Analysis and Research on Vehicle-mounted Mobile Nuclear Power System

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Abstract

Heat pipe cooled reactors have the characteristics of small size and high reliability, and have been widely used and studied in many system-design schemes for deep space exploration and vehicle mobility. In this paper, the vehicle-mounted mobile heat pipe reactor system MNPS-1000 with an output electric power of 1MW is selected as the research object, and a SIMULINK model for the whole system simulation including the reactor model and the energy conversion system model is established. Through comparing the simulation results of the system model with the design calculation values, the rationality of the model establishment is verified, and the maximum relative deviation does not exceed 5.4%. The model provides an effective tool for analyzing the system dynamic characteristics of MNPS-1000.

Keywords: Mobile nuclear power system, SIMULINK, System Modeling, System Analysis

1. Introduction

With the rapid development of the economy and the changing world situation, energy issue has become an important issue at the national strategic level. Compared with non-renewable resources such as oil and coal, as well as new energy sources like wind power and hydropower, nuclear energy has a greater advantage in terms of long-term stable power supply. For individual areas that cannot be connected to the grid, such as plateaus and isolated islands, small modular reactors can give full play to their many advantages, including small size, fewer environmental constraints, high power density, and high safety. According to the definition of the International Atomic Energy Agency (IAEA), small modular reactors (SMRs) are a type of advanced nuclear reactor, and the power of each unit does not exceed 300 MWe. At present, research institutions in various countries have proposed design schemes for small modular reactors based on large reactors such as pressurized water reactors and high temperature gas-cooled reactors. Microreactors are a subcategory of SMRs, and their designed power generation usually does not exceed 10 MWe. They have important application value and application prospects in special fields such as deep sea and deep space, and have attracted widespread attention from various countries. At the same time, China has successively released relevant technological innovation plans and development routes, including vehicle-mounted mobile nuclear power systems, deep-sea nuclear reactors, space nuclear power and other micro-nuclear energy systems as key research areas.

As an important application of micro-nuclear energy systems, mobile nuclear power systems based on microreactors have the characteristics of convenient transportation and arrangement, strong adaptability, etc. And it can be used as a mobile, high-power, stable and reliable power supply source. The heat pipe cooled reactor is a research hotspot among many microreactors, and has received special attention because of its high safety and good adaptability. Unlike traditional reactors that use coolant to dissipate heat from the core, heat pipe cooled reactors use high-temperature alkali metal heat pipes as the core heat transfer components to output heat to the energy conversion system. Aiming at different application environments, research institutions in various countries have carried out many studies on heat pipe cooled reactor nuclear energy systems. In 2012, NASA [1] of the United States started the research and development of Kilopower, a small heat pipe reactor system for deep space exploration, proposed a design scheme for a metal fuel-based compact reactor and high-temperature sodium heat pipe, and completed the nuclear operation test verification of the land test reactor KRUSTY [2] in 2018. For the vehicle-mounted mobile application scenario, the US LANL designed and studied the vehicle-mounted mobile heat pipe cooled reactor system Megapower [3], and the US Westinghouse Corporation proposed a vehicle-mounted mobile heat pipe cooled reactor system named eVinci [4]. In China, the NPIC, China Academy of Engineering Physics, Tsinghua University, Xi'an Jiaotong University and many other research units have carried out research on heat pipe analysis methods and nuclear energy system design, involving applications in deep space, deep sea, and vehicles.

Compared with large nuclear reactors, the vehicle-mounted mobile heat pipe cooled reactor nuclear energy system has the characteristics of compact structure and strong correlation between different equipment. Therefore, it is necessary to carry out research on the operating characteristics of the vehicle-mounted mobile heat pipe cooled reactor nuclear energy system, conduct system modeling and analysis, and determine that the design scheme of the reactor system and energy conversion system is reliable. Regarding the research on the system analysis model, many researchers have carried out work on their respective heat pipe cooled reactor systems. Zhang Z et al [5] developed a heat pipe cooled reactor transient analysis code HEART based on the conceptual design of Nuclear Silent Thermal-Electrical Reactor (NUSTER), which includes point reactor kinetics model, multi-channel model, core heat transfer model, heat pipe model, thermoelectric generator model, and coolant model, the steady-state performance of NUSTER was predicted using the HEART code. Yuan Y et al [6] took the typical heat pipe cooling space reactor power system SAIRS as the object, developed the system transient program TAPIRS, the model of the program mainly includes neutron dynamics model, core heat transfer model, heat pipe model, alkali metal thermoelectric conversion Device (AMTEC) energy conversion model and heat sink model. Ma Y et al [7] developed a heat pipe cooled reactor transient analysis code HPRTRAN, and used this code to analyze the thermodynamic characteristics of MegaPower reactor in heat pipe failure accidents. However, the heat pipe cooled reactor system design scheme is specific, and the reactor system and energy conversion system vary greatly between different schemes, and modeling and analysis for specific objects are required.

In this paper, taking the vehicle-mounted mobile nuclear power system MNPS-1000 as the object, the system analysis model is established by using the software SIMULINK, and the simulation value is compared with the design value to verify the correctness of the model establishment and analyze the steady state of MNPS-1000 performance.

2. MNPS-1000 Design

MNPS-1000 [8] is a conceptual design of megawatt-level mobile nuclear power system based on heat pipe cooled reactors and combined cycle energy conversion systems, led by the Advanced Nuclear Energy Team of Tsinghua University and jointly proposed by multiple research institutes. The system includes heat pipe cooled reactor, reactivity control system, heat pipe heat exchanger, open Brayton cycle system, closed Rankine cycle system and many other equipment and components. Fig. 1 shows the basic composition of MNPS-1000.

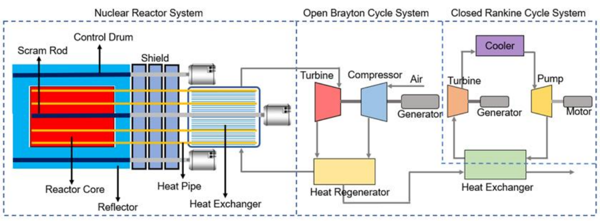

Fig. 1. The basic composition of MNPS-1000.

The reactor of MNPS-1000 is designed to provide 3MWt at full power for 3000 days, and utilizes the energy conversion system to generate about 1MWe. In terms of composition, the system can be divided into the reactor part and the energy conversion part, in which the heat pipe heat exchanger is used as the exchange device between the two parts to realize the energy transfer and dynamic response transfer of the two parts. The fission heat generated by the core is passively transferred to the heat pipe heat exchanger through the high-temperature heat pipes to heat the air flowing in the Brayton cycle, and the heated air directly enters the turbine to generate electricity. Before being released to the environment through the open Brayton cycle, part of the waste heat in the air is utilized by the closed Rankine cycle to further improve the energy conversion efficiency of the system. The advantage of the combination of these two cycles is to realize the gradient use of heat energy, so that the energy conversion efficiency of the system can reach 33.3%.

In the design scheme of MNPS-1000, the parameter matching calculation of the combined cycle system was carried out, and the parameter matching results of each point are shown in Fig. 2. In the results and discussions section, the system parameter matching calculation results is used as the basis for model parameter adjustment, and compared with the model simulation values after adjustment, to verify the correctness of the model.

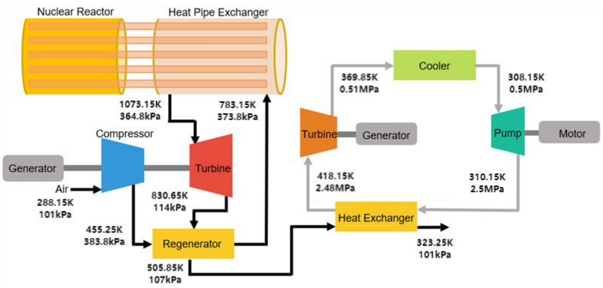

Fig. 2. The results of System parameter matching calculation.

3. Method and Model

The heat pipe cooled reactor nuclear energy system is characterized by compact structure and strong equipment coupling. Due to the strong coupling relationship between the reactor system and the energy conversion system, the interaction between the two needs to be considered when building the model. For the convenience of modeling and simulation requirements, the system analysis method based on lumped parameters and partition coupling is used for research. And the reactor core, heat pipe, heat pipe heat exchanger, and each part of the energy conversion system are modeled. This analysis method can realize fast and complete dynamic characteristic analysis of the whole nuclear energy system. Meanwhile, it provides reference for scheme design and safety analysis.

3.1 Reactor Model

The reactor core of MNPS-1000 is composed of 36 regular hexagonal fuel assemblies and a central control assembly, surrounded by radial reflector, top reflector, and bottom reflector. In the radial reflector, 12 control drums for control are evenly distributed. A total of 216 heat pipes are inserted in the core, that is, each fuel assembly has 6 heat pipe holes.

3.1.1 The equation of point reactor kinetics

The equation of point reactor kinetic is used to describe the dynamic characteristics of the fission power change in the reactor. In the MNPS-1000 model, the equations of point reactor neutron dynamic containing six groups of precursor of delayed neutron are used to solve the power variation with time, as follows:

$$\begin{cases} \dfrac{dn(t)}{dt} = \dfrac{\rho(t)-\beta}{\Lambda} n(t) + \sum_{i=1}^{6} \lambda_i C_i(t), \\ \dfrac{dC_i(t)}{dt} = \dfrac{\beta_i}{\Lambda} n(t) - \lambda_i C_i(t), i = 1, 2, ..., 6 \end{cases} \quad (1)$$

where n is the neutron density, β_i is the fraction of group i-th delayed neutrons, $\beta = \sum_{i=1}^{6} \beta_i$ is the total fraction of delayed neutrons, C_i is the concentration of group i-th delayed neutron precursors, λ_i is the decay constant of group i-th delayed neutron precursors, Λ is the neutron generation time, and ρ is the reactivity of the reactor.

The parameters in the equations of point reactor neutron dynamic are calculated by Monte Carlo code RMC [9], as shown in Table 1.

Table 1. The dynamic parameters of MNPS-1000

i-th group	1	2	3	4	5	6
β	0.0068					
Λ(s)	4.829E-07					
β_i	0.000231	0.001236	0.001175	0.002578	0.001097	0.000476
λ_i(s^{-1})	0.013339	0.032709	0.120830	0.303420	0.852130	2.862000

3.1.2 Reactivity Feedback

Unlike traditional pressurized water reactors, the heat pipe cooled reactor used in MNPS-1000 does not need to consider coolant temperature feedback, density feedback, and cavitation effect, but it needs to focus on detailed research on fuel doppler feedback, fuel expansion feedback, and heat pipe power feedback, etc. Based on the existing research results, it is considered that the reactivity composition of the heat pipe stack at time t should include:

$$\begin{aligned} \rho(t) &= \rho_0 + \rho_{ext}(\mathrm{t}) + \rho_d(\mathrm{t}) + \rho_e(\mathrm{t}) \\ &+ \rho_h(\mathrm{t}) + \rho_Q(\mathrm{t}) + \rho_{rr}(\mathrm{t}) + \rho_{ru}(\mathrm{t}) + \rho_{rl}(\mathrm{t}) \end{aligned} \quad (2)$$

where ρ_0 is the initial reactivity, ρ_{ext} is the externally introduced reactivity, ρ_d is the fuel doppler feedback, ρ_e is the fuel expansion feedback, ρ_h is the heat pipe temperature feedback, ρ_Q is the heat pipe power feedback, ρ_{rr}, ρ_{ru} and ρ_{rl} are the temperature feedback of radial reflector, top reflector and bottom reflector individually. Among them, the temperature-dependent reactivity feedback coefficient can be directly solved by using RMC. According to the existing research [10], the fuel deformation feedback coefficient and the heat pipe power feedback coefficient can also be calculated using OpenFOAM for thermal-mechanical coupling.

3.1.3 Core Model

Due to the high symmetry of the core, in order to more accurately simulate the temperature distribution of the fuel assemblies inside the core, the lumped parameter method was used to select the 1/6 reactor as the object for multi-layer modeling of the reactor model, as shown in Fig. 3. According to the symmetrical boundary, the 1/6 reactor fuel area is equivalently divided into 1 inner layer assembly, 2 middle layer assemblies, and 3 outer layer assemblies. The assembly uses W-Fe-based dispersed UC particle fuel, and the enrichment distribution of the three-layer fuel assembly increases from the inside to the outside.

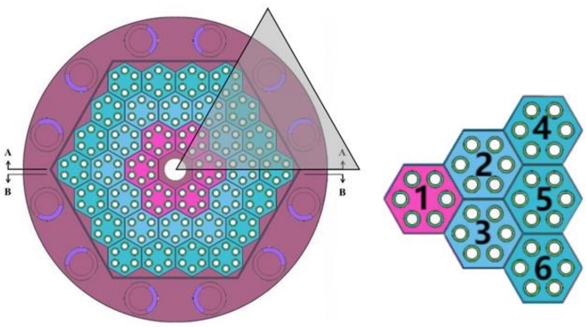

Fig. 3. Selection of 1/6 reactor (left) and equivalent fuel assembly (right).

In the equivalent fuel assembly, it is considered that the components conduct heat with each other, and there is a heat transfer process with the top reflector and the bottom reflector, and only the outer layer of the assembly has heat transfer with the radial reflector. Among them, the heat transfer between the component and the reflective layer is gap heat conduction, which is simplified into two processes of heat conduction and heat radiation.

Considering the gap heat conduction between the fuel assembly and the reflective layer, and the contact heat conduction between adjacent fuel assemblies, the temperature at the center point of each assembly is taken to represent the assembly temperature, and the temperature conservation equation is established.

Taking the inner layer fuel assembly as an example, it conducts heat conduction with the two middle layer assemblies through their respective contact surfaces, and conducts heat conduction with the top reflective layer and bottom reflective layer through gaps. The temperature conservation equation is as follows:

$$m_f c_{pf} \frac{dT_1}{dt} = Q_{fission1} - Q_{pipe1} - Q_{top1} - Q_{bottom1} - Q_{contact12} - Q_{contact13} \tag{3}$$

where m_f is the mass of the inner fuel assembly, c_{pf} is the specific heat capacity of the fuel assembly, $Q_{fission1}$ is the fission heat generated by the inner fuel assembly, Q_{pipe1} is the sum of the heat absorbed by the heat pipes in the inner fuel assembly, Q_{top1} is the heat conduction in the gap between the inner fuel assembly and the top reflector, $Q_{bottom1}$ is the gap heat conduction between the inner fuel assembly and the bottom reflector, $Q_{contact12}$ and $Q_{contact13}$ are the contact heat conduction between the inner fuel assembly and the two middle fuel assemblies.

The temperature conservation equations of the other five fuel assemblies are similar in form to (3). Because the three-layer fuel assembly uses different fuel core enrichment, and the location of the assembly is different, the fission heat generated by the fuel assembly in the conservation equation is different. The fission heat of the corresponding fuel assembly can be calculated by the point reactor kinetic model and the power peak factor, and the relative power density distribution of the MNPS-1000 reactor core has been calculated using RMC in previous studies.

3.1.4 Reflector Model

The reflective layer is divided into a radial reflective layer, a top reflective layer and a bottom reflective layer, all of which are made of beryllium oxide. The radial reflection layer is a hollow cylindrical structure, the inner surface is coupled with the fuel for heat transfer, the outer surface is arranged with an insulation layer, and the outer surface of the insulation layer and the environment are convective heat transfer. The temperature conservation equation based on the lumped parameter method is as follows:

$$m_r c_{pr} \frac{dT_{radial}}{dt} = Q_{radial} - Q_{envR} \tag{4}$$

Where, m_r is the mass of the radial reflector, c_{pr} is the specific heat capacity of the radial reflector, Q_{radial} is the heat conduction in the gap between the fuel and the radial reflector, and Q_{envR} is the natural convection heat exchange between the radial reflector and the environment.

The top and bottom reflector temperature conservation equations are similar to (4), the difference lies in their structure. The top reflector is a cylindrical structure with holes, and a heat pipe is inserted in the middle. The bottom reflector is a cylindrical structure without holes.

3.1.5 Heat Pipe Model

The high-temperature heat pipe model uses the network thermal resistance model [11] to simplify the description. The basic principle is shown in Fig. 4. It is divided into 6 sub-regions to establish the energy conservation equation. In this model, the heat transfer process is simplified as solid heat conduction, and the temperature drop caused by the steam flow in the tube is ignored, so that the fast calculation of the transient performance of the heat pipe can be realized.

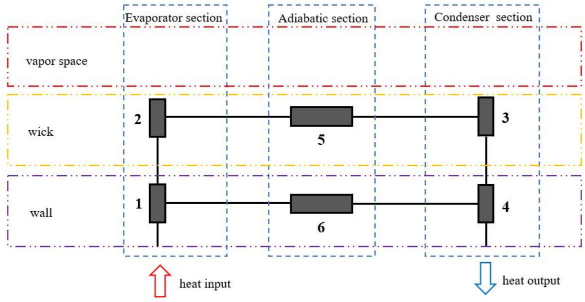

Fig. 4. Network thermal resistance model of heat pipe.

The equation for the node is as follows:

$$\frac{dT_i}{dt} = \frac{2\boldsymbol{\alpha}_i}{\boldsymbol{\lambda}_i^2}(T_{i,1} + T_{i,2} - 2T_i) \tag{5}$$

where T_i is the center temperature of the thermal resistance, $T_{i,1}$ and $T_{i,2}$ are the temperatures of the left and right ends of the thermal resistance respectively, $\boldsymbol{\alpha}_i$ is the thermal diffusion coefficient, and $\boldsymbol{\lambda}_i$ is the thickness of the thermal resistance.

3.2 Energy Conversation System Model

Due to the complexity of the energy conversion system model, a modular modeling approach is used. In the previous research, basic modules such as the control body module, the connector body module, the heat transfer module, the compressor module, the turbine module and the working medium pump module have been established. A simple functional description of the basic modules is given below.

The control body module obtains the output flow rate of two adjacent connecting body modules and the temperature output by the previous connecting body module, calculates the pressure and outlet temperature, and outputs the pressure to the two adjacent connecting body modules, and outputs the outlet temperature to the next connecting body module. For the state calculation of the working fluid whose state change passes through the gas-liquid two-phase region, since the pressure and temperature of the working fluid in the gas-liquid two-phase region are not independent of each other, the specific internal energy is used instead of the temperature.

The connection body module obtains the output pressure of two adjacent control body modules and the temperature output by the previous control body module, calculates the flow rate and outlet temperature, and outputs the flow rate to the two adjacent control body modules, and outputs the outlet temperature to the next control body module. The working fluid treatment of the state change through the gas-liquid two-phase region is similar to that of the control volume module.

The heat transfer module obtains the temperature of the back-end heat transfer module and the input heat flow of the front-end heat transfer module, and calculates the heat flow to each heat transfer module at the back end.

The compressor module and the turbine module are modeled similarly for both modules. They all calculate torque, mass flow, and outlet temperature based on inlet pressure, outlet pressure, inlet temperature, and rotational speed.

The modeling of the working fluid pump module is similar to that of the compressor module, except that the specific internal energy is used instead of temperature for calculation.

The energy conversion system of MNPS-1000 consists of an open Brayton cycle and a closed Rankine cycle. Through the combined use of basic modules, equipment models in two cycles can be established, such as heat pipe heat exchanger, regenerator, and heat exchanger.

4. Results and Discussions

According to the research on the analysis method of the vehicle-mounted mobile nuclear power system mentioned above, the SIMULINK model of each equipment except the cooler is established.

In the Brayton cycle, the temperature and pressure of the compressor inlet air are set as the boundary conditions. Meanwhile, in the Rankine cycle, the boundary conditions are used to replace the function of the original cooler. Specifically, the given specific internal energy and pressure are used as the inlet boundary conditions of the working fluid pump, and the given pressure is used as the outlet boundary conditions of the turbine. Combining the reactor model and the energy conversion system model, according to the connection relationship in Fig. 2, a simulation model of the vehicle-mounted mobile nuclear power supply system is built, as shown in Fig. 5.

After the model is established, it is necessary to perform steady-state adjustment of the system. To be specific, each equipment model is isolated, the import value is given, and the model parameters are adjusted to make the export simulation value close to the design calculation value.

After the system adjustment is completed, compare the operation simulation value of each device with the parameter matching calculation value in Fig. 2, as shown in Table 2.

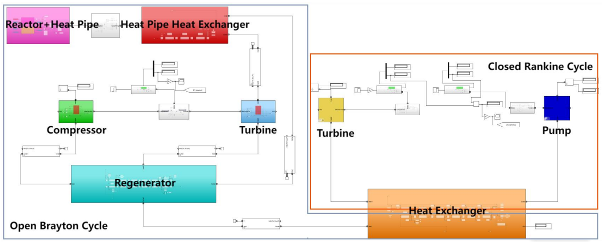

Fig. 5. MNPS-1000 whole system simulation model in SIMULINK.

Table 2. Comparison of model simulated and calculated values

Parameter	Design calculation value	Simulation value	Relative deviation (%)
Thermal power (MW)	3.00	3.00	0.00
Fuel average temperature (K)	1338.71	1384.00	3.38
Heat pipe condensing section temperature (K)	1212.20	1212.00	0.02
Heat pipe heat exchanger inlet temperature (K)	783.15	783.86	0.09
Heat pipe heat exchanger inlet pressure (kPa)	373.80	379.81	1.61
Heat pipe heat exchanger outlet temperature (K)	1073.15	1071.85	0.12
Heat pipe heat exchanger outlet pressure (kPa)	364.80	370.11	1.46
Turbine (Brayton) outlet temperature (K)	830.65	836.75	0.73
Turbine (Brayton) outlet pressure (kPa)	114.00	116.71	2.38
Compressor outlet temperature (K)	455.25	454.09	0.25
Compressor outlet pressure (kPa)	383.80	385.24	0.38
Regenerator hot side outlet temperature (K)	505.85	510.49	0.92
Regenerator hot side outlet pressure (kPa)	107.00	112.78	5.40
Working fluid pump outlet temperature (K)	310.15	310.15	0.00
Working fluid pump outlet pressure (MPa)	2.50	2.49	0.40
Turbine (Rankine) inlet temperature (K)	418.15	420.14	0.48
Turbine (Rankine) inlet pressure (MPa)	2.48	2.49	0.40
Heat exchanger hot side outlet temperature (K)	323.25	328.23	1.54
Heat exchanger hot side outlet pressure (kPa)	101.00	101.00	0.00
Brayton cycle flow (kg/s)	9.20	9.25	0.54
Rankine cycle flow(kg/s)	6.50	6.52	0.31

In order to distinguish the parameter values of the two cycles, the open Brayton cycle is prefixed with A and numbered from the compressor inlet; the closed cycle is prefixed with B and numbered from the pump inlet. The temperature relative deviation curve of the nodes is shown in Fig. 6, and the pressure relative deviation curve is shown in Fig. 7. Since A1, B1, and B4 are set boundary conditions, these nodes are not drawn.

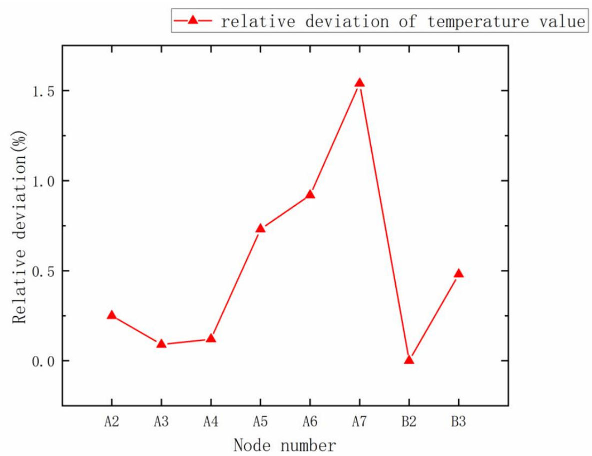

Fig. 6. The temperature relative deviation curve of the nodes.

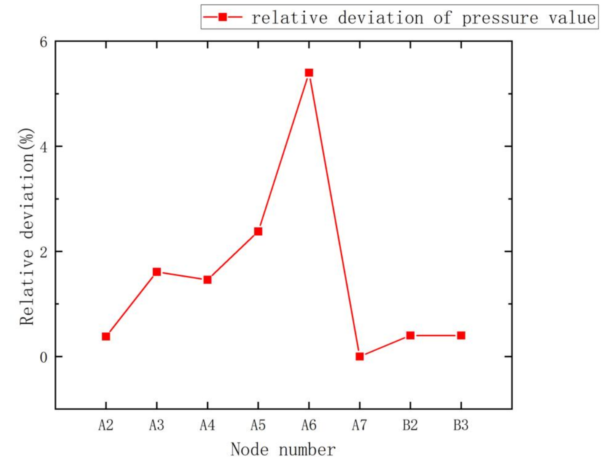

Fig. 7. The pressure relative deviation curve of the nodes.

It can be seen from Fig. 6 and Fig. 7 that the relative deviation between the simulated value and the calculated value of each node is small, all within 6%. Among them, the maximum relative deviation of temperature appears at point A7, which is the outlet of the gas side of the heat exchanger, which is 1.54%. The maximum relative deviation of pressure occurs at point A6, that is, at the outlet of the hot side of the regenerator, which is 5.4%. Reasons for this situation may include:

1) The parameter matching calculation value is an estimated setting value, which is not strictly self-consistent, and the factors and assumptions considered are different from those of the simulation.

2) The parameters of the steady-state adjustment of the system are not completely consistent with the calculated values of the parameter matching, and the resulting errors are accumulated layer by layer, resulting in slight differences.

From the perspective of nuclear power system safety analysis, it is considered that the established MNPS-1000 whole system SIMULINK model basically meets the requirements of transient analysis and safety analysis.

5. Conclusions

This paper takes the conceptual design of the vehicle-mounted mobile nuclear power system MNPS-1000 as the object, and uses SIMULINK to establish a whole-system simulation model. Comparing the simulation value of the model at the steady state point with the design calculation value, the maximum relative deviation is within 6%. It is considered that the built model basically meets the requirements of transient analysis and safety analysis. In the future, based on the established MNPS-1000 system analysis model, the research on the dynamic process of the system will be carried out and the dynamic characteristics will be analyzed.

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