogeneous model is conservative [12].

The core is divided in two parallel channels and thirteen axial layers, and a portion of the power is allocated to each layer during the steady state conditions. It is important to notice that the axial power profile has been chosen to be fixed and has been determined once from the reference core. The radial and axial power peaking factors are respectively 1.21 and 1.27. Overview of the Relap5 model of TMSR-SF1 is shown in Fig.5.Based on the model constructed, the four disturbed transients are analyzed.

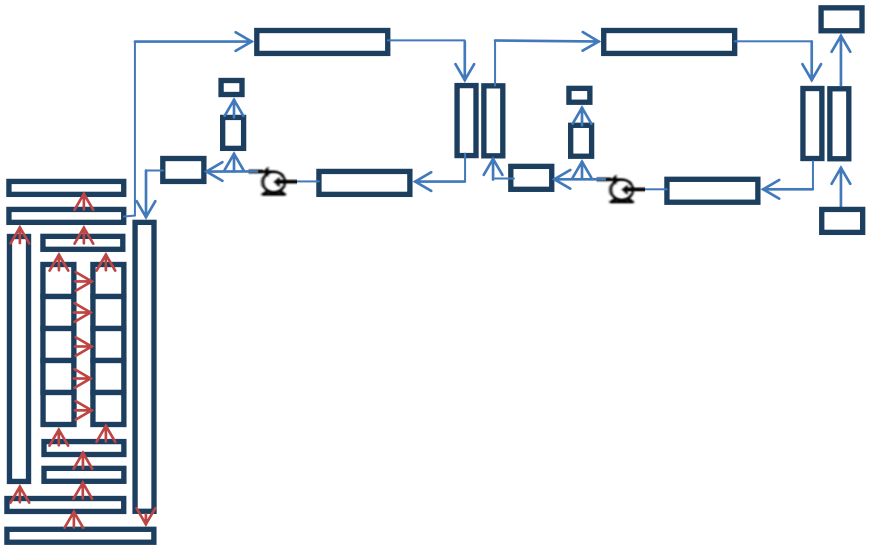
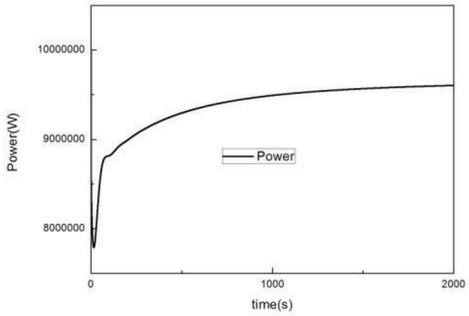
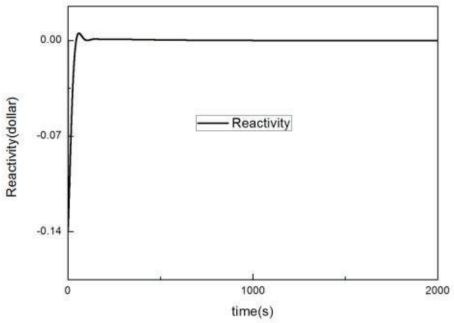


Figure 5. Overview of Relap5 Model of TMSR-SF1.

3.1. Reactivity Insertion

When -0.14$ reactivity is inserted by control rod at t=0.0s, power reaches valley value quickly, lead to a quick decrease of core outlet temperature and a slowly decrease of core inlet temperature, which introduces a positive reactivity, then the power rises again and finally gets to a steady state with a decrease of about 4%. The change of power, reactivity, temperature during the transient are shown in Fig. 6.The temperature of core outlet and inlet varies about 13℃and 12℃ respectively. The temperature of secondary loop changes about 12℃. Reactivity insertion by control rod is an effective means to adjust temperature of primary loop. For power regulation, it can be used to make a quick change but will be mostly offset by self-stability.





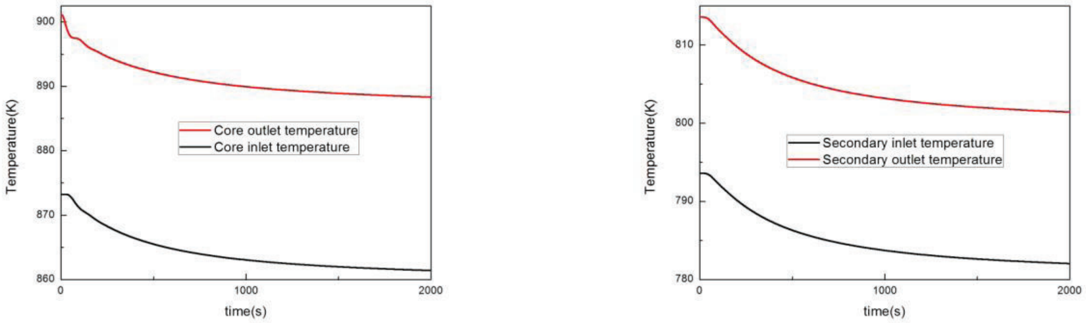


Figure 6. Response of Reactor Under Reactivity Insertion.

3.2. Mass Flow in Primary Loop

When mass flow in primary loop increases 10% by main pump, the core outlet temperature decreases immediately, the positive reactivity inserted by temperature variation causes an increase of power which finally leads to a rise of temperature again, the power tends to be stable with an increase of about 1% after two vibrations. The change of power, reactivity and temperature during the transient are shown in Fig. 7.The temperature of core outlet decreases about 1.6℃, and the inlet temperature increases less than 1℃.Inlet and outlet temperature of secondary loop both increase about 4℃ without vibration. Change mass flow in primary loop by main pump is an effective means to adjust temperature of secondary loop.

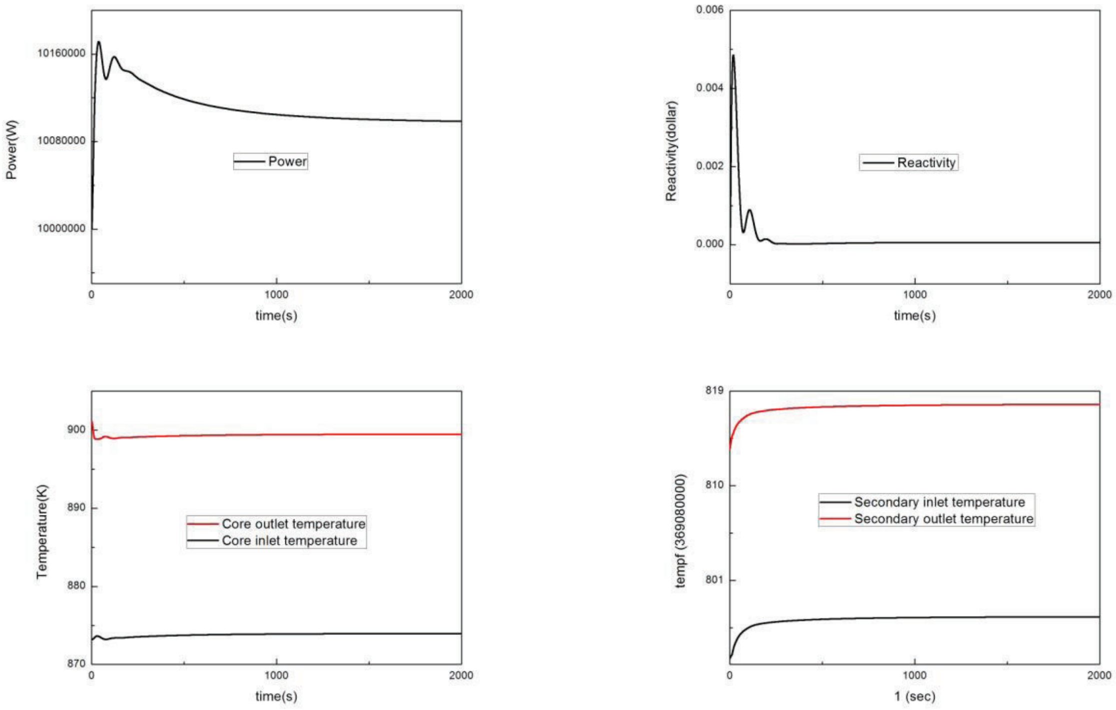


Figure 7. Response of Reactor Under Primary Loop Mass Flow Disturbance.

3.3. -10% Mass Flow in Secondary Loop

When mass flow in secondary loop decreases 10% by pump, the inlet temperature of secondary loop increases immediately, which leads to a slowly rise of primary loop temperature, and the negative reactivity inserted causes an decrease of power which finally leads to a drop of temperature again, the power tends to be stable with an decrease of about 5‰. The change of power, reactivity and temperature during the transient are shown in Fig. 8. The outlet and inlet temperature of core increases less than 1℃.Outlet and inlet temperature of secondary loop changes about 1℃respectively.

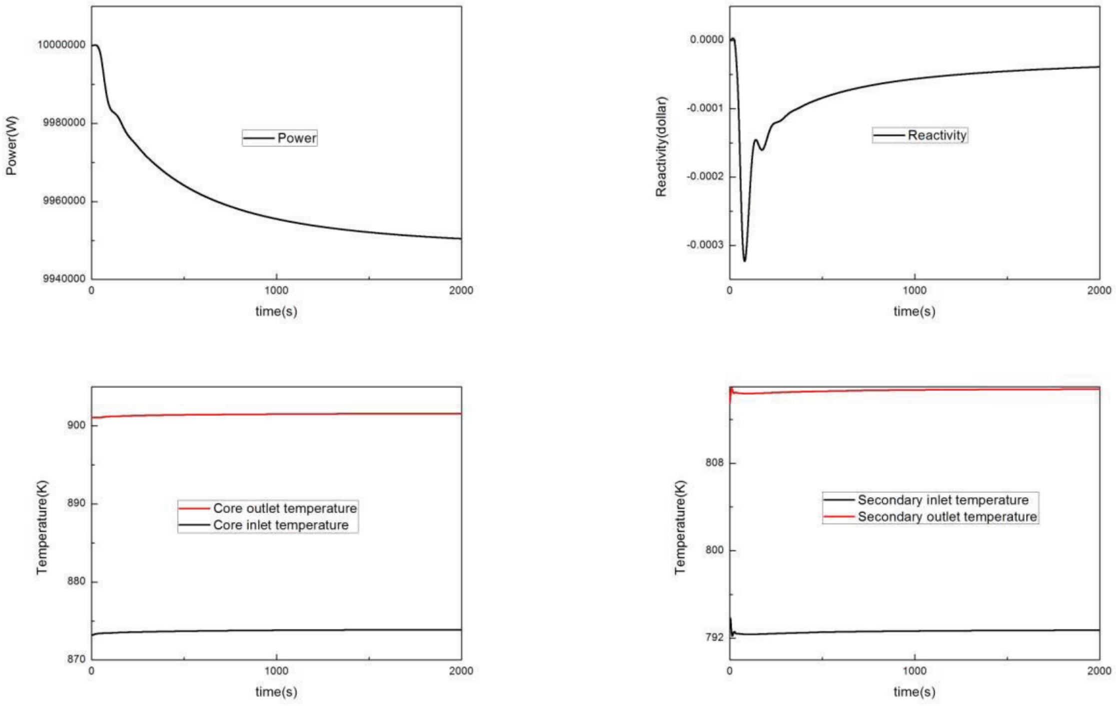


Figure 8. Response of Reactor Under Secondary Loop Mass Flow Disturbance.

3.4. Mass Flow in Air Radiator

When mass flow in radiator increases 10% by fan, outlet temperature of secondary loop decreases immediately, and core inlet temperature decreases accordingly, the positive reactivity inserted by temperature causes an increase of power which finally turns to be stable with an increase of about 4.5%. The change of power, reactivity and temperature during the transient are shown in Fig. 9. The temperature of core outlet and inlet temperature decreases about 5℃.Outlet and inlet temperature of secondary loop decreases about 10℃respectively.Change mass flow in radiator can be an effective means to adjust temperature of secondary loop. TMSR-SF1 has certain self-regulation ability, but it is very sluggish due to large thermal capacity of coolant salt.

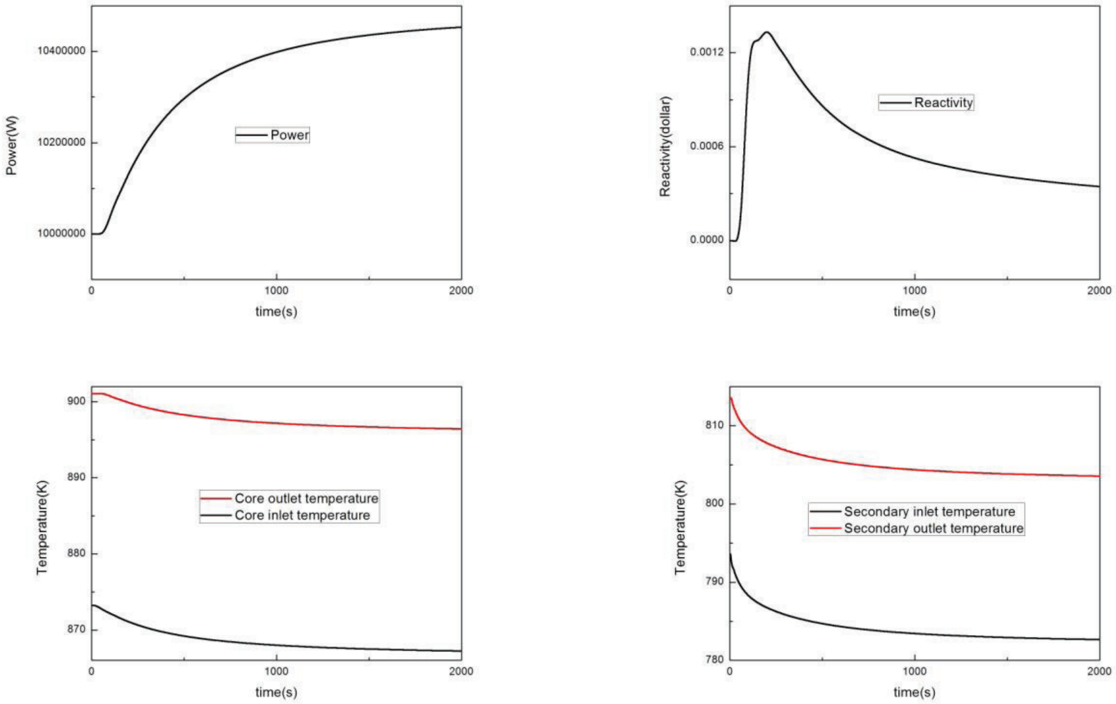


Figure 9. Response of Reactor Under Radiator Mass Flow Disturbance.

4. CONCLUSION

Comprehensive analysis of the disturbed transients: reactivity insertion, mass flow of primary loop, mass flow of secondary loop, mass flow in air radiator shows that the final state of TMSR-SF1 is stable. Though TMSR-SF1 has self-stability, time to reach stability is quite long, which means control system is still needed. For the control of power and temperature, the effective means of power regulation is reactivity introduction by control rods and radiator adjustment at the same time, temperature of primary loop should be adjusted by control rod, varying the speed of the main pump can be used to adjust temperature of secondary loop. A possible control scheme: keeping flow rate of primary loop proportional to reactor power, adjusting temperature of primary loop by control rod and adjusting power by radiator. When control scheme and control system are finally determined, operation transient analysis can be used to check the validity of control system.

REFERENCES

1. C.W. Forsberg, P. Pickard, and P.F. Peterson, "Molten-Salt-Cooled Advanced High-Temperature Reactor for Production of Hydrogen and Electricity, "*Nuclear Technology.* **144**, (2003).
2. Alain Griveau, "Modeling and Transient Analysis for the Pebble Bed Advanced High Temperature Reactor (PR-AHTR), UCBTH-07-001," Department of Nuclear Engineering, University of California, (2007).
3. "Relap5/MOD3.3 Code Manual Volume I: Code Structure, System Models, and solution Methods," Information Systems Laboratories, Inc. Rockville, Maryland Idaho Falls, Idaho (2001).
4. "Relap5/MOD3.3 Code Manual Volume II: User's Guide And Input Requirements," Information Systems Laboratories, Inc. Rockville, Maryland Idaho Falls, Idaho, (2001).

5. “Relap5/MOD3.3 Code Manual Volume IV: Models and Correlations,” Information Systems Laboratories, Inc. Rockville, Maryland Idaho Falls, Idaho (2001).
6. SINAP, 2013,“The technical data of molten salt property parameters ,” XDA02010200-WS-2013-04,Shanghai Institute of Applied Physics.
7. Kaviany M., “Principles of Heat Transfer in Porous Media”, edited by Springer-Verlag (1995).
8. SINAP, 2012,“Pre-conceptual Design of a 2MW Pebble bed Fluoride Salt Coolant High Temperature Test Reactor,” Shanghai Institute of Applied Physics.
9. Y. Yang et al., “Reactivity-insertion-transient Analysis of a Fluoride Salt Cooled High Temperature Reactor,” *PHYSOR 2014 – The Role of Reactor Physics Toward a Sustainable Future*, The Westin Miyako, Kyoto, Japan, September 28 – October 3, on CD-ROM (2014).
10. Ergun s., “Fluid Flow Through Packed Columns,” *Chem.Eng.PRog*. **48**(89), **(**1952).
11. Siemens. ZKIND manual. Siemens AG, Power Generation Group (KWU), first edition, 1980.
12. Yan-hua. Zheng, Lei. Shi, Fu-bing. Chen, “Coated Fuel Particle Temperature Analysis of the Pebble-bed Modular High Temperature Gas-cooled Reactor,” *Progress Report on China Nuclear Science & Technology.* **2**, (2011).