Preliminary Study on HTR-10 Operating in Higher Outlet Temperature

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Abstract. High Temperature Gas-cooled Reactor (HTGR), which has well-known safety features and high temperature heat supply capability, is expected to be widely used for heat supply and technology heat utilization including the hydrogen production, and so contributing to the reduction of carbon dioxide emissions in various sectors. The 10 MW High Temperature gas-cooled test Reactor (HTR-10) had been constructed and operated in China as a pilot plant to demonstrate the inherent safety features of the modular HTGR. The first criticality of HTR-10 at air condition was realized on December 1, 2000, and the full power operation for 72 h on January 29, 2003. Supported by Chinese National S&T Major Project, HTGR for hydrogen production are now being studied. The physical and thermal hydraulic design to raise the outlet helium temperature of the HTR-10 reactor core from 700 ºC to 850~1000 ºC is carried out. In this paper, the preliminary thermal hydraulic design of the HTR-10 with the outlet helium temperature of 950 ºC (HTR-10H) is introduced. The power density distribution, the fuel temperature distribution and the reactor pressure vessel (RPV) temperature are studied to identify what need to be focused on next. Besides, the typical DLOFC accident has been studied to evaluate the safety feature of the HTR-10 operating under higher core temperature and outlet temperature. The preliminary results show that, operated at the higher outlet helium temperature, the original acceptance criteria for HTR-10 will be challenged. In the future, the design optimization, as well as the possible modification of these acceptance criteria, which were set more than two decades ago, should be studied based on the current knowledge of the fuel element properties and structure material properties.

1. Introduction

High Temperature Gas-cooled Reactor (HTGR) with higher outlet temperature from 700 ºC to 800~1000 ºC is expected to be widely used for heat supply and technology heat utilization including the hydrogen production, steelmaking, seawater desalination, thermal recovery of heavy oil, coal liquefaction and gasification. Further popularization and application of the HTGR technology with well-known safety features can greatly contribute to reducing carbon dioxide emissions.

The 10 MW High Temperature gas-cooled test Reactor (HTR-10) had been constructed and operated in China as a pilot plant to demonstrate the inherent safety features of the modular HTGR [1, 2]. The primary circuit of the HTR-10 is shown in Figure 1, while the main parameters are listed in Table 1.
Supported by Chinese National S&T Major Project and National Key R&D Program of China, some research on HTGR, including the operation of HTR-10 in higher outlet helium temperature, combination of HTGR technology and hydrogen production, design of intermediate heat exchanger for HTR-10, and so on, are carried out in the Institute of Nuclear and New Energy Technology (INET), Tsinghua University, China.

The reactor core of the HTR-10 is a packed bed of 27,000 spherical fuel elements. The on-line charge and discharge of the fuel elements have been successfully demonstrated in the HTR-10. The heavy-metal loading per fuel element is 5g and the enrichment of fresh fuel element is 17%. In the equilibrium state, each fuel element may reach the target burn-up and then be discharged after 5 passes through the reactor core.

![Figure 1. Cross section of the HTR-10 primary circuit.](image)

| Parameter               | Unit      | Value    |
|-------------------------|-----------|----------|
| Thermal power           | MW        | 10       |
| Reactor core diameter   | cm        | 180      |
| Reactor core height     | cm        | 197      |
| Primary helium pressure | MPa       | 3        |
| Inlet/outlet helium temperature | ºC | 250/750 |
| Helium flow rate        | kg/s      | 4.32     |
| Number of fuel elements | -         | 27,000   |
| Average discharge burn-up | GWd/tHM | 80      |
| Feed water temperature  | ºC        | 104      |
| Steam pressure          | MPa       | 4        |
| Steam temperature       | ºC        | 440      |
| Steam flow rate         | kg/s      | 3.47     |

Table 1. Main design parameters of the HTR-10.
Based on the structure design and fuel cycle design of the 10 MW High Temperature gas-cooled test Reactor (HTR-10), a preliminary thermal hydraulic design with the outlet helium temperature of 950 °C (below is called HTR-10H) is introduced in this paper. The power density distribution, the fuel temperature distribution and the reactor pressure vessel (RPV) temperature are also presented. Besides, the Depressurized Loss of Forced Cooling (DLOFC) accident has been analyzed to study the maximal fuel temperature.

This preliminary study mainly focuses on the primary circuit. The primary helium pressure and the inlet helium temperature are same as those shown in table 1. To reach a higher outlet helium temperature of 950 °C, the mass flow rate of the coolant decreases to about 2.74 kg/s.

2. Thermal Hydraulic Parameters of the Equilibrium Core

The physical design and thermal hydraulic design of the HTR-10H operating in higher outlet helium temperature of 950 °C are carried out the V.S.O.P. code[3] and TINTE code[4]. The two-dimensional flow model of TINTE code is shown in Figure2.

Figure 2. Flow model of TINTE for the HTR-10H

Figure 3 shows the power density distribution of the HTR-10H (R=0 means the center of the core, H=0 means the top of the core, while H=217 means the bottom of the core). Maximal power density is about graphite reflector and carbon brick is also considered. It also can be seen that, based on the HTR-10 structure design, fuel design and fuel cycle design, the power density distribution seems flatter when it operated in higher outlet temperature.
Figure 3. Power density of the HTR-10H.

Figure 4. Solid temperature distribution of the HTR-10H.

Figure 4 shows the solid temperature, which means the fuel surface temperature within the core area (as shown in the Figure 2). The maximal fuel surface temperature and fuel center temperature at the bottom of the core are about 1290°C and 1390°C respectively, much higher than those of HTR-10. It can be explained as below: 1) The flatter power density distribution, in other words, the higher power density at the reactor bottom, will cause the higher temperature difference between the fuel center and fuel surface. 2) With the same power and same inlet helium temperature, to reach the higher outlet helium temperature, much lower mass flow rate of the coolant is adopted, which results in a weaker heat transfer between the fuel elements and gas. 3) In HTGR, there exists leakage flow, also called bypass flow,
through the tiny gaps between the graphite blocks. Due to the lower coolant flow rate, as well as this bypass flow, the radial temperature deviation at the core outlet is also larger.

Figure 5 shows the temperature distribution along the side of the RPV. Maximal temperature appears at about the center of the pebble bed core. With the higher fuel temperature, the temperatures of the RPV of the HTR-10H are also higher than those of the HTR-10.

![Figure 5. RPV temperature distribution of the HTR-10H](image)

As the first test HTGR in China established more than two decades ago, to ensure the fission product retention capacity of the coated particles in the fuel element, the temperature limitation of the fuel element of the HTR-10 during normal operation and all Design Basis Accidents (DBAs) is set as 1230 ºC. The temperature limitations of RPV during normal operation and DBAs are 320 ºC and 375 ºC respectively. All these acceptance criteria were set very conservatively with large margins, compared to those of the AVR (Arbeitsgemeinschaft Versuchsreaktor) in German and the later 200 MWe Pebble-bed Modular High Temperature gas-cooled Reactor (HTR-PM) in China. For example, the fuel temperature limitation for the HTR-PM in all DBAs is 1620 ºC, while the RPV temperature limitations during normal operation and DBAs are 350 ºC and 425 ºC respectively.

Therefore, based on the further understanding of the fuel element properties and structure material properties, the acceptance criteria for HTR-10H should be reconsidered and reasonable modification is expected.

Although the coated particles in the fuel element have excellent fission product retention capacity, the higher fuel temperature during the normal operation will result in a slight increase in radioactivity in the primary coolant. Besides, the higher fuel temperature and RPV temperature may reduce the margin for the accident conditions. Therefore, further design optimization should also be considered.

3. DLOFC Accident Analysis

Based on this preliminary thermal hydraulic design, the DLOFC accident is analyzed with the TINTE code.

It is conservatively assumed that the reactor loses all the primary coolant instantaneously and all the decay heat are carried out via the heat conduction and thermal radiation. Another conservatively assumption is that when accident happens the reactor is operated at the 102% rated power, and after reactor shutdown the decay heat is also 102% of the normal value. Figure 6 shows the maximal and average fuel temperatures during the accident.

Due to the low nuclear power (10 MW) and power density (~2 MW/m³), and also due to the large heat capacity of the graphite reflector and carbon brick, in accident condition, after reactor shutdown, the decay heat can be transferred to the reactor cavity and finally to the environment quickly. As the Figure 6 shows, the maximal fuel temperature, as well as the average fuel temperature will decrease continuously.
Figure 6. Fuel temperature of the HTR-10H during the DLOFC accident.

Figure 7. Fuel temperature of the HTR-10H during the DLOFC accident.

Figure 7 shows the center temperature of the fuel elements at the reactor center. It can be seen that, after reactor shutdown, the fuel temperatures of the lower part of the core will decrease quickly, while there exists little increase for the fuel temperatures of the upper part of the core.

But the RPV temperature will increase after the accident happen, because the decay heat transferred from the core to the RPV continuously, as shown in Figure 8. In the Figure 9, temperatures of the inner side and outer side of the RPV 25 hrs. after the accident happens, when the maximal fuel temperature of the RPV reaches the peak value, are shown.

With the decrease of the decay heat, as well as the increase of the heat transferred by the reactor cavity cooling system (RCCS), the RPV temperature will begin to decrease about 20 to 30 hrs. after the accident happens. Figure 10 shows the changes of the decay heat and the heat transferred by the RCCS during the accident.

The calculation results show that, during the DLOFC accident, the maximal fuel temperature and maximal RPV temperature will not exceed the temperature limitation for the HTR-PM (namely 1620 °C for fuel element and 425 °C for RPV). But they do exceed the conservative temperature limitation for the HTR-10.
Figure 8. Maximal RPV temperature of the HTR-10H during the DLOFC accident.

Figure 9. RPV temperature distribution 25 hrs. after the accident happens.

Figure 10. Decay heat and RCCS heat load during the DLOFC accident.
4. Conclusion and Future Work
A preliminary thermal hydraulic design for HTR-10 operated in higher outlet helium temperature increased from current 700 ºC to 950 ºC in the future is introduced in this paper. Based on this preliminary design, the DLOFC is also studied. The main results are as below:

1. With the same structure design, same fuel design and same fuel cycle design, the higher outlet helium temperature is realized only by decreasing the mass flow rate of the helium.
2. Operated in higher outlet helium temperature, the power density distribution seems flatter. The fuel temperature, the structure temperature and the RPV temperature have increased considerably.
3. Due to the lower power and power density, as well as the large heat capacity of the graphite reflector and the carbon brick, during the DLOFC accident, the maximal fuel temperature will decrease continuously.
4. As the first test HTGR in China designed and established more than two decades ago, the temperature limitations of the fuel element and RPV of the HTR-10 were set very conservatively. Analysis results show that, both in normal operation and accident condition, the acceptance criteria of fuel element and RPV designed for the HTR-10 would be exceeded. The acceptance criteria should be reconsidered based on the current further knowledge of the fuel element properties and RPV material properties.

According to above results, further design optimization and further research need to be carried out, including the in-depth thermal hydraulic design and accident analysis, the optimization of the fuel design or fuel cycle mode, the revaluation and modification of the acceptance criteria, and so on.

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