Thermal-hydraulic simulation of the primary loop of the HTR

ZHOU Yangping, WU Mengbai, ZHU Shutang, MA Yuanle, LI Fu, SHI Lei, and DONG Yujie

Institute of Nuclear and New energy Technology, Tsinghua University, Beijing, 100084 China (zhouyp@mail.tsinghua.edu.cn, jeffwmb@gmail.com, zhust@mail.tsinghua.edu.cn, mayl@mail.tsinghua.edu.cn, lifu@mail.tsinghua.edu.cn, shlinet@mail.tsinghua.edu.cn, dongyj@mail.tsinghua.edu.cn)

Abstract: Simulation of thermal-hydraulic processes taking place in the primary loop of the HTR (High Temperature gas–cooled Reactor) plays an important role in the development of a full scale HTR simulator. The thermal-hydraulic processes in the primary loop of the HTR are analyzed based on the design data and the current computational code. Then, various components of the primary loop are modeled, including the steam generator, the blower, and the pipeline. In addition, conservation of mass, momentum and energy and properties of the helium gas in the primary loop are analyzed in this paper. A methodology is proposed to solve the conservation equations. The computational code for simulating the primary loop of the HTR is developed using the FORTRAN language. The simulation results obtained using the computational code and the calculation results output by the THERMIX code are in close agreement with each other, which enables to verify the models and the methodology advanced in this paper.

Keyword: thermal-hydraulic simulation; simulator; primary loop; HTR

1 Introduction

The first commercial High Temperature gas-cooled Reactor (HTR) project, HTR-PM [1,2] (Pebble bed Module), which is designed by the Institute of Nuclear and new Energy Technology, Tsinghua University, and will be constructed with the cooperation of the China Huaneng Group and the China Nuclear Engineering & Construction Corporation, has already started at the end of 2006 in Shandong province, China. Preliminary studies show that the HTR–PM is feasible technologically and economically [3,4].

The development of a full scale simulator of the HTR-PM is an indispensable part of the HTR project which has to be carried out from the pre-commission stage. The availability of a simulator prior to fuel loading or commission will be beneficial to the safety and economy of the plant's operation. Early plant-specific training can help operators and others to familiarize with the Distributed Control System (DCS) and the Human Machine Interface (HMI), the checkout operation procedure, the validation of the DCS, and so on. The development of a simulator on the basis of design data and experience requires flexibility to meet the requirements and for the probable changes caused by frequent of design data with the progression of the HTR project until the plant construction.

The newly designed HTR-PM is in some aspects different from the experimental high temperature gas cooled reactor HTR-10 [5,6]. The HTR-10 was designed and constructed by the Institute of Nuclear and New Energy Technology and reached criticality in 2001. The thermal-hydraulic processes in the primary loop of the HTR-PM is conceptually similar to the ones of the HTR-10.

In this paper, a thermal-hydraulic model is proposed to simulate the thermal-hydraulic processes in the outside-core part of the primary loop of the HTR. The simulation models and the methodology proposed in this paper can be easily applied to the simulation of the HTR-PM, since it is based on the design data and analysis results of the HTR-10. A thermal-hydraulic simulation is adopted to describe the change of temperature, pressure and flow rate of helium gas in the primary loop. The governing equations according to the conservation of mass, momentum and energy are computed to model the thermal-hydraulic processes. Models of the components in the primary loop such as hot gas duct, steam generator and helium

---

Received date :September 29, 2009
Revised date: November 22, 2010

blower are proposed to describe their thermal and hydraulic properties.

In this paper, the calculation results produced by the present model are compared with another analysis program called THERMIX [7,8] in order to verify the accuracy of the simulation models developed by the authors of this paper. The THERMIX code was developed by the German Julich Nuclear Research Center. It is a computer program specifically developed for the analysis of High Temperature Gas-cooled Reactor, The THERMIX model features a two-dimensional cylindrical geometry and consists of a general purpose steady-state or transient heat conduction code and a quasi-steady-state convection code. The THERMIX code includes a two-dimensional transient solid temperature model, a quasi-stationary gas flow model, a primary loop model, one point neutron kinetics model and a graphite corrosion model. It can analyze the thermal-hydraulic performance of the pebble-bed reactor under normal operation and accident conditions. The THERMIX code has been validated and improved according to many experiments [9]. Recently, it has been validated by experimental data of the HTR-10 [10]. Some new 3-D code based on THERMIX has also been validated by the old AVR experiment data [11]. The THERMIX code is also applied for safety analysis of the newly designed HTR-PM [12].

However, using THERMIX to analyze the HTR-PM normally consumes a lot of computational time. Therefore, it is necessary to develop a fast running (real time) simulation method for the HTR-PM. This is the objective of the authors' work presented in this paper. In the future, by using design data of the demonstration HTR-PM project and experimental data of the HTR-10, the modeling work for the primary loop as well as for other sub systems will be carried out concurrently to the progress of the ongoing design and to future constructions of the demonstration HTR-PM project.

As for the remainder of this paper, section 2 introduces the HTR-10 plant and its primary loop. Then, section 3 describes the thermal-hydraulic models for the primary loop. Section 4 shows the results of a typical case. Finally, section 5 presents conclusions and perspectives of this paper.

2 The HTR-10

2.1 General description of the HTR-10

The HTR-10 is the first High Temperature Reactor test project developed in China. In 2001, the HTR-10 power plant reached criticality and then started to generate electricity. The main design parameters are listed in Table 1.

Table 1 Major design parameters of the HTR-10

Item	Unit	Value
Thermal power	MW	10
Electric power	MW	2.5
Reactor core diameter	cm	180
Average core height	cm	197
Primary helium pressure	MPa	3.0
Average helium temperature at reactor inlet/outlet	°C	250/700
Helium mass flow rate at full power	kg·s^{-1}	4.3
Average core power density	MW·m^{-3}	2
Power peaking factor		1.54
Number of control rods in the side reflector		10
Number of absorber ball units in the side reflector		7
Nuclear fuel		UO_2
Heavy metal loading per fuel element	g	5
Enrichment of fresh fuel element	%	17
Number of fuel elements in the core		27000
Fuel management	Multi-pass	
Average residence time of one fuel element in the core	Effective Full Power Days	1080
Max. power rating of the fuel element	kW	0.57
Max. fuel temperature	°C	919
Max. burn-up	MWd tH·M^{-1}	87 072
Average burn-up	MWd tH·M^{-1}	80 000
Max. thermal flux in the core (E<1.86 eV)	n·cm^{-2} ·s^{-1}	3.43×10^{13}
Max. fast flux in the core (E>1MeV)	n·cm^{-2}· s^{-1}	2.77×10^{13}

2.2 Primary loop of HTR-10 plant

The Main Power System of the HTR-10 mainly consists of the reactor, the primary loop and the secondary loop. The pressure boundary of the HTR-10 reactor and primary loop consists of the reactor pressure vessel, the steam generator pressure vessel and the hot gas duct vessel. The reactor core and the steam generator are installed respectively in the reactor vessel and the steam generator vessel, which are positioned side by side, and are connected by the horizontal hot gas duct.

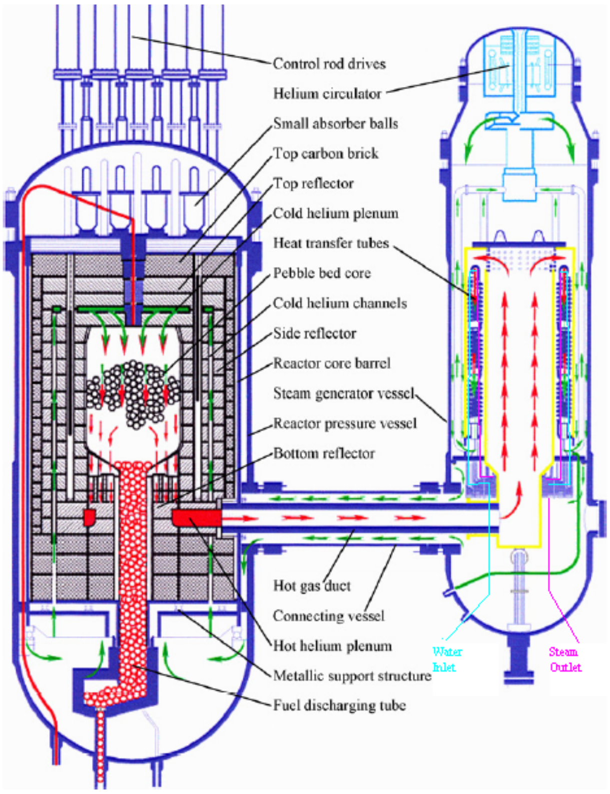

Fig. 1 Thermal-hydraulic process in the primary loop of the HTR-10.

As shown in Fig. 1, the thermal-hydraulic process related with the reactor and the primary loop of the HTR-10 can be mainly explained as following:

Before entering the reactor vessel, the helium gas is compressed by a helium blower at approximately 7MPa and the temperature of the inlet gas is around 250°C. After the helium gas has flown through the hot fuel spheres in the reactor core, its temperature reaches 750°C. The hot helium gas exits the reactors and flows through the hot gas duct. The hot helium gas transfers its thermal power to the water in the steam generator where it is cooled down to around 250°C. Then, the helium blower blows the cold helium gas through the outer coaxial pipes of the hot gas duct. Finally, the cold helium gas flows into the reactor pressure vessel where it is heated again. In this way, a closed cycle of helium gas flow takes place in the primary loop.

At the side of the secondary loop of the HTR-10 plant, the water initially at a temperature of 205°C in the steam generator is heated to 540°C by hot helium gas and becomes hot steam. Then, superheated steam with a pressure of 13.73MPa drives the steam turbine and its connected generator in order to generate electrical power based on the Rankin cycle.

3 A thermal-hydraulic model for the primary loop of the HTR-10

The primary loop of the HTR-10 can be described as a thermal-hydraulic network which consists of several components such as hot gas duct, steam generator, helium gas blower, etc. According to thermal-hydraulic properties of these components, they are classified into the follow three elements

- Pipeline: central channel of hot gas duct and annular channel of hot gas duct.
- Steam generator: superheating segments and other segments (including preheating segments and boiling segments). According to the structure of the steam generator of the HTR-10, a tube bundle model is used to describe the thermal-hydraulic process of the helium gas in the steam generator. It is based on the same governing equations as the pipeline models.
- Helium blower: the model of the blower is based on the characteristic constant of the blower and vendor-provided data maps on its characteristic curve.

3.1 Properties of the helium gas

The properties of the helium gas such as density, thermal conductivity, dynamic viscosity, etc., are necessary to analyze the thermal-hydraulic behavior of the primary loop of the HTR-10. Table 2 shows some basic properties of the helium gas used in this study [13,14].

In addition, some other properties of the helium gas are calculated by using experiential formula.

The thermal conductivity of the helium gas is experientially calculated as follows:

$$\eta = 2.682\times10^{-3}\times[1+1.123\times10^{-3}\times P]\times T^{0.71\times(1-2\times10^{-4}\times P)} \quad (J/(kg\cdot K)) \tag{3}$$

In Eqs. (1)- (3), P is the pressure of the helium gas (in bar), while T is the temperature (in Kelvin).

Table 2 Basic properties of the helium gas

Property	Value
Molecular weight	4.003g/mol
Boiling point	-268.94°C
Melting point	-272.2°C
Gas constant	2077.1 J/(kg·K)
Critical pressure	0.229 MPa
Critical density	69.3 kg/m^3
Specific heat at constant pressure	5198J/(kg·K)
Specific heat at constant volume	3121J/(kg·K)

3.2 Thermal-hydraulic models for pipelines and tube bundles

The primary loop system of the HTR can be considered as a thermal-hydraulic network [15] composed of a flow channel, a pipeline, a steam generator and a helium blower. This network deals with the change of pressure, temperature and flow rate when the helium gas flows through the primary loop system. When analyzing the behavior of this thermal-hydraulic network, some basic assumptions are adopted:

- The pressure and flow rate of the helium gas in the thermal-hydraulic network are analyzed based on a quasi-steady model.
- The helium gas flows through the whole network with a one-dimensional direction.
- Helium gas is compressible and treated as a continuum medium.
- Every component in this thermal-hydraulic network fulfills conservation of mass, momentum, and energy. The cross-sectional area of each component is equal.

According to the assumptions mentioned above, some governing equations can be formulated as follows:

- Mass conservation

$$u / v = const \tag{4}$$

- Momentum conservation

$$g \sin\theta dL + udu + \frac{dP}{\rho} = -\lambda \frac{u^2}{2}\frac{dL}{D_i} \tag{5}$$

- Energy conservation

$$dQ = g\sin\theta dL + dh + udu \tag{6}$$

In Eqs. (4)-(6), u is the velocity of the helium gas flow; v is the specific volume of the helium gas; ρ is the density of helium; P is the pressure of the helium gas; dL is the length of the helium gas flow; λ is the thermal conductivity; D_i is the equivalent diameter of the pipe or bundle; g is the acceleration of gravity; θ is the angle between the flow and the horizontal direction; dQ is the heat absorbed by the helium gas; h is the enthalpy of the helium gas.

About the heat absorbed by the tube wall, we have:

$$dQ = \frac{\alpha(T_w - T_f)dF_S}{u_m} \tag{7}$$

where α is the convection coefficient of heat transfer; T_w is the temperature of the tube wall; T_f is the temperature of the helium gas flow; dF_S is the heat exchange surface area; u_m is the mass flow rate of the helium gas flow.

The heat exchange between the tube wall and the water-cooled wall is unsteady state and the temperature of the water-cooled wall is stable.

The steam generation is simplified as three stable sessions: preheat session, evaporation session superheat session. In the final stage, the temperature of water is equal to that of the tube wall. The temperature of water in these three sessions is set in advance according to the power level of the HTR.

In the three conservation equations (*i.e.* Eqs. (4)-(6)) in the one-dimensional model, the independent variables are pressure P and temperature T. The related differential equations are described by:

$$\begin{aligned} \frac{dP}{dL} &= f_1(P,T) \\ \frac{dT}{dL} &= f_2(P,T) \end{aligned} \tag{8}$$

In order to get the above two equations from the three conservation equations, the following expression of enthalpy and specific volume are employed:

$$\begin{aligned} \frac{dh}{dL} &= \frac{\partial h}{\partial P}\frac{dP}{dL} + \frac{\partial h}{\partial T}\frac{dT}{dL} \\ \frac{dv}{dL} &= \frac{\partial v}{\partial P}\frac{dP}{dL} + \frac{\partial v}{\partial T}\frac{dT}{dL} \end{aligned} \tag{9}$$

From Eqs. (4), (5), (6), (7) and (9), Eqs. (10) and (11) are deduced:

$$\left(v+\frac{u^2}{v}\frac{\partial v}{\partial P}\right)\frac{dP}{dL}+\left(\frac{u^2}{v}\frac{\partial v}{\partial T}\right)\frac{dT}{dL} = -\left(g\sin\theta+\lambda\frac{u^2}{2}\frac{1}{D_i}\right) \tag{10}$$

$$\frac{dQ}{dL}=g\sin\theta+\left(\frac{\partial h}{\partial P}\frac{dP}{dL}+\frac{\partial h}{\partial T}\frac{dT}{dL}\right) +\frac{u^2}{v}\left(\frac{\partial v}{\partial P}\frac{dP}{dL}+\frac{\partial v}{\partial T}\frac{dT}{dL}\right) \tag{11}$$

Then the following two equations are reduced by solving Eqs. (10) and (11) for dP/dL and dT/dL:

$$\frac{dP}{dL}=\frac{BF+CE}{AE-BD} \tag{12}$$

$$\frac{dT}{dL}=\frac{AF+CE}{BD-AE} \tag{13}$$

In Eqs. (12) and (13), the terms A, B, C, D, E and F are given by:

$$A=\left(v+\frac{u^2}{v}\frac{\partial v}{\partial P}\right), B=\left(\frac{u^2}{v}\frac{\partial v}{\partial T}\right)$$
$$C=\left(g\sin\theta+\lambda\frac{u^2}{2}\frac{1}{D_i}\right), D=\left(\frac{\partial h}{\partial P}+\frac{u^2}{v}\frac{\partial v}{\partial P}\right) \tag{14}$$
$$E=\left(\frac{\partial h}{\partial T}+\frac{u^2}{v}\frac{\partial v}{\partial T}\right), F=\left(\frac{dQ}{dL}-g\sin\theta\right)$$

Eqs. (12), (13) and (14) are numerically solved using a fourth-order explicit Runge-Kutta method with fixed stepsize. The simulation code was programmed by FORTRAN language. This is the essential point of the fast running simulation method proposed by the authors.

3.3 The helium blower model

The pressure and temperature changed by the helium blower are calculated according to the rotation rate of the blower, the mass flow rate of the helium gas and characteristic constant of this blower, which are known from vendor-provided data. Other parameters, such as the pressure ratio and the efficiency of the blower, are also obtained from the vendor-provided data maps.

The change of pressure achieved by the helium blower is calculated as follows:

$$\Delta P = P_2 - P_1 = a_1 N^2 + a_2 N W + a_3 W^2 \tag{15}$$

Where P_2 is the outlet pressure of the blower; P_1 is the inlet pressure of the blower; N is the rotation rate of the blower; W is the mass flow rate; a_1, a_2, and a_3 are the characteristic constants of the blower.

Once the pressure rise is calculated, according to the energy change relation, the temperature rise in the blower can be obtained as

$$\Delta T = \frac{\Delta P}{C_P} v \tag{16}$$

Where v is the specific volume of the helium gas; C_p is the specific heat at constant pressure of the helium gas.

4 Simulation cases and results

4.1 Calculation models

According to section 3, the primary loop of the HTR-10 can be separated in three basic components: the pipelines, the blower, and the steam generator which is simulated by the models of tube bundles. In the pipeline and tube bundles, the physical parameters of helium can be calculated by two coupled differential equations. In the helium gas blower, the physical parameters can be obtained by specific formulas. In this section of the paper, a detailed model of the primary loop is described according to the rules formulated in section 3.

As shown in Fig.2. The primary loop is divided into 12 parts as listed in Table 3.

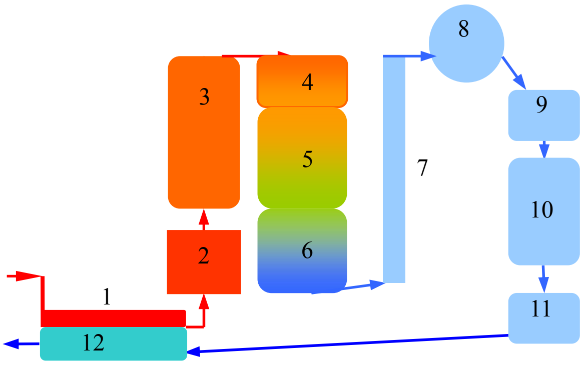

Fig.2 Calculation model of the primary loop of the HTR-10

Table 3 Calculation model of the primary loop of the HTR-10

No	Item	Type
1	Central channel of the hot gas duct	Pipeline
2	Conjoining channel between the hot gas duct and the steam generator	Pipeline
3	Central channel of the steam generator	Pipeline
4	Entrance part of the steam generator	Bundles
5	Middle part of the steam generator	Bundles
6	Outlet part of the steam generator	Bundles
7	Entrance pipeline of the helium blower	Pipeline
8	Helium Blower	Blower
9	Outlet pipe of the helium blower	Pipeline
10	Annular channel of the steam generator	Pipeline
11	Pipeline under the steam generator Vessel	Pipeline
12	Annular channel of the hot gas duct	Pipeline

A case was chosen for testing the models and the calculation method. This case is a simulated accident involving a loss of coolant without pressure drop which may be caused by a failure of the helium blower, a shutting of the baffle preceding the helium blower, etc. In this case, the helium blower starts to slow down from the full power situation. At 0.1 second, the rate of the rotation starts to decrease, as does the mass flow rate. By taking results under typical situations, the models and the calculation methods are tested hereafter. Data relative to the study case are listed in Table 4.

Table 4 Simulated loss of coolant accident

Time (sec)	Mass flow rate (kg/s)	Inlet pressure (MPa)	Inlet temperature (K)	Rotation velocity (RPM)
0.2	4.30	3.0249	999.3	3199.4
2.6	3.98	3.0163	1000.8	2959.3
5.6	3.60	3.0038	1002.0	2678.3
7.6	3.36	2.9981	1003.1	2499.1
10.6	3.06	2.9915	1004.1	2277.2
22.2	2.11	2.9852	1010.4	1596.1
33.7	1.48	3.0508	1015.8	1141.8
39.8	1.28	3.0925	1017.5	990.3
48.7	0.98	3.1245	1020.3	767.3
58.7	0.65	3.1581	1021.1	509.0
73.7	0.39	3.1773	1009.8	312.4
85.6	0.265	3.1681	987.0	205.2
96.9	0.18	3.1579	967.7	143.7
117	0.10	3.1411	922.0	92.0

4.2 Comparing results

In this paper, calculation results are compared with output from the analysis program THERMIX under the same situation in order to verify the validity and accuracy of the authors' developed program. In this part, comparisons of the pressure and temperature changes in some components are presented. Some typical results are chosen to allow making reasonable conclusions.

The pressure drop in component 1, the hot gas duct, is shown in Fig.3. The line with round dots represents the results calculated using the methods proposed in this paper, while the line with squares represents the results from the THERMIX program.

The drop of gross pressure in component 4, 5 and 6, which represents the pressure drop in the steam generator, is shown in Fig.4.

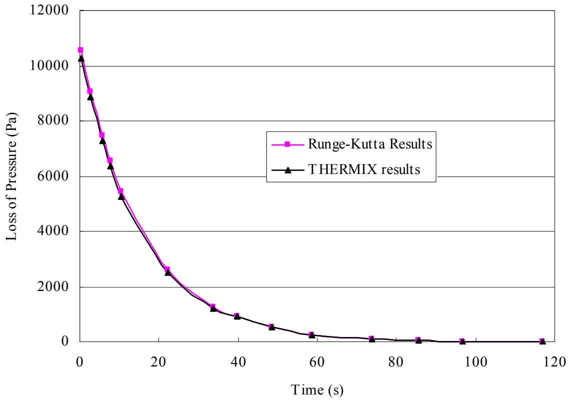

Fig. 3 Pressure change in the hot gas duct.

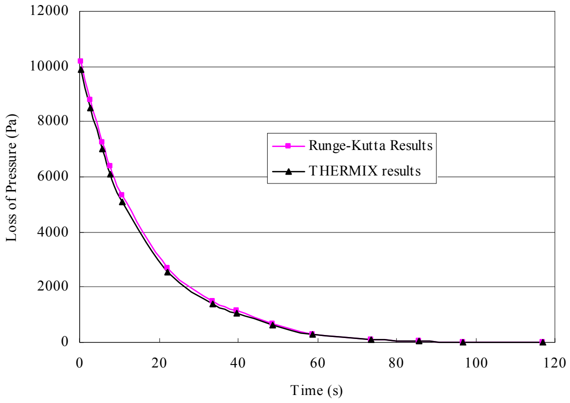

Fig.4 Pressure change in the steam generator.

The gross temperature in component 1, the hot gas duct, is shown in Fig.5.

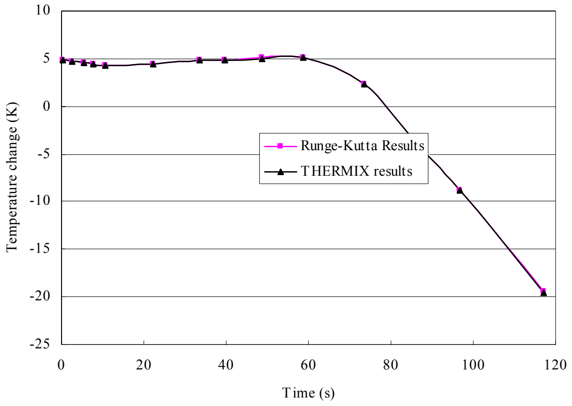

Fig.5 Temperature change in the hot gas duct.

The gross temperature in component 4, 5 and 6, which represents the temperature change in the steam generator, is shown in Fig.6.

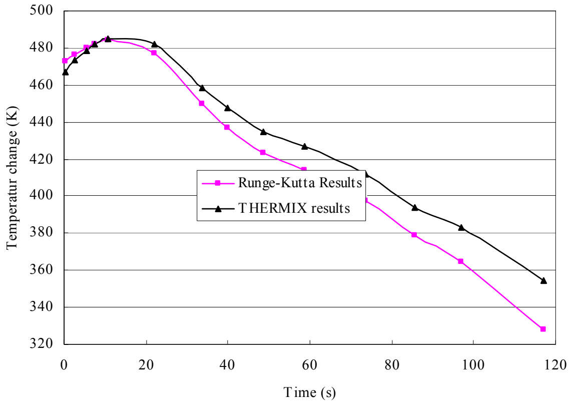

Fig.6 Temperature change in the steam generator.

From Figs.3-5, both the pressure and temperature change results match well most of the calculated points. However, the differences in temperature change in the steam generator between the two methods become larger when the flowrate of helium gas and water becomes smaller over time. This means that the proposed simulation method gives smaller temperature values than THERMIX when the coolant flow decreases because of natural circulation condition.

4.3 Brief summary and analysis

In this section, the results from the models and the methods proposed in this paper were compared with results from the THERMIX program. The comparison shows that the results of the two methods match well with each other, which proves that the models and the methods used in this paper are proper and reasonable, and can offer predictions more quickly than the THERMIX program. As a consequence, it can fulfill the simulator's real-time requirement.

However, some problems remain as explained below, and they are to be solved in the future:

- First of all, the relative deviation is higher in tube bundle components than in pipeline components. One main reason for this problem is that the tube bundle model is a simplified model of steam generator. The steam generator model used by the THERMIX program is also a simplified one. The simplification may cause deviation. Another reason may be the solving algorithm. In this paper, a fixed stepsize fourth-order explicit Runge-Kutta method is used to solve the differential equations. This formula is less accurate than a variable stepsize Runge-Kutta method, especially when the stepsize becomes large.
- Another problem is that the deviation of the results gets more sensitive when the mass flow rate becomes very small. Namely, when the mass flow rate becomes very small, the relative deviation becomes higher. One probable reason may be ascribed to the numerical algorithm employed in this paper. Therefore, further analysis is needed to explain this and improve the simulation's accuracy.

5 Conclusions and perspectives

A thermal-hydraulic model was proposed to simulate the thermal-hydraulic processes in the primary loop of the HTR without reactor. By dividing the primary loop into three basic components, building a calculation model for each of them, and processing the conservation equations of mass, momentum and energy, this paper advanced a new simulation methodology to render the thermal-hydraulic processes in the primary loop. By choosing a detailed case and comparing the calculation results with the output of the THERMIX program, the validity of the simulation method was tested. Consequently, the models and algorithms proposed in this paper can be basically adopted for the development of the full scale simulator of the demonstration HTR project, HTR-PM.

In the future, a more precise model of steam generator should be built to improve the accuracy, and more research on numerical algorithms should be made to improve both the accuracy and the computation time of the simulation method. In addition, a correction on the helium gas flow according to time derivatives should be considered for the simulation of natural convection.

Acknowledgement

Thanks to Mr. CHEN Fubing and Mr. ZHOU Kefeng, Institute of Nuclear and New Energy Technology, Tsinghua University, for providing the technology to support to this study.

References

[1] ZHANG, Z., WU Z., SUN, Y., LI F.: Design Aspects of the Chinese Modular High-temperature Gas-cooled Reactor HTR-PM. Nuclear Engineering and Design, 2006, 236(5-6): 485-490.

[2] ZHANG, Z., WU, Z., WANG, D., XU, Y., SUN, Y., LI, F., DONG, Y.: Current Status and Technical Description of Chinese 2 × 250 MWth HTR-PM Demonstration Plant, Nuclear Engineering and Design, 2009, 239(7): 1212-1219.

[3] ZHANG, Z., SUN, Y.: Economic Potential of Modular Reactor Nuclear Power Plants Based on the Chinese HTR-PM Project, Nuclear Engineering and Design, 2007, 237(23): 2265-2274.

[4] DONG, Y., GAO, Z.: Thermal–hydraulic Feasibility Analysis on Uprating the HTR–PM, Nuclear Engineering and Design, 2006, 236(5-6): 510-515.

[5] WU, Z., LIN, D., ZHONG, D.: The Design Feature of the HTR-10, Nuclear Engineering and Design, 2002, 218(1-3): 25-32.

[6] XU, Y., ZUO, K.: Overview of the 10 MW High Temperature Gas Cool Test Module Project, Nuclear Engineering and Design, 2002, 218(1-3): 13-23.

[7] CLEVELAND, J.C., GREENE, S.R.: Application of THERMIX-KONVEK Code to Accident Analysis of Modular Pebble Bed High Temperature Reactors (HTRs), ORNL/TM-9905, 1986.

[8] SHI, L., LIU, H., YANG, X., GAO, Z., DONG, Y., ZHANG, Z.: A Personal Computer-based Simulation-and-control Integrated Platform for 10 MW High-temperature Gas-cooled Reactor, Nuclear Technology, 2004, 145(2): 189-203.

[9] ZIERMANN, E.: Review of 21 Years of Power Operation at the AVR Experimental Nuclear Power Station in Julich, Nuclear Engineering and Design, 1990, 121(2): 135-142.

[10] CHEN, F., DONG, Y., ZHANG, Z., ZHENG, Y., SHI, L., HU, S.: Post-test Analysis of Helium Circulator Trip without Scram at 3 MW Power Level on the HTR-10, Nuclear Engineering and Design, 2009, 239(6): 1010-1018.

[11] DING, M., BOER, B, KLOOSTERMAN, J.L., LATHOUWERS, D.: Evaluation of Experiments in the AVR with the DALTON–THERMIX Coupled Code System, Nuclear Engineering and Design, 2009, 239(12): 3105-3115.

[12] ZHENG, Y., SHI, L., DONG, Y.: Thermohydraulic Transient Studies of the Chinese 200 MWe HTR-PM for Loss of Forced Cooling Accidents,. Annuals of Nuclear Energy, 2009, 36: 742-751.

[13] ZHOU, Y., DONG, Y., WU, M., ZHU, S., MA, Y., LI, F.: Simulation of Thermal-fluid Behavior in Primary Loop of HTR-PM, In: Proceedings of the 1st International Symposium on Symbiotic Nuclear Power Systems for 21st Century, Wakasa-wan Energy Research Center, Japan, 2007.

[14] GAO, Z., SHI, L.: Thermal Hydraulic Transient Analysis of the HTR-10, Nuclear Engineering and Design, 2002, 218(1-3): 65-80.

[15] MA, Y., LI, T.: A Method for Compressible Fluid Network Modeling, Acta Simulata Systematica Sinica, 1992, 4(1): 15-23.