Experimental Study on the Residual Heat Removal System in HTR-10

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Abstract – The 10MW high temperature gas-cooled reactor (HTR-10) is a modular pebble-bed type reactor, of which the inlet and outlet helium temperature are 250 and 700 °C, respectively. It reached to its first criticality in December, 2000, and operated for nearly twenty years successfully. Currently, HTR-10 is the only pebble-bed type high temperature gas-cooled reactor that can operate in the world. To verify the natural circulation operating characteristics and safety features of the passive residual heat removal system, a series of experimental studies have been performed under different operation conditions of HTR-10, which include the performance tests of the passive residual heat removal system under various reactor operating power, different ambient temperature and single loop run mode. According to the data collation and result analysis, it shows that the performance of the residual heat removal system in HTR-10 meets the design and safety requirements.

1. Introduction

The 10MW high temperature gas-cooled reactor (HTR-10) is a modular pebble-bed type reactor with passive safety characteristics. It is the first high temperature gas-cooled reactor with independent intellectual property rights which was designed, built and operated in China. The HTR-10 adopts graphite spheres containing ceramic tri-structural coated particles, high temperature resistant graphite, and helium as fuel elements, core structural material, and primary coolant. The rated thermal power of the reactor is 10 MW, the primary operating pressure is 3.0 MPa, and the core outlet temperature of helium is 700 °C [1].

The first tank of concrete of HTR-10 was poured on June 14, 1995, the cold commissioning was finished in November, 2000, and the first criticality was reached on December 1, 2000. In January, 2003, the 72 hours of full power operation and acceptance test of grid-connected power generation were completed. Since then, relevant safety and high-power operation tests have been performed successively until July 2007. All parameters were fully reached the design target, indicating that China has mastered a series of core technologies and design technologies for the HTGR, as well as system integration technologies for the research, development, design, processing and construction of new reactors [2].

The residual heat removal system is one of the important guarantees and embodiment of the inherent safety of HTR-10. It adopts the idea of passive design which relies on the radiation, heat conduction and natural convection to carry out the heat. After shutdown of the reactor, it can continue to run without
any operation [3-7]. In this paper, we introduce a series of experimental studies which have been performed under different operation conditions of HTR-10 to verify the natural circulation operating characteristics and safety features of the passive residual heat removal system.

2. Residual Heat Remove System of HTR-10

During normal operation of the HTR-10 reactor, the residual heat removal system performs the cooling functions of the pressure vessel support and reactor compartment. During normal shutdown, especially after the accident shutdown, it takes the function of residual heat removal [8-12]. The reactor residual heat is carried out of the reactor compartment, which can ensure that the temperature of the reactor internals and pressure vessels are lower than the specified limits. The HTR-10 residual heat removal system includes two independent loops, each with a design capacity of 134 kW. One loop of operation can meet the requirement of residual heat removal. As described in Figure 1, the system is composed of water cooling wall, expansion tank, air cooler, connecting pipe and air cooler.

The residual heat of the reactor is carried out through two natural circulation loops. The heat transferred by radiation and natural convection from the pressure vessel and compartment was absorbed to heat the cooling water in the water cooling wall. The cooling water increases in temperature and decreases in density, thus flows upward along the hot water pipe to the air cooler driven by buoyancy lift. After cooling water is cooled in the air cooler, it flows back to the water cooling wall along the cold-water pipe due to gravity, and continues to absorb heat to form a natural circulation in the water. Ambient air enters from the bottom of the air-cooling tower by lifting force. After heating by the air cooler, the temperature increases and the density decreases, and then the air is discharged through the upper outlet of the air-cooling tower into the final heat sink—atmosphere.

3. Thermal Hydraulic Calculation and Experimental Studies

3.1. Thermal hydraulic calculation

The design of residual heat removal system of HTR-10 is on the basis of thermal hydraulic calculation. The whole heat transfer process was calculated during the system design. In the calculation, it is assumed that the pressure vessel wall and the water cooling wall are two concentric cylinders of finite length, and the ratio between the annular space from the pressure vessel to the water cooling wall and the pressure vessel height is only approximately 0.058. Therefore, the convection heat transfer can be estimated according to the natural convection in the finite space.

The radiative heat transfer calculation formula can be expressed as follows:
\[ Q = \varepsilon_n C_0 F_1 \left[ \left( \frac{T_1}{100} \right)^4 - \left( \frac{T_2}{100} \right)^4 \right] \]  

(1)

\[ \varepsilon_n = \frac{1}{\varepsilon_1 + \frac{F_1}{F_2} \left( \frac{1}{\varepsilon_2} - 1 \right)} \]  

(2)

Where, \( \varepsilon_1 \) is the blackness coefficient of the pressure vessel wall, \( \varepsilon_2 \) is the blackness coefficient of the water cooling wall, \( C_0 \) is the absolute blackness coefficient, \( F_1 \) is the outer wall area of the pressure vessel, \( F_2 \) is the surface area of the water cooling wall, \( T_1 \) is the outer wall temperature of the pressure vessel, \( T_2 \) is the surface temperature of the water cooling wall.

The calculation formula of the convective heat transfer can be expressed as follows:

\[ Q = \frac{F \lambda_e}{\delta} (t_1 - t_2) \]  

(3)

\[ G_r = \frac{9.81 \times \delta^3 \times \frac{1}{\beta} \times (t_1 - t_2)}{\nu^2} \]  

(4)

\[ \varepsilon_K = \frac{\lambda_e}{\lambda} = 0.4(G_r \cdot P_r)^{0.2} \]  

(5)

Where, \( F \) is the surface area of the pressure vessel wall, \( \delta \) is the annular space, \( \lambda_e \) is the equivalent thermal conductivity, \( t_1 \) is the wall temperature of the pressure vessel, \( t_2 \) is the temperature of the water cooling wall, \( \beta \) is the gas expansion coefficient, \( \nu \) is the gas viscosity, and \( P_r \) is the Prandtl number.

Assuming that the temperature of the pressure vessel wall is 234 °C and the temperature of the water cooling wall is 80 °C, the thermal hydraulic calculation shows that the radiant heat transfer from the wall of the pressure vessel to the water cooling wall is approximately 214 kW, and the natural convection on the wall of the pressure vessel can generate a heat of 17.2 kW.

The air cooler heat dissipation and the air cooling tower heat load formulas can be expressed as follows:

\[ Q_2 = K \cdot F \cdot \Delta T \]  

(6)

\[ Q_1 = G \cdot C_p \cdot \Delta T \]  

(7)

According to the above formulas, the heat transfer power is calculated to be approximately 135 kW, which can meet the requirement of heat transfer power of 134 kW designed for the residual heat removal system.

3.2. Performance verification tests under different operating power of reactor

As shown in Fig 2, performance tests for the residual heat removal system under different operating power of the HTR-10 reactor were performed. The variation trends of operating parameters related to the residual heat removal system from reactor start-up, power increase, stable operation to the emergency shutdown were recorded, which mainly include the nuclear power, main feed water flow, the wall temperature of the pressure vessel, the inlet and outlet water temperature of the water cooling wall, and the inlet and outlet air temperature of the air cooler.
Figure 2. Parameter curves of the residual heat removal system under different operating conditions

From the variation of the parameter curves of the residual heat removal system at different operating powers of HTR-10, it can be seen:

1. The reactor power and the wall temperature of the pressure vessel rise rapidly in the start-up process of the reactor. However, due to certain heat capacity of the heat transfer materials and working medium, the parameter change of residual heat removal system is delayed behind those of the reactor power and the wall temperature of the pressure vessel. With the increase of the temperature of the outer wall of the pressure vessel, the driving forces of radiation and convective heat transfer to the water cooling wall are correspondingly increased, and more heat is absorbed by the cooling water in the residual heat removal system. Therefore, the driving force of buoyancy is increased, the flow rate is increased, and the carrying heat is also gradually increased.

2. During the stable operation of the reactor, the operating parameters of the residual heat removal system fluctuate with the change of the ambient temperature at the inlet of the air cooler. The temperature difference between the inlet and outlet of the water cooling wall is maintained at approximately 10 °C and the residual heat load is approximately 100 kW. The water temperature at the outlet of the water cooling wall is far below the boiling point of 100 °C, which meets the requirements of stable operation.

3. The reactor power drops rapidly after the emergency shutdown of the reactor. However, due to the certain heat capacity of heat transfer materials and working mediums, the change of the parameters of the residual heat removal system is delayed behind significantly and is closely related to the in-reactor cooling. When the reactor is cooled inside, the wall temperature of the pressure vessel and the parameters of the residual heat removal system decrease obviously. While when the in-reactor cooling is lost, the wall temperature of the pressure vessel decreases slowly, and the inlet and outlet temperature of the water cooling wall and outlet temperature of the air cooler increase rapidly.

3.3. Effects of different ambient temperatures on the performance of residual heat removal system
As shown in Figure 3, the changes of relevant performance parameters of the residual heat removal system at different ambient temperatures under the steady-state operating conditions of the reactor are presented. The lowest and highest ambient temperatures are approximately -12.7 °C and 36.4 °C, and
the inlet and outlet temperatures of the water cooling wall and outlet temperature of the air cooler increase as the ambient temperature changes from low to high. The wall temperature of the pressure vessel only changes with the temperature of the primary coolant and behaves a certain lag.

![Figure 3. Parameter curves of residual heat removal system at different ambient temperatures.](image)

Based on the parameter curves of residual heat removal system under different ambient temperatures, the ambient temperature has a great influence on the inlet and outlet temperatures of the water cooling wall and outlet temperature of the air cooler. The low ambient temperature is more conducive to the operation of the residual heat removal system. However, it should be noted that the opening of cooling air valve should be adjusted timely in the startup and shutdown of the reactor to prevent the abnormal freezing blocking in the water cooling wall caused by the excessively low ambient temperature. When the maximum ambient temperature is reached, the outlet temperature of the water cooling wall of the residual heat removal system is approximately 80 °C. There is a large margin from the normal boiling point of 100 °C, so it can meet the requirements of safe operation.

3.4. Single loop run test
The single loop run test was carried out at 3MW stable power operation of the reactor during the time interval from 8h to 14h, in order to verify the passive residual heat removal ability of single loop run when one of the two loops of residual heat removal system fails. The two loops are denoted as #1 and #2, respectively. The test was carried out by artificially closing the inlet and outlet damper of #1 air cooler. The operating parameters of #1 and #2 loops of the residual heat removal system during the test were shown in Figure 4.

The test began when the operator manually closed the inlet and outlet damper of #1 air cooler at the time point of 8h, and ended when the operator manually opened the inlet and outlet damper of #1 air cooler at the time point of 14h. From the operating parameter curves of the residual heat removal system during the single loop run test, it can be seen:

(1) Due to the loss of a loop of heat load, both the inlet and outlet temperatures of the water cooling wall of the two loops of the residual heat removal system increased with the conduct of the test, and only began to decrease approximately 4 hours after the re-commissioning of the #1 air cooler with a certain time lag.
(2) The cooling water flow and heat load of #1 air cooler decrease rapidly when the inlet and outlet damper is closed, and the wall temperature of the pressure vessel, cooling water flow and heat load of #2 air cooler increase slightly with a certain time lag.

(3) Under the 3 MW stable power working condition of the reactor, the maximum heat load for the single loop of the residual heat removal system is approximately 100 kW, the maximum outlet temperature of the #2 water cooling wall is 68.6°C, and the maximum wall temperature of the pressure vessel is approximately 155°C. The operating parameters and operating limits have a large margin. Historical records show that even if after the emergency shut-down of the 10 MW full power operation, the maximum temperature of the wall of the pressure vessel is approximately 197°C, and the maximum temperature of the outlet of the water cooling wall is 80°C, which has a large margin based on the assumption of thermal hydraulic calculation. Therefore, the single loop run can meet the requirements of the safe operation of passive residual heat removal.

Figure 4. Single loop operating parameter curves of the residual heat removal system under stable power operation.
4. Conclusion

As a reactor safety-related system, the residual heat removal system of HTR-10 has been verified through the thermal hydraulic design calculation, test verification and operation tests, which prove that the design has sufficient heat load capacity following the single failure criterion. The system operation tests under different working conditions, different ambient temperature and a single loop run mode have been performed successfully. The main parameters and variables affecting the performance of the system are analyzed and verified. It is confirmed that the residual heat removal system of HTR-10 meets the design and safe operation requirements and possesses sufficient heat removal capacity to ensure the safety characteristics of the reactor under normal operation and accident conditions.

Considering that the HTR-10 residual heat removal system adopting passive natural circulation has many complex factors which can affect the cooling water circulation in the water cooling wall and the air flow in the air cooling tower, the performance of the residual heat removal system of HTR-10 and its improvement still need to be further tested and studied.

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References

[1] Z.X. Wu, D.C. Lin, D.X. Zhong, The design features of the HTR-10, Nuclear Engineer and Design, v218, p.25, 2002.
[2] Z.Y. Zhang, Y.J. Dong, F. Li, Z.M. Zhang, H.T. Wang, X.J. Huang, H. Li, B. Liu, X.X. Wu, H. Wang, X.Z. Diao, H.Q. Zhang, J.H. Wang, The Shandong Shidao Bay 200MWe High-Temperature Gas-Cooled Reactor Pebble-Bed Module (HTR-PM) Demonstration Power Plant: An Engineering and Technological Innovation, Engineering, v2, p.112, 2016.
[3] X.Y. Yun, Y.H. Zheng, X.Q. Jing, F. Li, Uncertainty Analysis on Decay Heat of Pebble-bed High Temperature Gas-Cooled Reactor, Atomic Energy Science and Technology, v47, No.7, p.1121, 2013.
[4] X.W. Li, X.X. Wu, L. Zhang, S.Y. He, Analysis of Passive Residual Heat Removal System of Modular High Temperature Gas-Cooled Reactor, Atomic Energy Science and Technology, v47, No.7, p.790, 2011.
[5] L.H. Chen, Y.H. Zheng, T. Ma, X.M. Chen, Y.Z. Ma, Modeling and Computation of Residual Heat Removal System of HTR-10 with Experimental Verificaiton, Atomic Energy Science and Technology, v50, No.10, p.1771, 2016.
[6] D.F. Zhang, Q.S. Su, Y.J. Zhang, H. Chen, J.F. Lu, S.L. Sun, The Experimental Study for Residual Heat Removal System in 5MW Nuclear District Heating Plant, Nuclear Power Engineering, v12, No.2, p.56, 1991.
[7] M.Z. Peng, D.J. Wan, Y. Gao, Analysis for residual heat removal system with natural circulation, Journal of Tsinghua University (Sci& Tech), v36, No.12, p.51, 1996.
[8] H.X. Li, Y.J. Zhang, Z.S. Li, HTR-10 primary cavity cooling system and its features, Journal of Tsinghua University (Sci& Tech), v38, No.5, p.99, 1998.
[9] D.Y. Wang, Ch. Hao, F. Li, Operating Characteristic Analysis of Passive Residual Heat Removal System of HTR-PM, Science and Technology Review (special Issues), v30, No.20, p.33, 2012.
[10] K. Kugeler, Z.Y. Zhang, Modular High-temperature Gas-cooled Reactor Power Plant, First Edition, p.418, Tsinghua University Press, Beijing, 2019.
[11] Z.Y. Gao, Sh.Y. He, M. Zhang, Afterheat Removal for HTR-10 Test Module under Accident Conditions, Decay heat removal and heat transfer under normal and accident conditions in gas cooled reactors, Jülich, Germany, 6-8 July 1992.
[12] W. Rehm, H. Barthels, W. Jahn, Analytical and Experimental Investigations of the Passive Heat Transport in HTRs under Severe Accident Conditions, Decay heat removal and heat transfer under normal and accident conditions in gas cooled reactors, Jülich, Germany, 6-8 July 1992.