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Research Article

Procedure of Active Residual Heat Removal after Emergency Shutdown of High-Temperature-Gas-Cooled Reactor

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After emergency shutdown of high-temperature-gas-cooled reactor, the residual heat of the reactor core should be removed. As the natural circulation process spends too long period of time to be utilized, an active residual heat removal procedure is needed, which makes use of steam generator and start-up loop. During this procedure, the structure of steam generator may suffer cold/heat shock because of the sudden load of coolant or hot helium at the first few minutes. Transient analysis was carried out based on a one-dimensional mathematical model for steam generator and steam pipe of start-up loop to achieve safety and reliability. The results show that steam generator should be discharged and precooled; otherwise, boiling will arise and introduce a cold shock to the boiling tubes and tube sheet when coolant began to circulate prior to the helium. Additionally, in avoiding heat shock caused by the sudden load of helium, the helium circulation should be restricted to start with an extreme low flow rate; meanwhile, the coolant of steam generator (water) should have flow rate as large as possible. Finally, a four-step procedure with precooling process of steam generator was recommended; sensitive study for the main parameters was conducted.

1. Introduction

In China, a commercial modular high-temperature-gas-cooled reactor pebble-bed module (HTR-PM) nuclear power plant entered its conceptual design phase in the year 2002 and aimed to complete a demonstration plant in 2012 [1]. Like other high-temperature-gas-cooled reactors (HTGR), HTR-PM has inherent negative temperature coefficient of reactivity of the core, which makes it have the unique characteristic of being able to remove the residual heat through the reactor vessel surface to the ultimate heat sink entirely by passive heat transfer mechanisms (radiation, convection, and conduction) [2]. However, the duration of passive heat transfer process will be hundreds of hours [3], which is too long to meet the requirement of rapid restart of the reactor after accident elimination. In the case of accidents (may be any kind that is able to induce the reaction of emergency system and cause shutdown of the core, such as loss of total electricity, earth quake, disabling of instruments, even false signals, etc.) happening in the nuclear part of the plant, the electric supply for both helium circulators of primary loop and feed water pump of secondary loop is available, and the steam generators (SG) and condenser are still functioning. These conditions make it feasible to remove the residual heat of reactor core actively via SG and secondary loop rather than through passive natural heat transfer, in order to shorten the cooling process and reduce the time cost. This meets the economic consideration, which is one of the main design philosophies of HTR-PM [4].

For HTR-PM, the active residual heat removal process (ARHRP) can be accomplished by SG and start-up loop (STL), while the latter is designed for start process of the plant. After the shutdown of the core in emergency, SG will be switched to connect with STL and insulated from the main steam loop (MSL). Residual heat of the core can be transferred to STL through SG in an active manner by the coolant circulation.

However, the situation becomes very complex after core is shut down. First of all, the temperature distribution of boiling tubes of SG has a configuration with low temperature (205°C) at water inlet and high temperature (600°C) at steam outlet. Any inappropriate coolant flow into SG will cause heat/cold

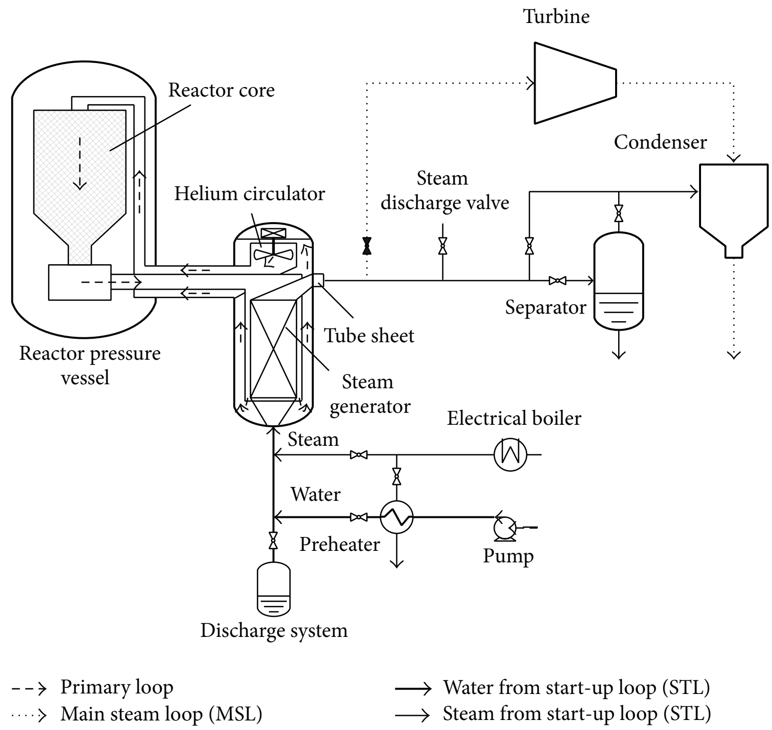

Figure 1: Schematic of flow diagram of HTR-PM.

shock to structures. Meanwhile, helium, the coolant of the core, has very high temperature (about 780°C). Miss match between primary loop and STL may cause sudden load to SG, which brings heat shock to the boiling tubes and makes its temperature exceed design value. All these situations are very dangerous; therefore, it is necessary to carry out transient analysis of ARHRP and choose flow parameters properly for both primary loop and STL.

In early HTGR plants, such as AGR of United Kingdom, AVR of Germany, and HTGRs in the United States of America, gas coolant circulator and SG were used to remove the heat from the reactor core under certain circumstances. But the procedure detail and transient analysis for the structure were not presented. Breitenfelder reported three different procedures for residual heat removal operation of THTR-300 power plant initiated according to the type of accident [5]. Transient analysis was presented for one active procedure, which utilized helium circulator and SG. However, to positions where failures inclined to happen due to thermal stress, such as boiling tubes and tube sheet, temperature transient analyses were not introduced.

This paper is going to present the conceptual design of ARHRP for HTR-PM, which results in good safety and reliability. A one-dimensional thermohydraulics model is developed to investigate the transient characteristics of SG and STL, which uses homogeneous model for two-phase flow in boiling tubes and compressible model for helium flow. Based on this model, transient analysis for two different ARHRP are carried out and sensibility study for the main parameters is conducted. Finally, a four-step ARHRP is recommended.

2. Active Residual Heat Removal System

2.1. Configuration of Active Residual Heat Removal System. The schematic of flow diagram of HTR-PM is shown in Figure 1. Following the concept of the modular high-temperature-gas-cooled reactor (MHTGR), HTR-PM has the configuration of two identical reactor modules (i.e., the primary loop) connected to one turbine. Each module consists of a reactor, circulator, and SG, which are assembled in two connecting pressure vessels. Coolant of the core, helium, is driven by the circulator located at top of the SG vessel and heated to about 750°C in the core. When hot helium enters SG, it will flow downward and transfers heat to the feed water of secondary loop to generate steam with a temperature of 570°C at outlet. The main design parameters of HTR-PM are shown in Table 1. During ordinary operation, the two reactor modules can work simultaneously or separately; for simplicity only one module is shown in Figure 1.

SG of HTR-PM is a once-through steam generator that consists of helically coiled boiling tubes, where water/steam flows inside the tube and helium flows outside crossing the bundle. There are 19 identical modules in one SG and each of them consists of 35 tubes, so total of 665 tubes will penetrate the tube sheet and conduct steam to the steam pipe. The weld joints connecting boiling tube and tube sheet and that connecting tube sheet and steam pipe are the most damageable positions of SG, as is shown in Figure 2.

The STL is designed for start process of the plant connecting SG in parallel with the MSL. It is equipped with an electrical boiler, which can produce steam to preheat the feed water or to feed the steam into SG directly as coolant. 2. STL is

Table 1: Design parameters of HTR-PM.

Parameters	Design value
Primary loop	
Helium pressure	7.0 MPa
Helium temperature at reactor outlet	750°C
Helium temperature at reactor inlet	250°C
Helium flow rate	176 kg/s
Secondary loop	
Steam pressure at SG outlet	13.9 MPa
Steam temperature at SG outlet	570°C
Feed water temperature	205°C
Feed water flow rate	155.4 kg/s
Start-up loop	
Coolant pressure	1.0 MPa
Steam at electrical boiler outlet	140~200°C
Maximum steam flow rate	9.7 kg/s

a closed loop which also has many other pieces of equipment including heat exchangers, deaerator, and control valves. These pieces of equipment were eliminated from Figure 1 since the system is too complicated to be completely shown and do not have direct relevance with the active cooling process.

2.2. Criterions for ARHRP. The principal criterion of ARHRP is safety. First of all, for the core, the inlet temperature and flow rate of helium need to be controlled to avoid too fast cooling. However, the major risk comes from SG where the flow states of primary loop and STL should be designed appropriately in order to avoid heat/cold shock to the positions shown in Figure 2. The preliminary criterions for ARHRP are listed in Table 2. Only when all these criterions are fulfilled can we take further measures to accelerate ARHRP.

3. Numerical Model

3.1. Mathematical Representation. The mathematical representation of SG and STL is shown in Figure 3, which models both helium and water/steam flow as one-dimensional channel flow. In SG the node numbers of helium channel, boiling tube wall channel, and water/steam channel are identical ($N = 100$ and $M = 50$, for this paper's calculation, after grid independence analysis) and for each channel the node dimension is a constant equal to the channel length divided by node number. Heat transfer happens on the boundary of corresponding nodes of two adjacent channels, and the heat transfer coefficient and pressure drop are calculated by correlations.

The core is simulated by a simple lumped parameter method and treated as a boundary condition of helium flow, despite its complicated structures. Detailed analysis of the core is beyond the scope of this paper. However, this model is reasonable for the transient analysis for SG and STL, for the helium temperature at core outlet is stable because of the large heat capacity of core structures and low flow rate of helium.

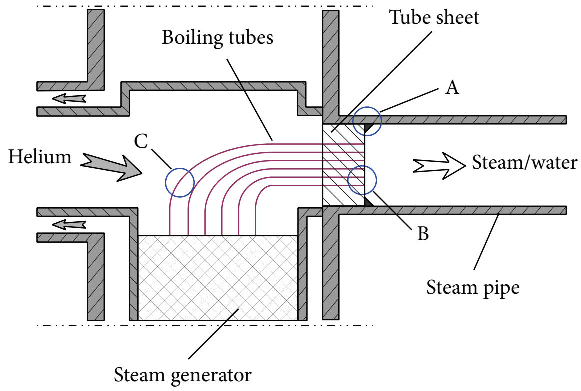

Figure 2: Damageable positions of SG (A: weld of tube sheet with steam pipe; B: joint of boiling tube with tube sheet; C: boiling tubes at steam outlet of SG).

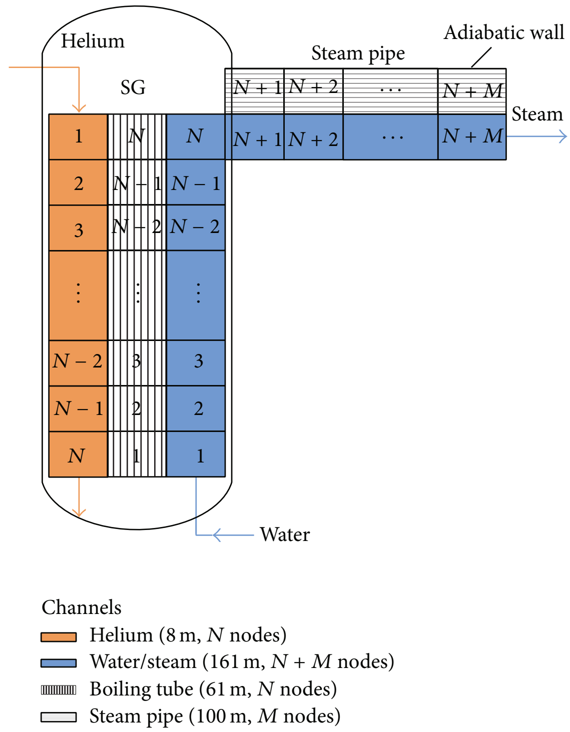

Figure 3: Nodalization of SG and STL.

3.2. Governing Equations and Solution Method. A quasi-one-dimensional homogeneous model is used for water/steam flow, which includes governing equations as below:

Continuity equation:

$$\frac{\partial(\rho_m A)}{\partial t}+\frac{\partial}{\partial x}(\rho_m u_m A)=0. \tag{1}$$

Table 2: Criterion for ARHRP.

Position	Description	Value
Core	Helium flow rate	<10% design value
	Inlet helium temperature	>100°C
SG (A)	Temperature difference between tube sheet and steam pipe	<100°C
	Temperature variation rate	<5°C/min
SG (B)	Temperature variation rate	<5°C/min
SG (C)	Temperature variation rate	<5°C/min
	Maximum temperature	<650°C

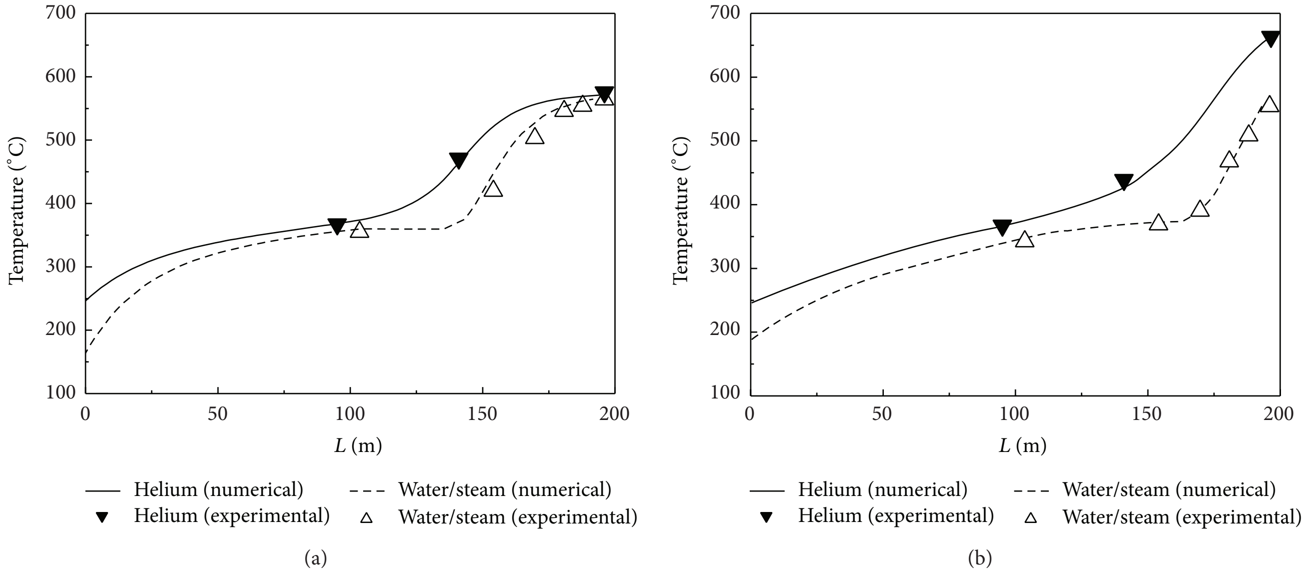

Figure 4: Validation of numerical model by THTR-300 experiments: (a) temperature distribution under 40% power load and (b) temperature distribution under 100% power load.

Momentum equation:

$$\frac{\partial\left(\rho_m u_m A\right)}{\partial t}+\frac{\partial}{\partial x}\left(\rho_m u_m^2 A\right) = A\left(-\frac{\partial p_m}{\partial x}-\rho_m g_m-\frac{f_m}{2D_m}\rho_m u_m^2\right). \quad (2)$$

Energy equation:

$$\frac{\partial\left(\rho_m h_m A\right)}{\partial t}+\frac{\partial}{\partial x}\left(\rho_m h_m u_m A\right)=A\left(\frac{Dp_m}{Dt}-\frac{4q_m}{D_m}\right), \quad (3)$$

where ρ_m, u_m, p_m, and h_m are density, velocity, pressure, and enthalpy, respectively; A is the cross area of the channel, which is included in this model because it has different value for boiling tube and steam pipe; D_m is diameter of flow channel; q_m is heat flux; and f_m is friction factor. Void fraction, α_g, is computed by state equations as we assume thermal equilibrium between liquid phase and gas phase. Subscript m denotes the fluid is water if $\alpha_g < 0$, steam if $\alpha_g > 1$, or two-phase mixture if $0 \le \alpha_g \le 1$.

A compressible flow model is used for helium flow, whose governing equations are

Continuity equation:

$$\frac{\partial \rho_h}{\partial t}+\frac{\partial}{\partial x}\rho_h u_h = 0. \quad (4)$$

Momentum equation:

$$\frac{\partial \rho_h u_h}{\partial t}+\frac{\partial}{\partial x}\left(\rho_h u_h^2\right)=-\frac{\partial p_h}{\partial x}-\rho_h g_h-\frac{f_h}{2D_h}\rho_h u_h^2. \quad (5)$$

Energy equation:

$$\frac{\partial\left(\rho_h h_h\right)}{\partial t}+\frac{\partial}{\partial x}\left(\rho_h h_h u_h\right)=\frac{Dp_h}{Dt}-\frac{4q_h}{D_h}, \quad (6)$$

where ρ_h, u_h, p_h, and h_h are density, velocity, pressure, and enthalpy, respectively; D_h is diameter of flow channel; q_h is heat flux; f_h is fraction factor.

Both water/steam and helium are modeled as compressible flow according to the governing equations mentioned above. However, divergency will arise in the solving process if regular solution method is used, because the Mach numbers of water/steam and helium are much lower than unity. Therefore, a pressure-correction method devised for low

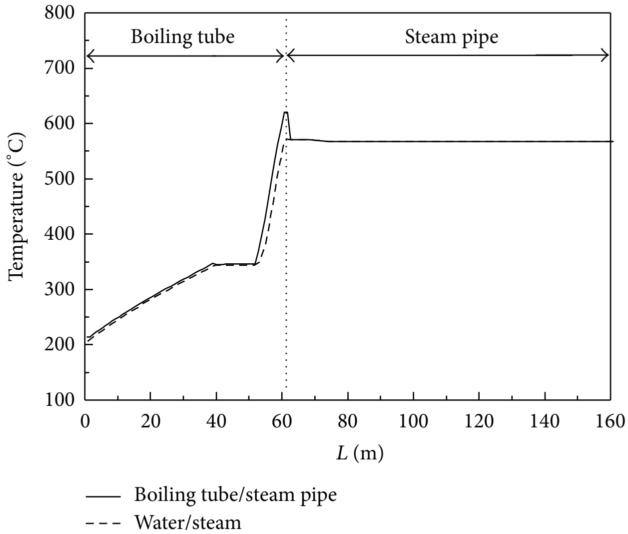

FIGURE 5: Temperature distribution of boiling tube and steam pipe after shutdown of the core.

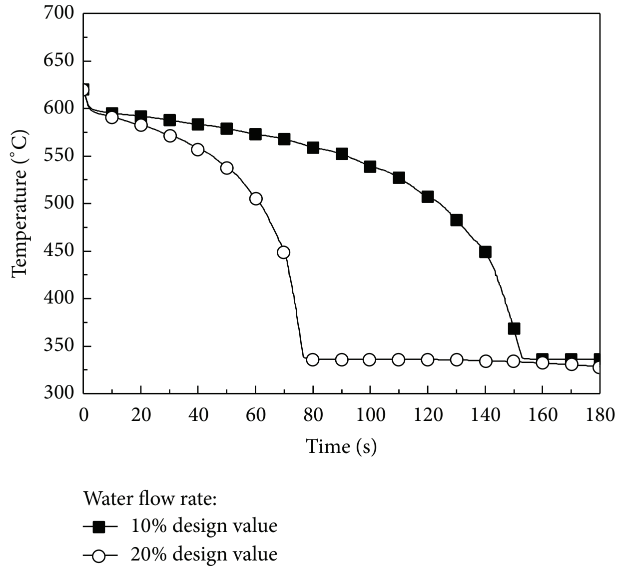

FIGURE 6: Temperature transient of boiling tube (steam outlet) during delay time; helium flow rate: 0; feed water temperature: 105°C; and pressure: 13.9 MPa.

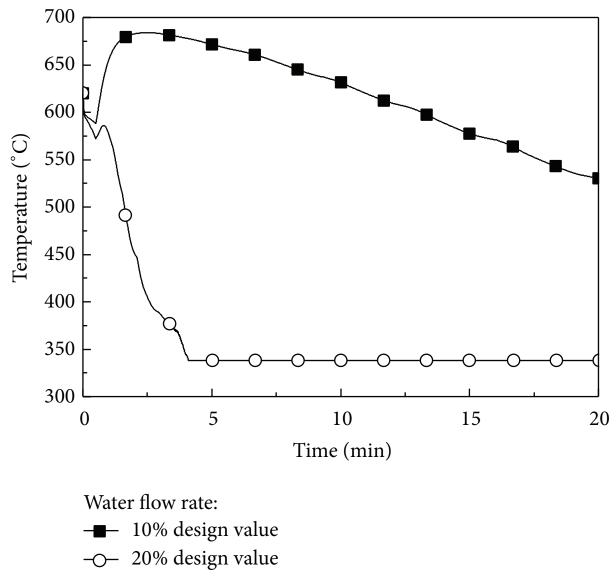

FIGURE 7: Temperature transient of boiling tube (steam outlet), with 30 s delay of helium circulation; helium flow rate: 10% design value; feed water temperature: 105°C; and pressure: 13.9 MPa.

Mach number compressible problems is used in this paper, which was developed from the famous SIMPLE method of Patankar and Spalding [6]. Additionally, staggered grid system and backward Euler implicit scheme for momentum equation and energy equation discretization are adopted to improve the convergency. The code was validated by the experimental results of THTR-300 steam generator, as shown in Figure 4. The predicted temperature distribution for both helium side and water side meet well with the experiments.

4. Transient Analysis of ARHRP

4.1. ARHRP without Precooling. As mentioned in Section 1, the temperature of SG tubes and steam pipe will be maintained after the core is shutdown if without any further operation, as shown in Figure 5. It is straight forward to run primary loop and STL directly and simultaneously without any preconditioning of SG and STL, with the water/steam staying in the boiling tube; for if flow parameters are designed appropriately, no obvious change would appear in the temperature distribution of SG and STL and consequently the heat/cold shock to structures due to the shift of flow states will be minimized.

However, in practice there must be a delay between the starts of STL and primary loop. The feed water pump should be started first in order to eliminate the risk of heat shock caused by the high-temperature helium and overheating of boiling tubes of SG (position C in Figure 2). This makes the delay time be a crucial parameter, during which the temperature of SG tubes decreases rapidly, as shown in Figure 6. For feed water flow rate being 10% design value, the temperature of tubes at SG outlet will decrease from 570°C to 340°C within only 3 minutes, and with the increase of feed water flow rate this process will be accelerated further. This phenomenon is caused by boiling. After shutdown of the core, water occupies downside of the boiling tube and steam occupies upside; at the interface of them water and steam are still saturated and boiling will occur when water is heated by the tube during proceeding upward (toward the hot end) driven by the pump. Tube's temperature in the boiling area will experience a sharp decrease because of the large heat transfer coefficient. Thus a cold shock is introduced, which proceeds as fast as water/steam interface.

To decrease the feed water's flow rate is helpful to postpone the cold shock. However, the minimum flow rate of feed water is limited to be not less than 10% of design value to avoid two-phase flow instabilities. The only way to exclude the cold shock when water exists in the boiling

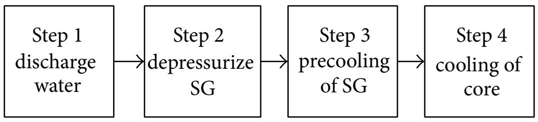

Figure 8: ARHRP with precooling of SG.

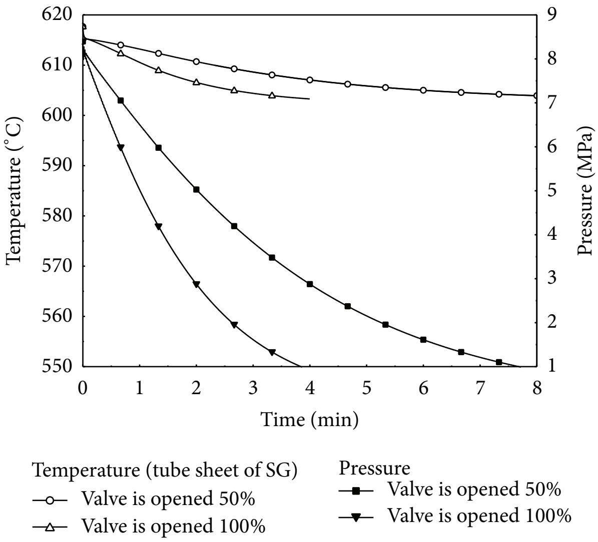

Figure 9: Temperature and pressure transient during depressurization.

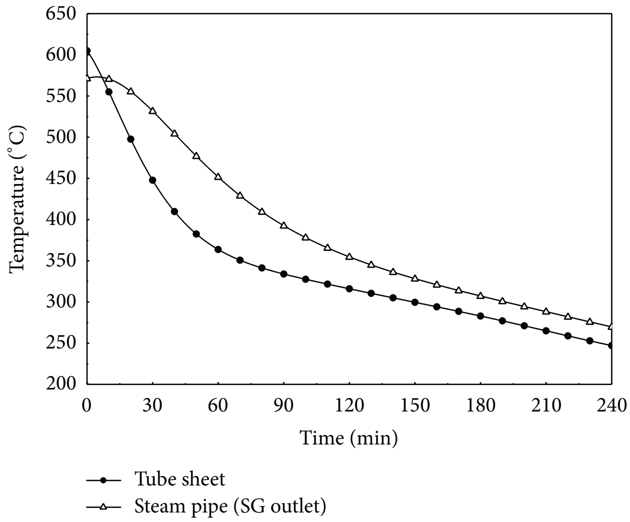

Figure 10: Temperature variation of SG outlet during precooling using steam as coolant; steam temperature: 190°C; pressure: 1.0 MPa; and flow rate: 0.74 kg/s.

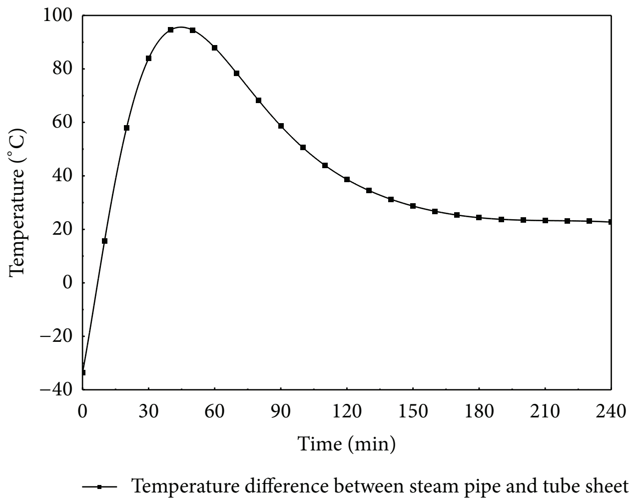

Figure 11: Temperature difference of steam pipe and tube sheet during precooling using steam as coolant; steam temperature: 190°C; pressure: 1.0 MPa; and flow rate: 0.74 kg/s.

tubes is to shorten the delay time as much as possible. This is a rigid demand for the reliability of controls system and helium circulator. Even though the circulator is started in the permit time, the temperature variation of boiling tubes is still difficult to control, as shown in Figure 7. It is in a dilemma that large feed water flow rate aggravates the cold shock and low feed water flow rate makes the boiling tube be overheated. Furthermore, if helium circulator fails to start in a short time, this process must be interrupted and cannot be repeated because the permit delay time was already passed. Therefore this process is not reliable.

4.2. ARHRP with Precooling. To cool down boiling tubes and steam pipe before the coolant enters SG is a fundamental way to eliminate the risk of cold shock. Therefore we considered including a precooling process and presented a four-step ARHRP as shown in Figure 8. Boiling will occur if water stays in boiling tubes of SG, which is unfavorable as analyzed for ARHRP without precooling in Section 4.1. Hence we choose to discharge water from SG in the first step and then use steam as coolant to cool down SG and STL slowly. As the steam is supplied by the electrical boiler of STL with a pressure of about 1 MPa, the SG and STL should be depressurized in the second step. In the following, each step of ARHRP will be analyzed in detail.

Step 1. Discharge liquid water from SG. This step is accomplished by discharge system, which can remove the water entirely in no more than one minute, which occupies 2/3 space of boiling tube after shutdown of reactor core. At the end of this step the pressure in SGs boiling tube and STL will be reduced to about 8 MPa, while the temperature variation of SG tubes and tube sheet is neglectable for the water is discharged from bottom (cold end) of SG and the duration is very short.

Step 2. Depressurize SG and STL. Through the discharge valve on the steam pipe, steam in SG and STL can be discharged to the ambient directly, until the pressure decreases to be lower than 1 MPa. The speed of depressurization can be controlled through adjusting the valve's open degree, as shown in Figure 9. The temperature decreased about 15°C in this step and the speed meets the demands listed in Table 2 even when the valve is fully opened.

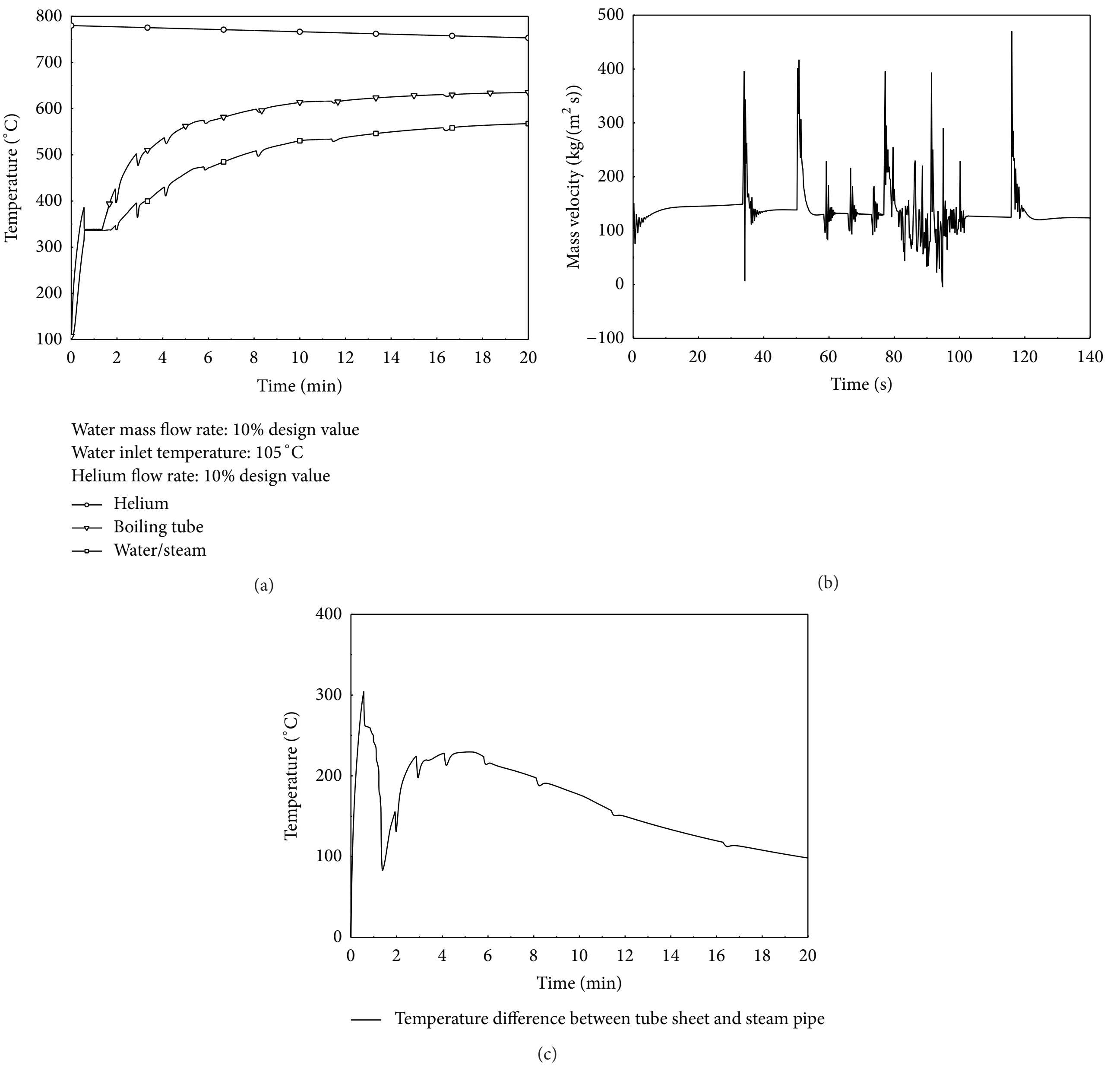

Figure 12: Temperature transient of SG outlet during cooling of reactor core; water mass flow rate: 10% design value; inlet temperature: 105°C; pressure: 13.9 MPa; and helium mass flow rate: 10% design value: (a) temperature of SG outlet; (b) flow oscillation; and (c) temperature difference between tube sheet and steam pipe.

Step 3. Precool SG and STL. In this step steam produced by the electrical boiler of STL is fed to SG directly, with temperature of 190°C and pressure of 1 MPa. The flow rate of steam needs to be controlled to keep the temperature variation rate less than 5°C/min to meet the demands of Table 2. Figure 10 shows the temperature transient of boiling tubes at SG outlet with steam flow rate of 0.74 kg/s. The temperature varies with a speed close to 5°C/min in the first hour and slows down in the following. This profile suggests that steam flow rate should be increased after the first hour to accelerate the process.

It is noticeable that an obvious delay exists between the temperature variations of boiling tube and steam pipe, despite the fact that their positions are very close. Under lumped parameter analysis, this phenomena is caused by the difference between the time constant of SG tubes and steam pipe, which represent the response time of an object's temperature to boundary convection and is expressed as

$$\tau = \frac{\rho c_p V}{hS}, \tag{7}$$

where ρ is the density, c_p the heat capacity, h the convection heat transfer coefficient, V the volume, and S the surface area for convection. For SG boiling tubes the ratio of V and S is 0.004, while for steam pipe it is 0.032; this is the principal reason that makes the time constant of steam pipe be much

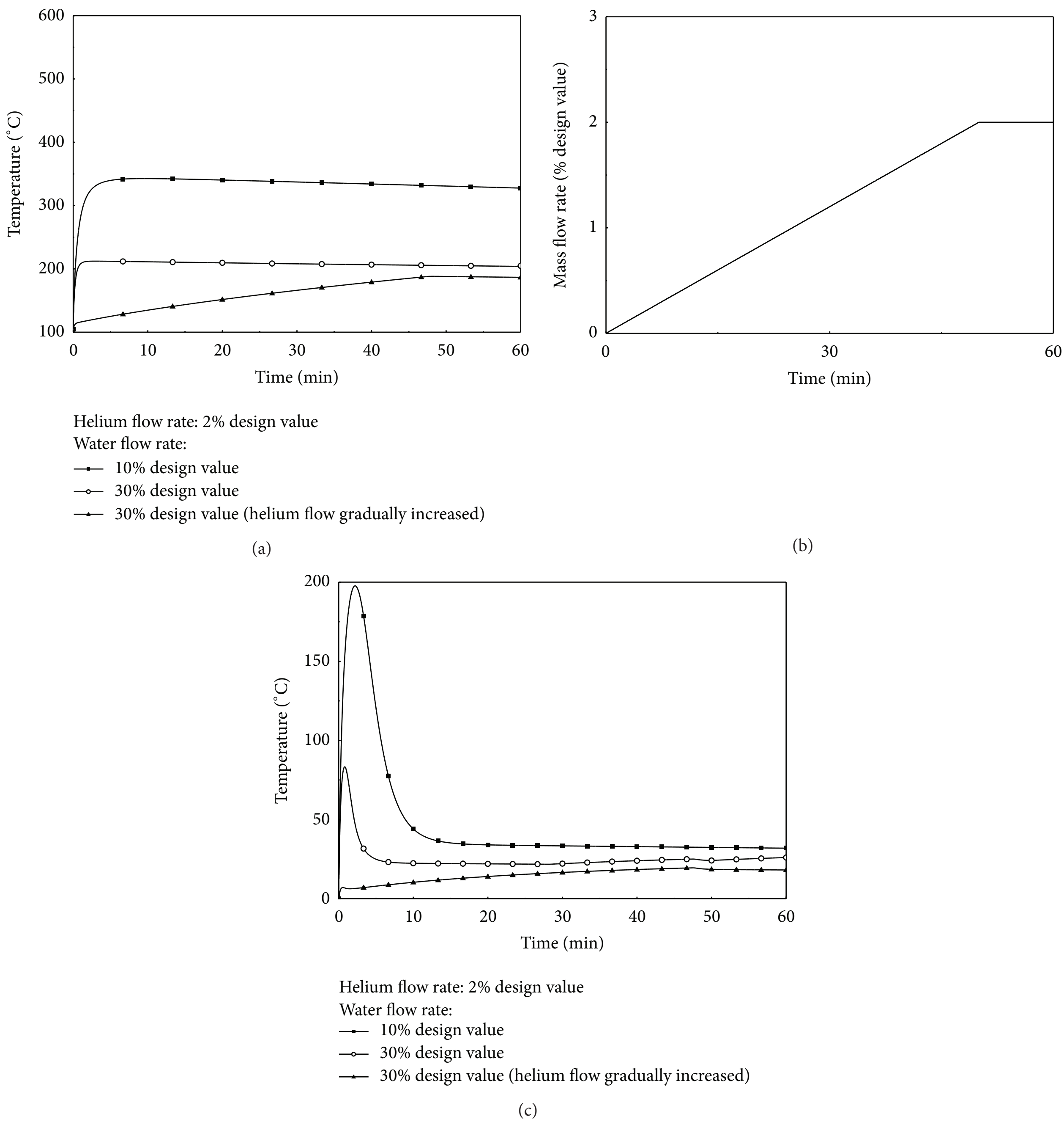

Figure 13: Temperature transient of SG outlet during cooling of reactor core; water inlet temperature: 105°C; pressure: 13.9 MPa; helium mass flow rate: 2%; and design value: (a) temperature at SG outlet; (b) mass flow rate of helium; and (c) temperature difference between tube sheet and steam pipe.

bigger than that of boiling tubes. This temperature delay caused a remarkable temperature difference between steam pipe and tube sheet, as shown in Figure 11, which is dangerous to the weld at position A of Figure 2 although the maximum value is less than 100°C and still meets the demands. To lower this temperature difference the steam flow rate should be reduced.

After maximum temperature of the system decreases to 200°C, the electrical heater of start-up loop will be shifted to supply water with pressure of 13.9 MPa and temperature of 105°C to cool SG and STL further to about 105°C.

Step 4. Cool the core. In the final step the coolant of SG is feed water with temperature of 105°C and pressure of 13.9 MPa. After Step 3, boiling tubes and steam pipe all have temperature of 105°C, which is much lower than that of helium in the core (nearly 750°C). Therefore a heat shock may be introduced to position C in Figure 2 when helium enters SG if the flow rate of helium and feed water are designed inappropriately.

Figure 12 shows the temperature transients at SG outlet when the flow rates of helium and water are set to be 10%

of design value, respectively. In the first minute boiling tube's temperature rises rapidly to nearly 400°C due to the sudden load of hot helium and then decreases to 340°C abruptly when water began to boil. After that, a staggered temperature profile arises and lasts about 10 minutes, accompanied with the oscillation of mass flow rate of steam at boiling tube outlet. The oscillation was caused by the two-phase flow instabilities because of the low mass flow rate of water. Meanwhile the maximum temperature difference between tube sheet of SG and steam pipe enlarges to 300°C. Obviously this process is unacceptable.

This series of problems is caused by big helium flow rate combined with small water flow rate. Figure 13 shows the temperature transient of SG steam outlet with helium flow rate being 2% of design value. Compared with Figure 12(a) the heat shock is alleviated and reduced further with the increase of water flow rate. However, this is still not sufficient to eliminate the heat shock. The helium flow must be controlled to increase slowly from a tiny flow rate as shown in Figure 13(b). Under such operation the temperature difference of SG tube sheet and steam pipe can be confined within 25°C. Therefore the combination of big water flow rate and gradual increase of helium flow from tiny flow rate is the optimum option for this step. However, the present helium circulator may have difficulties to work under so small flow rate. To accomplish this step a smaller circulator should be supplemented to this system.

5. Conclusion

In the present work the ARHRP of HTR-PM has been studied theoretically based on a one-dimensional mathematical model. Transient analysis was carried out for the whole process and following conclusions were obtained.

(1) Boiling is unfavorable for ARHRP, due to both the cold shock to the hot structures induced by large heat transfer coefficient and potential two-phase flow instabilities when feed water flow rate is low. Actually, safety is principal for ARHRP which demands to exclude any fast heat transfer process.

(2) Tube sheet at steam outlet of SG is one of the most damageable positions during ARHRP, for its welds with boiling tubes and steam pipe will suffer thermal stress caused by the temperature differences. Particularly, according to the fact that the time constant of tube sheet is much smaller than that of steam pipe, an obvious delay of temperature variation appears and makes the temperature difference between these two objects remarkable.

(3) For ARHRP without precooling of SG and STL, boiling and cold shock are inevitable when water begins to proceed in the hot boiling tubes before helium begins to circulate. Although the cold shock can be alleviated through shortening the start time of helium circulator, this type ARHRP is not robust.

(4) A four-step ARHRP with precooling of SG and STL can eliminate the cold shock fundamentally. In precooling process steam is used as the coolant to make sure no cold shock will be introduced. After that, the main consideration is to avoid the heat shock to boiling tubes and tube sheet at steam outlet when the hot helium enters SG. A combination of large feed water flow and gradually increased helium flow can eliminate the hot shock and confine the temperature difference between tube sheet and steam pipe effectively. This type ARHRP is recommended in this paper, although a new helium circulator which can supply small helium flow rate should be supplemented to this system.

This work is instructive to the engineering design of ARHRP for HTR-PM, which can shorten the cooling time of reactor core and improve the economic performance of the plant. However, more detailed calculations are needed to specify the flow parameters for each step of ARHRP.

Nomenclature

A: Cross area [m^2]
c_p: Specific heat capacity [J/(kg·K)]
D: Diameter [m]
f: Friction factor
g: Gravity [m/s^2]
h: Specific enthalpy [J/kg]
M: Node number of steam pipes
N: Node number of boiling tube
p: Pressure [Pa]
q: Heat flux [W/m^2]
S: Surface area [m^2]
V: Volume [m^3].

Greek Letters

α_g: Void fraction
ρ: Density [kg/m^3]
τ: Time constant [s].

Subscripts

g: Vapor
m: Mixture of liquid phase and vapor phase
h: Helium.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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