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Thermal behavior of the HTR-10 under combined PLOFC and ATWS condition initiated by unscrammed control rod withdrawal

Feng Gou[1] · Yuan Liu[1] · Fu-Bing Chen[1] · Yu-Jie Dong[1]

Abstract Two tests initiated by unscrammed control rod withdrawal were performed on the High Temperature Gas-Cooled Reactor-Test Module (HTR-10) in November 2003 after the reactor achieved its full power, and the test conditions represented a typical transient scenario of modular high-temperature reactors (HTRs), called pressurized loss of forced cooling, and anticipated transient without scram. Based on the test parameters, the HTR-10 thermal behaviors under the test conditions were studied with the help of the system analysis code THERMIX. The combination of the test results and the investigation results makes the HTR-10 safety potential better understood. Key phenomena, such as the helium natural circulation and the temperature redistribution in the reactor, were revealed. As the safety feature of most significance, there is a large margin between the maximum fuel temperature and its safety limit in each test. Temperatures of thermocouples in different components were calculated by THERMIX and compared with the test values. The applicability of the code was verified by good agreement obtained from the comparison.

Keywords HTR-10 · Control rod withdrawal · ATWS · THERMIX

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1 Introduction

The modular high-temperature reactor (HTR) is considered as a safe, efficient, economic, and environmentally friendly high-temperature heat source for electricity generation as well as process heat production [1]. Such benefits stem from the design options and unique safety features of this reactor type, mainly including the following aspects: chemical stability and compatibility of the core materials under normal operation, because the inert helium is used as coolant; negative temperature feedback and large margin of temperature increase under accident conditions, the combination of which could bring about reactor self-shutdown, even without the action of active shutdown systems; passive decay heat removal depending on natural mechanisms, such as heat conduction, natural convection, and radiation; very slow transient progress due to the large heat capacity of ceramic structural materials; and strong retention capability for radioactive fission products provided by the high-quality coated fuel particles [2]. Among various accident conditions of modular HTRs, a typical accident scenario is called pressurized loss of forced cooling (PLOFC), which could be initiated by different postulated initiating events (PIEs), e.g., inadvertent withdrawal of one control rod, uncontrolled acceleration of the helium circulator, and loss of offsite power, loss of secondary feed water [3]. The PLOFC characteristics generally include the reactor emergency shutdown from steady-state operation and the subsequent core heat-up caused by the loss of forced coolant circulation, while the system pressure of the primary circuit is still maintained, and the reactor cavity cooling system (RCCS) continues to operate to cool the reactor pressure vessel (RPV) [4]. The maximum fuel temperature is the safety-relevant parameter of most

importance in this accident scenario. Another concern is associated with the shift of heat load to the upper part of the reactor, which may increase temperatures of the RPV as well as the top internals [5]. If it is further assumed that, after the initiation of a certain PLOFC accidents, all the control rods fail to drop due to malfunctions, then the anticipated transient without scram (ATWS) condition will occur and may give rise to additional challenges to the safety performance of a modular HTR. This is because, in the long term, the reactor could be critical again and will experience power oscillations, provided that the secondary shutdown system, e.g., the small absorber ball system, could not be put into operation [6]. Thus, the thermal response of a modular HTR under the combined PLOFC and ATWS condition must be investigated to demonstrate the safety potential or safety margin with respect to the concerned safety-relevant parameters.

In China, the first modular HTR is called the HTR-10, of which the first criticality and the full power occurred in 2001 and 2003, respectively [7]. After that, two control rod withdrawal (CRW) ATWS tests were carried out on this reactor at 30% rated power [8]. The tests were initiated by withdrawing one selected control rod while the two shutdown systems were bypassed, so these tests represented an obvious and typical combined PLOFC and ATWS scenario of a modular HTR. In this study, the two CRW ATWS tests are reanalyzed with the help of the THERMIX code based on the actual test conditions. The posttest simulations provide important parameters of great interest that were not obtained during the tests because of the lack of measuring devices, e.g., the time-dependent core temperature profile or the maximum fuel temperature. The combination of the test results and the analysis results makes the HTR-10 thermal behaviors better understood and provides a strong verification of the excellent safety features of modular HTRs. Thermocouples were installed in the top reflector and on the outer surface of the RPV. The temperatures of these components were calculated and compared with the test values. The satisfactory agreement obtained from the comparison verifies the code capability of simulating the combined PLOFC and ATWS condition initiated by the unscrammed CRW.

2 The HTR-10 and its test conditions

Figure 1 shows the primary system of the HTR-10 [9]. The reactor and the steam generator in side-by-side arrangement are housed by two separate pressure vessels. These two vessels are connected with each other by another horizontal pressure vessel where the hot gas duct is installed. Table 1 gives some important design parameters of this reactor.
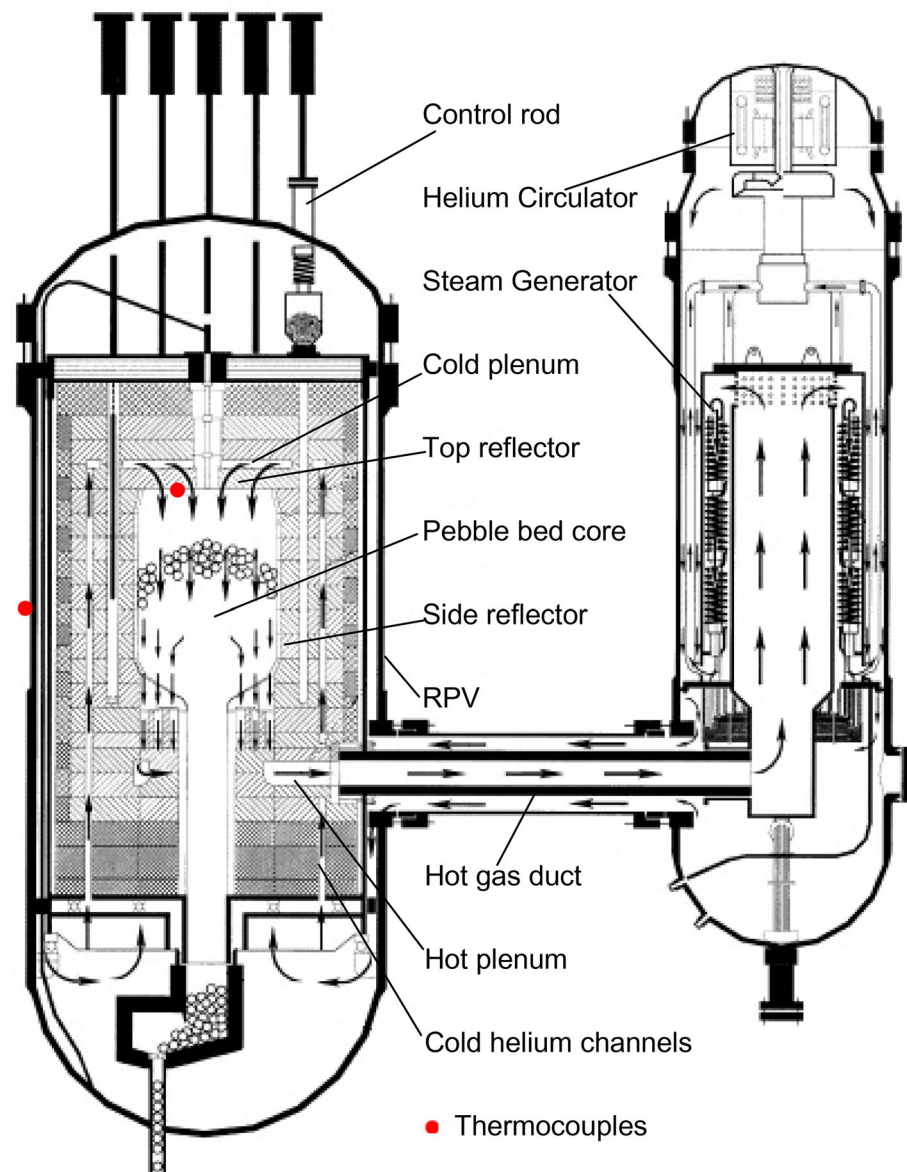
The HTR-10 is a pebble-bed HTR; thus, it contains numerous spherical fuel elements in its reactor core. The fuel ball, which is 6 cm in diameter, contains an inner zone with fissile materials and an outer graphite shell without fuel. The pebble-bed core is enclosed by three categories of graphite reflectors, i.e., the top reflector, the side reflector, and the bottom reflector. The cold helium plenum is designed in the top reflector, and the hot helium plenum is located at the bottom reflector. Several channels with different functions are drilled in the side reflector, e.g., guiding channels in the inner ring for control rods and small absorber balls, and cold helium channels in the outer circumference. Carbon bricks are adopted to surround the graphite reflectors. These materials are thermal insulation of the reactor and provide neutron shielding to the RPV. Ultimately, all the reactor internals are enveloped by the RPV.

The helium flow direction under normal operation is indicated by the arrows in Fig. 1 and could be described as follows. After driven by the helium circulator, the coolant flows into the RPV and arrives at its bottom cavity. Then, the coolant flows upward in the cold helium channels in the side reflector and merges into the cold helium plenum. The mainstream flows downward through the pebble bed; thus, it is heated by the reactor core. Subsequently, the hot helium is collected and mixed in the lower plenum. In the steam generator, the helium transfers energy to the secondary water. After that, the coolant flows back into the RPV again.

Before the CRW ATWS test, the HTR-10 was under steady-state operation, and the power level was 3 MW. The initial conditions of the two tests were very close: the core inlet temperature was 207 °C, the core outlet temperature was 650 °C, and the coolant pressure was 2.4 MPa. Such tests were initiated by withdrawing a selected control rod. In the first test, 1‰ $\Delta k/k$ positive reactivity was introduced within 60 s, and 5‰ $\Delta k/k$ positive reactivity was inserted in the second test in 120 s [10]. According to the test procedure, both the control rod system and the small absorber ball system were intentionally bypassed with the purpose of reflecting the ATWS condition. However, other protection actions were implemented by the protection system, and the protection signal was "power growth rate is too high". Because of such protection actions, the helium circulator was switched off, and the blower baffle was closed so the primary circuit was shut off. In addition, the secondary circuit was isolated.

Figure 2, taken from Ref. [8], shows the reactor power measured during the two tests. It could be observed that the core state experiences the following stages after the initiation of a CRW ATWS test: (1) rapid power increase in the short term resulting from the positive reactivity insertion; (2) automatic reactor shutdown owing to the negative temperature feedback; (3) reactor recriticality after

Fig. 1 Primary system of the HTR-10

- Control rod
- Helium Circulator
- Steam Generator
- Cold plenum
- Top reflector
- Pebble bed core
- Side reflector
- RPV
- Hot gas duct
- Hot plenum
- Cold helium channels
- ● Thermocouples

relatively long-term subcriticality because of the core cooldown; (4) power oscillations due to the internal interaction of the core reactivity, the fission power, and the core temperature; and (5) stabilization of the critical core with a very low power level, which corresponds to the heat dissipation by the RCCS surrounding the RPV. Detailed discussions of the reactor power, including both the test results and the simulation ones, can be found elsewhere [11]. In addition to the reactor power, key transient parameters monitored and recorded include the temperatures of important components, such as the reactor internals and the RPV. Test values obtained from thermocouples in the top reflector, the upper part of the RPV, are utilized to benchmark the code results. The positions of these measuring points are indicated in Fig. 1 [12].

3 Analysis codes and models

In this study, the THERMIX code was used to simulate the two CRW ATWS tests of the HTR-10. This code is widely applied to the thermal hydraulics design and transient analysis of pebble-bed HTRs. It mainly comprises the following analysis modules [13, 14].

3.1 Neutron kinetics module

This module adopts a point kinetics model and considers six groups of delayed neutrons to calculate the transient fission power. Both the feedback reactivity and the external reactivity input can be taken into account. Generally, the feedback reactivity is a result of the variation of the

Table 1 Design parameters of HTR-10

Parameters	Value
Primary circuit	
Reactor power (MW)	10
Power density in average (MW/m^3)	2.0
Coolant pressure (MPa)	3.0
Cold helium temperature (°C)	250
Hot helium temperature (°C)	700
Secondary circuit	
Inlet water temperature (°C)	104
Outlet steam temperature (°C)	440
Mass flow rate (kg/s)	3.49
Outlet steam pressure (MPa)	4.0

following variables: fuel temperature, moderator temperature, reflector temperature, and xenon concentration. However, the external reactivity is usually caused by the insertion or withdrawal of control rods. In addition, decay heat resulting from fission products can also be considered through their kinetic equations. The basic nuclear data used in this simulation are listed as follows: the effective delayed neutron fraction is 7.26×10^{-3}, the prompt neutron lifetime is 1.68×10^{-3} s, and the integrated temperature coefficient of reactivity (fuel, moderator, and reflector) is $- 1.4 \times 10^{-4}$ $\Delta k/k/$ °C.

3.2 Heat conduction module

In this module, a two-dimensional heat conduction equation is adopted for the calculation of the temperature field in the reactor. The pebble bed is regarded as homogenous porous media [15]. The temperature

distribution in the spherical fuel element is treated by one-dimensional heat conduction. Different components of the HTR-10 can be modeled with the assignment of different material compositions. These typical components include the pebble-bed reactor core, the reflectors made by graphite, the boracic bricks made by carbon, and the metallic RPV.
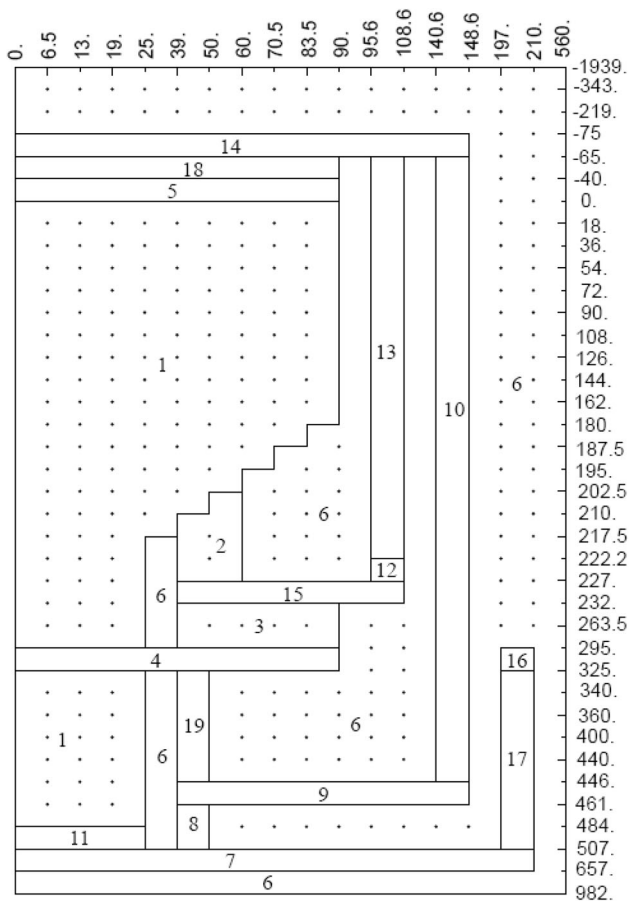
3.3 Gas convection module

The flow conditions in a pebble-bed HTR can be simulated by this module. A two-dimensional quasistationary coolant flow model is used and coupled with the time-dependent temperature distribution of the reactor provided by the heat conduction module. Figure 3 shows the gas convection model of the HTR-10. It is established in (*r*, *z*) geometry and is axisymmetric in two dimensions. The zero point of the radial coordinate is on the core centerline, whereas the zero point of the axial coordinate is located at the core top surface, and the plus direction is toward the reactor bottom. All the flow paths inside the HTR-10 RPV are described in this calculating model, including the pebble-bed core and different channels mentioned in Sect. 2.

3.4 Primary circuit module

This module aims at the pipes and components in the primary circuit and calculates the temperature and pressure of the coolant in such structures. A one-dimensional quasistationary flow model is also used here. The concerned components include the hot gas duct and its coaxial outer pipe, flow paths in the primary side of the steam generator, the helium circulator, and so on.
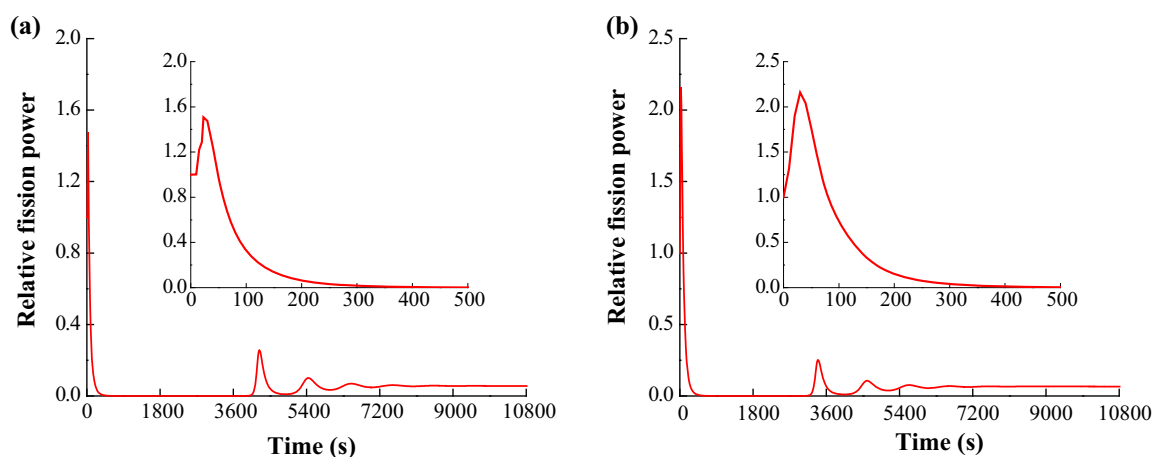
Fig. 2 (Color online) Reactor power measured during the CRW ATWS tests: **a** 1‰ reactivity insertion and **b** 5‰ reactivity insertion

Fig. 3 Gas convection model of the HTR-10. (1) Reactor core; (2, 3) flow channel in the bottom reflector; (4) hot helium plenum; (5) top cavity of the core; (6) nonflow region; (7) bottom cavity of the RPV; (8, 9) bottom coolant channels; (10) flow channel in the side reflector; (11, 12) throttle plate; (13) control rod channel; (14) cold helium plenum; (15) small plenum in the bottom reflector; (16) inlet cavity of the RPV; (17) annular space of the RPV; (18) flow channel in the top reflector; (19) leak flow region

4 Analysis results

The time duration of a CRW ATWS test is 3 h; therefore, the posttest transient simulation for each test was performed for 3 h. As mentioned in Sect. 2, the blower baffle of the helium circulator plays the role of the shutoff valve. In one CRW ATWS test, the blower baffle was closed after the reactor protection system was triggered; therefore, the HTR-10 primary circuit was subsequently cut off. However, the helium in the RPV was still maintained at 2.4 MPa, and this relatively high pressure led to high coolant density. As a consequence, the buoyancy effect was caused by temperature gradients in both the radial direction and the axial direction. Then, the helium natural circulation was established due to the helium buoyancy effect. The flow paths of the helium's natural circulation were the pebble-bed core, the cold helium plenum, the

helium plenums, the control rod guiding channels, and the fuel discharging tube. Arrows in Fig. 4 show the helium flow direction inside the RPV at different times during the two CRW ATWS tests. For each test, the figure indicates both the flow direction of the natural circulation after the cutoff of the primary circuit and that under steady-state operation before the test. The shape and zone of the pebble-bed core are represented by the broken lines in Fig. 4. In the natural circulation loop, the coolant flows upward in the central part of the core and flows downward in the peripheral part. Thus, the hot helium directly heats up the upper region of the core, as well as the top reflector. At the same time, the outer region of the pebble bed and the side reflector can also receive the heat transferred by the helium. In contrast, the core bottom is cooled down in this process. In addition to heat conduction and radiation, this helium natural circulation is another major natural mechanism for the heat removal from the core.

The natural circulation resulted in significant temperature redistribution in the reactor, as shown by isotherms in Fig. 4. In the first test, the temperature of the core upper region rose from the steady-state value of 200–400 to 400–800 °C in 3 h, whereas, in the core bottom region, the temperature decreased from the initial value of more than 600–800 to 400–600 °C. Such a heat-up effect for the core upper region and cooldown effect for the core bottom region could also be observed for the second test. During the two tests, the high-temperature zone of the core always kept a temperature scope of 800–900 °C, and its spatial range was wider in the second test.

For the first test, Fig. 5a gives the axial temperature distribution on the reactor centerline ($R = 0$ cm), where the hottest spot of the core exists. The highest solid temperatures of the core at different times were 843 °C ($Z = 180$ cm) at 0 s, 815 °C ($Z = 106$ cm) at 4240 s, and 831 °C ($Z = 18$ cm) at 10,800 s. For the hottest spot, its location at the end of the test was 1.6 m higher than that at the beginning of the test. Also, the top reflector experienced a temperature increase of more than 300 °C. For the second test, the same effects, i.e., elevation of the hottest spot and the heat-up of the top reflector, could be found.

As illustrated in Fig. 1, there was a thermocouple arranged on the undersurface of the top reflector. The calculated temperature at this position and its comparison with the test value are presented in Fig. 5b. The flow direction of the before-mentioned natural circulation and the location of this thermocouple made it directly confront the hot helium. Therefore, its temperature increased approximately 235 °C in 3 h. THERMIX reproduces the temperature change very well, and the agreement obtained from the comparison is satisfactory.

For the second test, Fig. 6a gives the radial temperature distribution at the reactor upper region ($Z = 18$ cm).

(a)

(b)
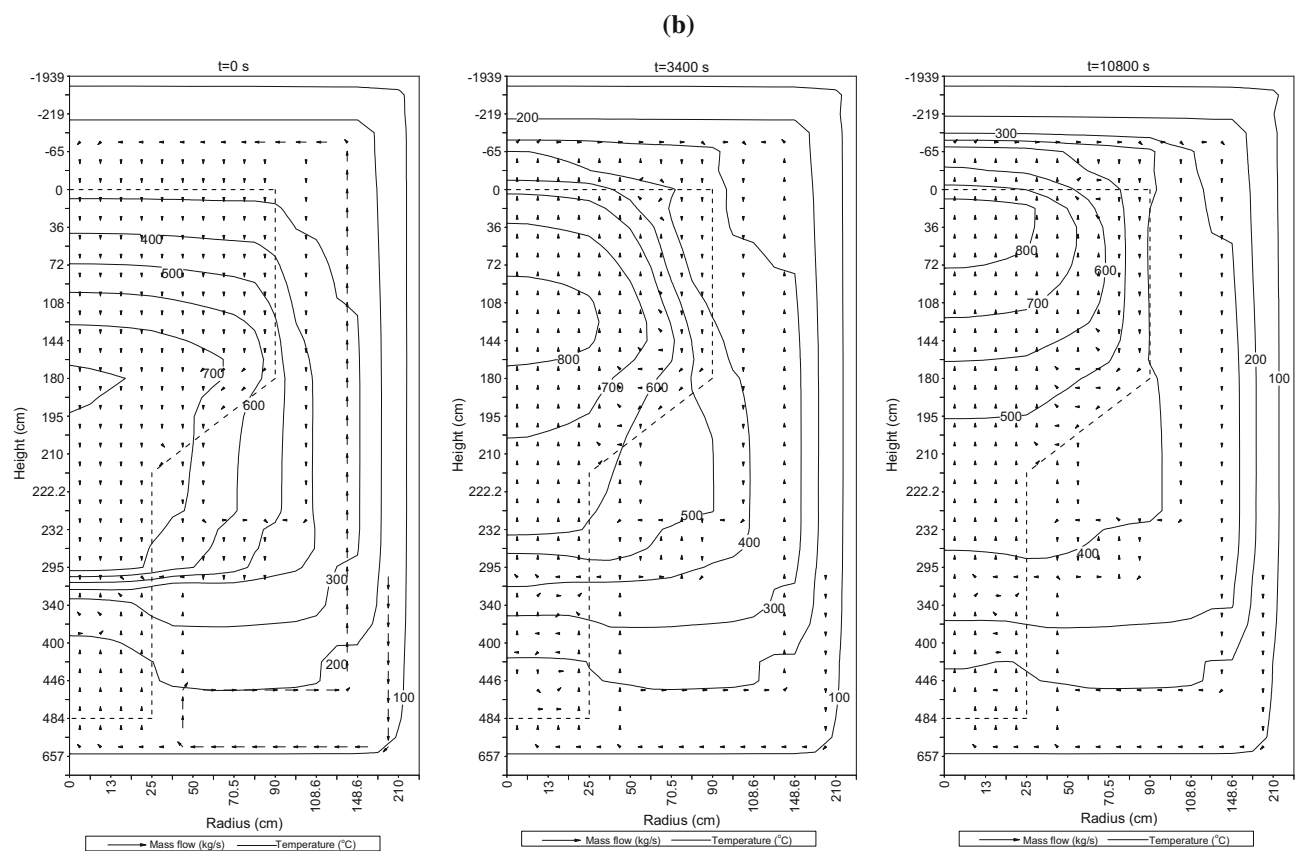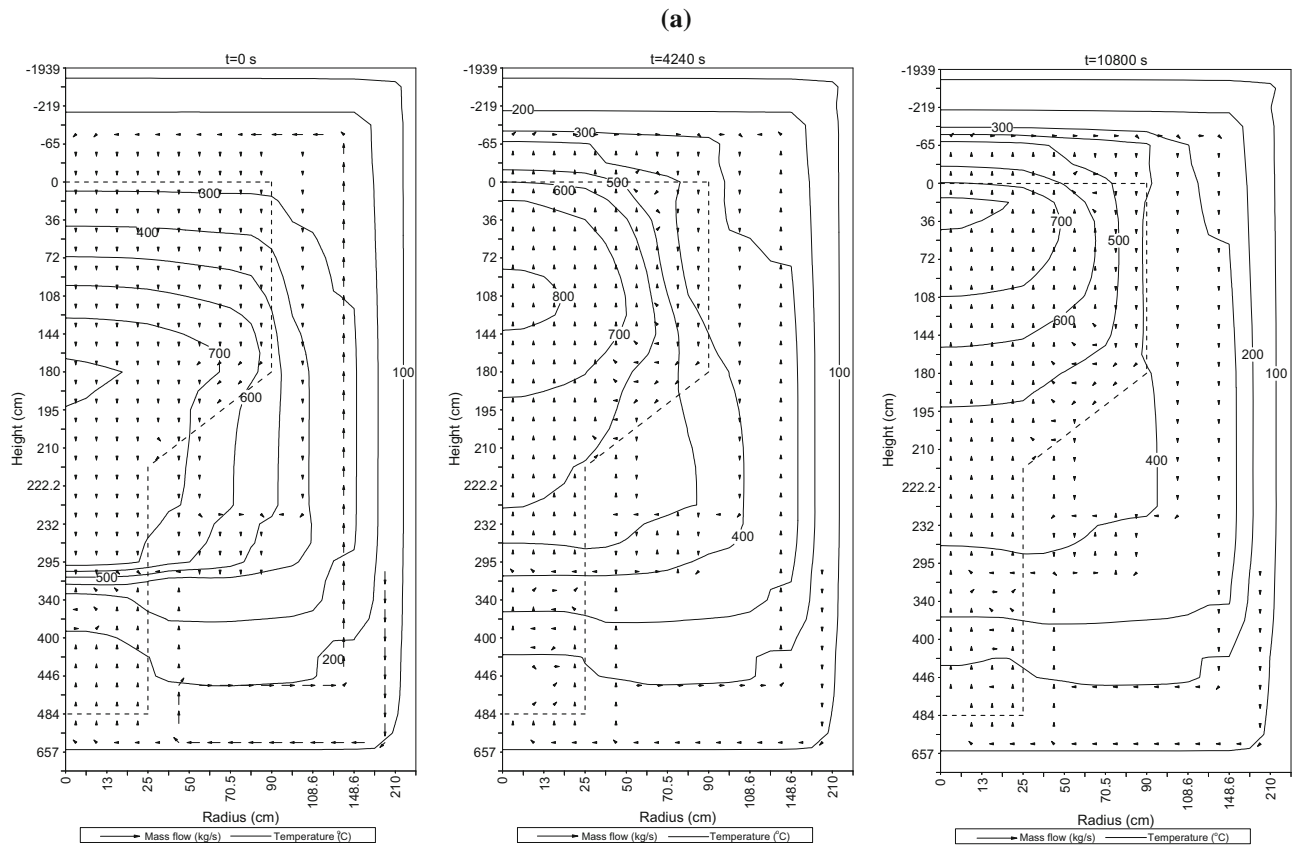
◀**Fig. 4** Flow distribution and temperature distribution from simulations of the CRW ATWS tests: **a** 1‰ reactivity insertion and **b** 5‰ reactivity insertion

Because the core upper part was heated by the helium natural circulation, the lateral temperature difference in the

core and in the side reflector was intensified with time at this height. However, the RPV temperature decreased slightly, because of the heat storage of the core and the graphite reflector due to their large heat capacity, and the strong cooling capability of the RCCS surrounding the RPV. For the first test, a similar phenomenon, i.e., the

(1) Top reflector (3) Pebble bed core
(2) Top cavity   (4) Fuel discharging tube
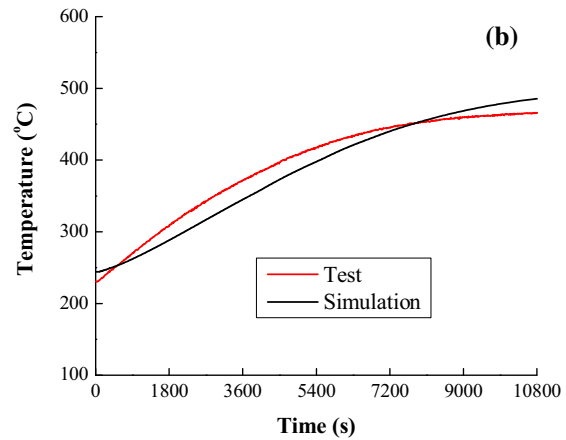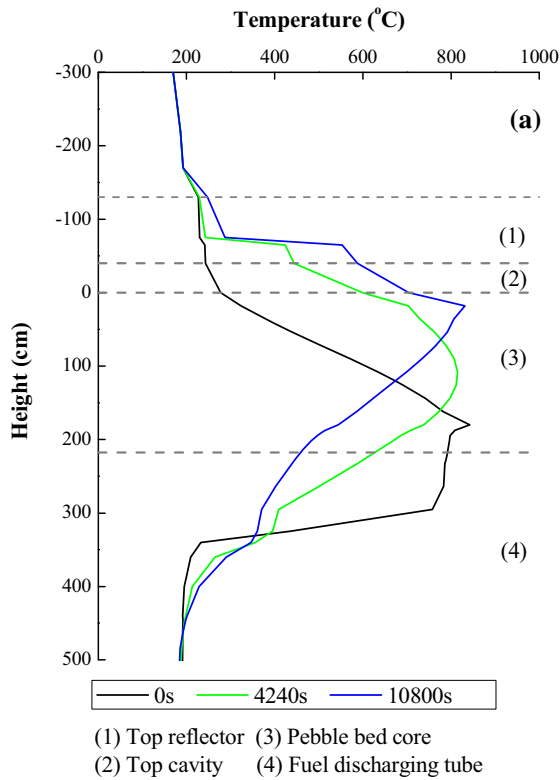
Fig. 5 (Color online) Temperature profiles in the 1‰ reactivity insertion ATWS test: **a** core centerline ($R = 0$ cm) and **b** top reflector

(1) Pebble bed core (3) Core barrel and gaps
(2) Side reflector   (4) Reactor pressure vessel
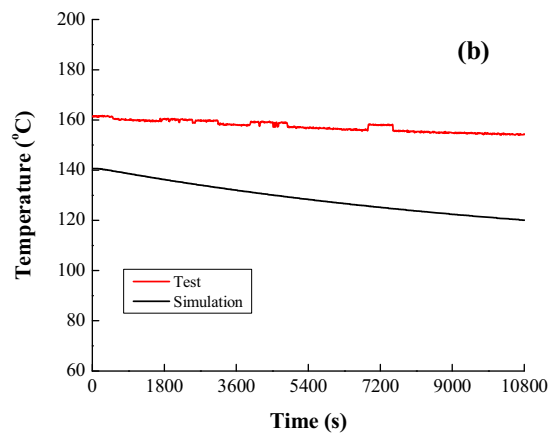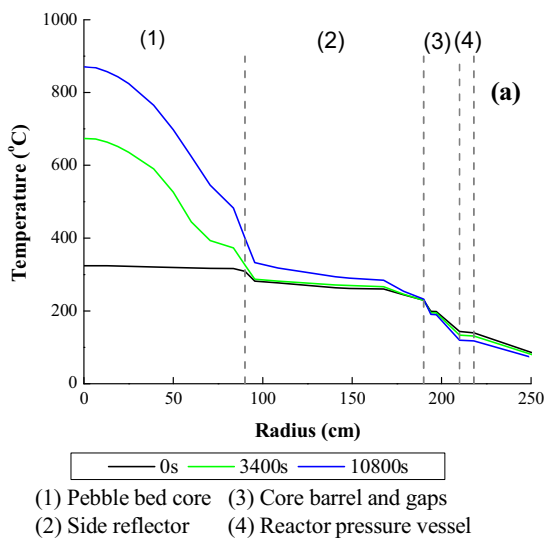
Fig. 6 (Color online) Temperature profiles in the 5‰ reactivity insertion ATWS test: **a** reactor upper region ($Z = 18$ cm) and **b** RPV outer surface
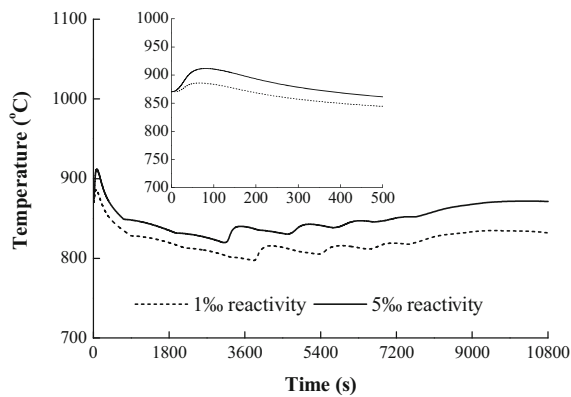
Fig. 7 Calculated maximum fuel temperatures during the CRW ATWS tests

decoupling of the core temperature and the RPV temperature, was observed.

On the upper part of the RPV surface, there was also a thermocouple, as illustrated in Fig. 1. The calculated temperature of this measurement point is presented in Fig. 6b and is compared with the test value. Basically, the analysis result is in accordance with the temperature variation tendency of this thermocouple, although the code obviously underestimates the test curve with a largest discrepancy of 40 °C. For the RPV temperature during the two tests, either the calculated value or the measured value was not found to be higher than 200 °C, so there were not any thermal problems posed on the RPV integrity.

The maximum fuel temperature is the safety-relevant parameter of most importance, and Fig. 7 gives this value versus time for the two tests. In the first test, the peak value was 886 °C at 65 s. In the second test, it achieved 912 °C at 80 s. Because such temperature values are far away from the safety limit of 1620 °C [16], there was a large safety margin for the HTR-10 in the CRW ATWS tests.

5 Conclusion

After the HTR-10 realized the full power, two CRW ATWS tests were carried out at 30% rated power. Each test was initiated by withdrawing a selected control rod, while the reactor shutdown systems were intentionally bypassed. In the first test, 1‰ positive reactivity was introduced into the core; in a second test, 5‰ $\Delta k/k$ positive reactivity was added. The test conditions represent an obvious and typical combined PLOFC and ATWS scenario of modular HTRs. Based on the actual test parameters, the HTR-10 thermal behaviors in these two tests were studied with the help of the THERMIX code.

From the analysis results, similar physical phenomena could be observed for the two tests. Dozens of seconds

after the initiation of a certain test, the reactor loses coolant forced circulation because of the helium circulator switch-off and the blower baffle close, which are the actions implemented by the protection system. The helium buoyancy effect induces an obvious natural circulation loop in the reactor. This provides an effective heat transport mechanism and leads to a significant temperature redistribution in the reactor during the test process. In each test, the hot zone of the core falls in a temperature range of 800–900 °C; however, the hottest spot of the core is elevated for 1.6 m along the core centerline 3 h later. For thermocouples installed in the top reflector and on the RPV outer surface, the THERMIX code reproduces the temperature change tendency very well, but it underestimates the RPV temperature. The RPV integrity is not challenged in the two tests, because both the calculated temperature and the test one are under 200 °C, which is far below the safety limit. In each test, the most important safety parameter, i.e., the maximum fuel temperature, always keeps far below 1620 °C, set as the safety limit for fuel elements of modular HTRs. The investigation results of the reactor thermal behaviors indicate the HTR-10 safety potential under the combined PLOFC and ATWS condition initiated by unscrammed CRW. The THERMIX code is benchmarked by the test results for its applicability and reasonability. The current study could provide a good reference and a credible tool for the analysis of such accident or test conditions of the HTR-PM, which is the first commercial-scale demonstration project of a pebble-bed modular HTR [17].

As mentioned before, the THERMIX code adopts two-dimensional axisymmetric models for both the heat conduction and the helium flow inside the RPV. However, several complex structures in the reactor, e.g., the bottom reflector or the fuel discharging tube, may challenge the simulation capability provided by the two-dimensional models. Therefore, three-dimensional calculation modules are under development in INET with the purpose of more accurate simulation for the temperature field of the reactor, and the mass flow, the pressure and the temperature of coolant in complex zones. The newly developed modules continue to use the fundamental physical models provided by THERMIX, such as formulas describing the equivalent heat conductivity of the pebble bed and the pressure drop in different components.

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