Study on the influence of ambient temperature and RPV temperature on operation performance of HTR-PM reactor cavity cooling system

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Abstract: High Temperature Gas-cooled Reactor (HTGR) is the Generation IV advanced nuclear reactor, which can realize inherent safety and prevent the occurrence of core melting accidents. Institute of Nuclear and New Energy Technology (INET) of Tsinghua University has developed a commercial scale 200 MWe High Temperature gas-cooled Reactor Pebble bed Module project (HTR-PM), which entered commercial operation on December 6, 2023. A passive Reactor Cavity Cooling System (RCCS) is designed for HTR-PM to export heat from the reactor cavity in normal operation and also in accident condition, keeping the safety of the reactor pressure vessel (RPV) and reactor cavity. RCCS of HTR-PM has been designed as three independent sets, two sets of RCCS work can guarantee the safety of the PRV and reactor activity. The heat from the RPV through thermal radiation and natural convection can be transmitted to the final heat sink, atmosphere, through the natural circulation of water and air. The CAVCO code has been developed by INET to simulate the behavior of RCCS. In this paper, assuming different RPV temperatures and different ambient temperatures, as well assuming all or parts of the RCCS sets work, the performances of RCCS are studied by CAVCO to evaluate its operational reliability, so as to provide reference for further optimization. The analysis results indicate that even at conceivable extremely high RPV temperatures, two sets of RCCS could effectively carry out the heat, without resulting in the boiling of the water or failure of the system. However, in the case of low ambient temperatures in winter, especially when reactor operates at lower RPV temperature, more attention needs to be paid to the operation safety of the system. System failure caused by freezing of the circulating water and freezing crack of the water-cooling pipe need to be avoided. Parts or all of the 3 sets need to be quit operation depending on the reactor status and environmental conditions. Besides, the maximum heat carrying capacity of the RCCS with only two sets working exceeds the design requirement of 1.2MW. When the ambient temperature changes dramatically, it can be considered to increase the number of RCCS sets to avoid the impact of drastic changes in cooling water temperature on pipeline thermal stress.

Keywords: HTGR, reactor cavity cooling system (RCCS), CAVCO, safety

1. INTRODUCTION

High Temperature Gas-cooled Reactors (HTGR) are internationally listed as one of the reactor types that meets the technical requirements of the Generation IV advanced nuclear reactor which have excellent inherent safety. HTGR use helium gas with good chemical stability as a coolant, and graphite with large heat capacity as a moderator. Besides, HTGR can achieve excellent high-temperature resistance by utilizing encapsulated particulate fuel elements., the reactor can naturally export residual heat without any external energy supply, thereby eliminating the possibility of core melting accident. Even if accident happens, it can effectively contain radioactive products and control radiation level at a lower level [1].

High Temperature gas-cooled Reactor Pebble bed Module (HTR-PM) is the world's first modular HTGR nuclear power plant (NPP) with inherent safety characteristics and has the most commercial valuable among the f Generation IV advanced nuclear reactors, designed by Institute of Nuclear and New Energy Technology (INET), Tsinghua University, and constructed in Shidao Bay, Rongcheng city, Shandong province, China. In HTR-PM, reactor cavity cooling system (RCCS) is designed to export residual heat from the reactor core during normal operation and accident conditions, ensuring the safety of the reactor. RCCS relies on the natural circulation of water to carry the heat, without the need for external support. Figure 1 shows the system structure components of RCCS [2], which consists of three independent sets. The water-cooling panel (WCP) is arranged on the inner layer of the reactor cavity with vertical water-cooling pipes welded on it. The heat can be transferred from reactor pressure vessel (RPV) to the WCP by radiation and natural convection. The heated water in the water-cooling pipes then flows upwards to the air cooler in the air-cooling tower and finally transfers the heat to the environment via natural circulation. The design capability of the RCCS for each reactor module is 1.2MW with a 3x50% redundancy design, which means that two sets working normally can meet the design requirements and effectively remove the heat [3,4].

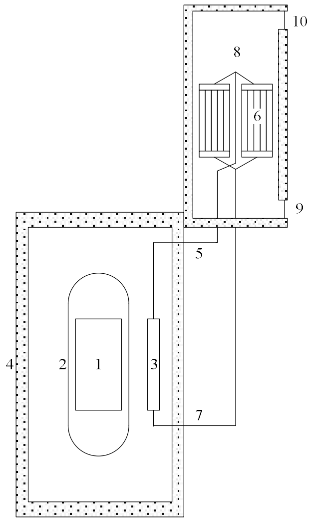


Figure 1. The system components of RCCS (1: Reactor core; 2: Reactor pressure vessel; 3: Water-cooling panel; 4: Reactor cavity concrete; 5: Hot water main pipe; 6: Air-cooler; 7: Cold water main pipe; 8: Air-cooling tower; 9: Air inlet; 10: Air outlet)

In this paper, the operational characteristics of RCCS is analyzed by the CAVCO code, developed by INET, Tsinghua University for analyzing the operating characteristics of HTGR's RCCS [5,6,7]. The effects of RPV temperature and ambient temperature on the performance of the RCCS with different number of sets working are analyzed. The failure model of the RCCS, for example, heat transfer deterioration caused by the boiling of the water in hot summer and at higher RPV temperature or pipe break caused by the freezing of water in cold winter and at lower RPV temperature, are especially paid attention to, for further understand and optimization of the system. The work introduced in this paper proves that RCCS can effectively remove residual heat to ensure the safety of the reactor, and also could provide a certain reference for the safe operation of RCCS.

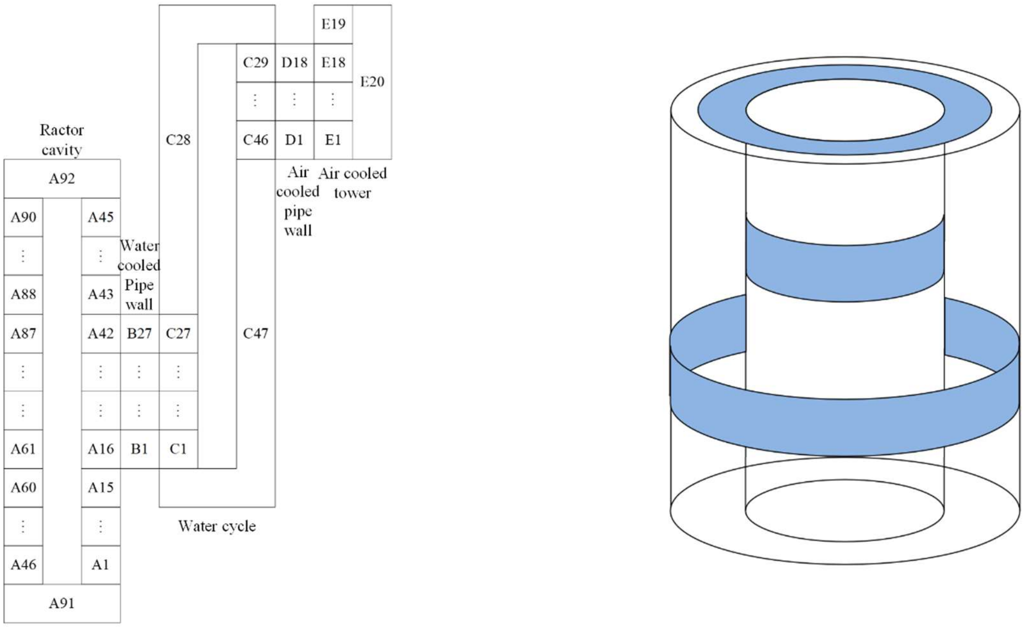
2. CODE and MODEL

The CAVCO code is developed to simulate the behavior of the RCCS using water natural circulation and air natural circulation to carry out heat, with temperature of the RPV outer wall as a temperature boundary. Besides, this code has also been coupled with TINTE code, a system code developed by the Research Center Jülich, Germany for thermal hydraulic and transient analysis of pebble-bed HTGR, to analyze the influence of RCCS behavior on reactor core and RPV. Figure 2a shows the calculation nodes of RCCS in CAVCO code, where A-nodes represent the annular reactor cavity, which is composed by cylinder RPV wall and WCP, as well as the insulation walls up and below the WCP: A1-A15 and A43-A45 are the outer insulation walls of the annular cavity, A16-A42 represent the WCP, A46-A90 represent the inner wall of the annular cavity (outer wall of the RPV), A91 and A92 are the bottom and top surfaces of the cavity (insulation wall); C-nodes represent the water circulation part, B-nodes and D-nodes are the walls of the water-cooling pipes and the air cooler pipes, respectively. C1-C27 represent the water inside the water-cooling pipes, while C29-C46 the water inside the air cooler pipes, C28 and C47 correspond to the water along the rising and falling sections of the pipes, respectively; E-nodes represent the air-cooling tower section, where E19 is insulated, and the other nodes correspond to air nodes. In the calculation process of RCCS code, it is necessary to provide the temperature of A46-A90 (outer wall temperature of RPV) and E20 temperature (ambient temperature) as boundary conditions.

During the calculation process, the temperature distribution on the outer wall of the RPV is specified as the heat source, and the ambient temperature is specified as the cold source. The natural convection in the cavity area between the RPV and the WCP is calculated using empirical formulas (equation 1), while radiation heat transfer is calculated considering radiation between the annular cavity micro-elements (RPV and water-cooled wall), excluding the pipe sections (equation 2). Therefore, the operational set of the RCCS does not affect the heat transfer surface in radiation heat transfer view factors (Fig.2b) calculations [8]. In the calculation, changes in heat transfer area are used to reflect the impact of different numbers of RCCS. The periodic temperature distribution of the water-cooling panel and the water-cooling pipe in the circumferential direction, and also the resulting uneven temperature distribution in the circumferential direction of the RPV, are not considered.

$$Q_c = -0.9799\, A_{RPV}\, \Delta t^{1.3787} R^{0.7171} e^{0.3896X+0.0004\Delta T} \times H(H+0.3502)(H-1.3714) \quad (1)$$

$$Q_{RPV\rightarrow WCP} = \sigma A_{RPV} F_{RPV\rightarrow WCP}(\epsilon_{RPV} T_{RPV}^{4} - \epsilon_{WCP} T_{WCP}^{4}) \quad (2)$$



(a) RCCS Calculation Nodes (b) View Factor Calculation Unit

Figure 2. Calculation model of HTR-PM RCCS

3. RESULT AND DISCUSSION

3.1. Calculation Condition

This study mainly evaluates the impact of RPV temperature, ambient temperature, and the number of operating sets of RCCS on the system's heat carrying capacity and cooling water temperature. Additionally, the work focuses on the possible failure mode of the system, for example, deterioration of heat transfer or rupture of pipe caused by boiling or freezing of water.

Table 1 lists the operating conditions studied in this paper, and also the main variables used. In each case, the RPV temperature keeps constant along its height. The working pressure of the cooling water in the water-cooling pipes is 0.3MPa, which corresponds to a boiling point of 131.4 °C. It is conservatively considered that RCCS would totally fail and computation would interrupt when the outlet water temperature (node C28 in Figure 2a) reaches 130 °C.

Table 1. Calculate Conditions and Variables

(a) Calculate Conditions

Case	RPV temperature (K)	Ambient temperature (K)	Set of RCCS
Case 1	373.15	258.15/263.15/268.15/ 273.15/278.15/283.15/ 288.15/293.15/298.15/ 303.15/308.15	1/2/3
Case 2	473.15		
Case 3	523.15		
Case 4	573.15		
Case 5	673.15		

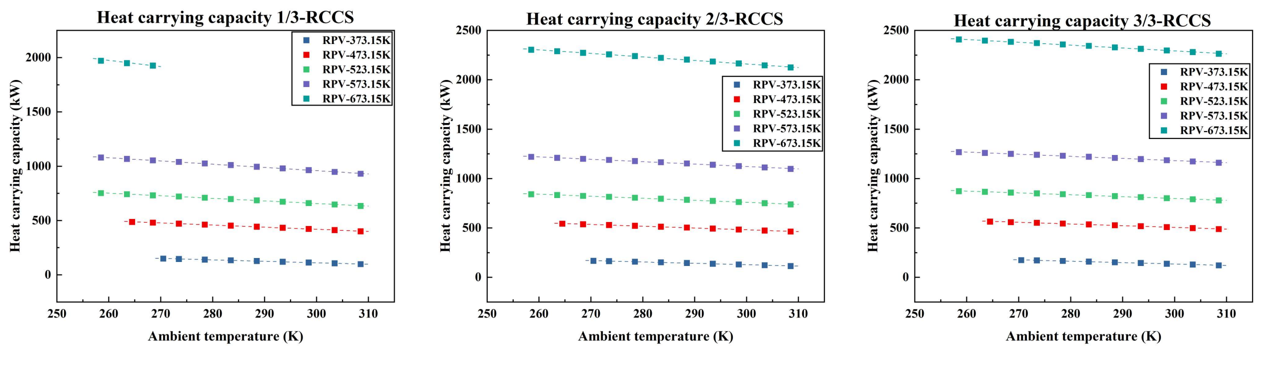
(b) Variables

Variable	Unit	Physical significance
P	kW	Heat carrying capacity
T_a	K	Ambient temperature
T_{RPV}	K	RPV temperature
T_{WCP}	K	WCP temperature
$T_{freezing}$	K	Ambient temperature corresponding to water zero point
$T_{boiling}$	K	Ambient temperature corresponding to water boiling point
ΔT	K	The difference between the highest and lowest temperatures on the RPV wall
Δt	K	The average temperature difference between the inner and outer walls of the annular cavity
Q_c	W	Natural convection heat power on the outer wall of the annular cavity
R		Ratio of inner and outer wall radius in the annular cavity
H		WCP height to annular cavity height ratio
n		Operational sets of RCCS
$Q_{RPV \to WCP}$	W	Radiation heat transfer power from RPV to WCP
A_{RPV}	m^2	Area of RPV
$F_{RPV \to WCP}$		View factor between RPV and WCP
ϵ		Surface emissivity
σ	$W/(m^2 \cdot K^4)$	Stefan-Boltzmann constant

3.2. Calculation results

3.2.1. Heat carrying capacity

Figure 3 displays the calculation results of heat carrying for cases 1 to 5. Figures 3 (a), (b), and (c) respectively correspond to different operating sets of RCCS, and different colors represent different RPV temperatures. The points which are not shown on the figure indicate system failures (cooling water is freezing or boiling) at the respective operating conditions.



(a) Heat carrying capacity under one set of RCCS

(b) Heat carrying capacity under two sets of RCCS

(c) Heat carrying capacity under three sets of RCCS

Figure 3. Heat Carrying Capacity of RCCS

It can be observed that, the total heat carrying capacity of the system is positively correlated with the RPV temperature and the number of RCCS sets, and negatively correlated with the ambient temperature. Besides, the heat carrying capacity of each system is positively correlated with the RPV temperature, and negatively correlated with the ambient temperature and number of RCCS sets. When the temperature difference between the cold source (ambient temperature) and the heat source (RPV temperature) is larger, the system can carry more heat. Therefore, when the RPV temperature is higher and the ambient temperature is lower, the total heat carrying capacity of the system is larger, and the average heat carrying capacity of each set will also increase. As the number of RCCS sets increases, the total heat carrying ability of the system is enhanced, but the average heat carrying capacity of each set decreases.

Additionally, under same RPV temperatures and numbers of RCCS sets, there is a nearly linear relationship between the heat carrying capacity and the ambient temperature (shown as equation 3), with minimal sensitivity to changes in ambient temperature. This means that the system's heat carrying capacity is primarily influenced by the temperature of the RPV. This can be explained by the primary heat transfer mode between the RPV and the water-cooled panel, the thermal radiation, with surface thermal radiation capacity directly proportional to the fourth power of temperature. Consequently, heat transfer mainly depends on the temperature of the hotter region (RPV).

Equation 4 and Figure 4 further illustrate the influence of ambient temperature variations on heat carrying capacity. The smaller b_p / k_P, the less significant the impact of ambient temperature changes on heat carrying capacity. Figure 4 shows b_p / k_P under different RPV temperatures and numbers of RCCS sets. The calculation results reveal that, b_p / k_P is negatively correlated with the RPV temperature and numbers of RCCS sets. This is because as the RPV temperature rises, the difference between the ambient temperature and the RPV temperature increases, minimizing the impact of ambient temperature variations on radiation heat transfer. At the same RPV temperature, the larger the number of RCCS sets, the larger the heat exchange area and the stronger the heat carrying capacity, enhancing adaptability to ambient temperature changes. Consequently, with more sets working normally, the ambient temperature variations have less effect on the heat carry capacity.

$$P = P(T_a\,,\, T_{RPV}\,,\, n) = k_P T_a + b_P \tag{3}$$

$$P(T_a + \Delta T_a\,,\, T_{RPV}\,,\, n) \,/\, P(T_a\,,\, T_{RPV}\,,\, n) = (k_P(T_a + \Delta T_a) + b_P) \,/\, (k_P T_a + b_P) = 1 + \Delta T_a \,/\, (b_P / k_P + \Delta T_a) \tag{4}$$

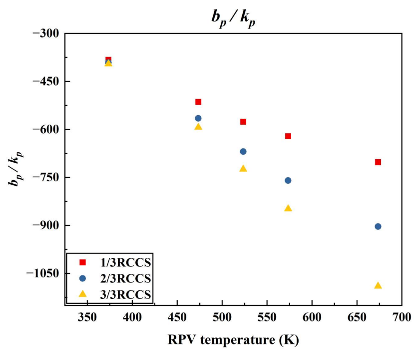
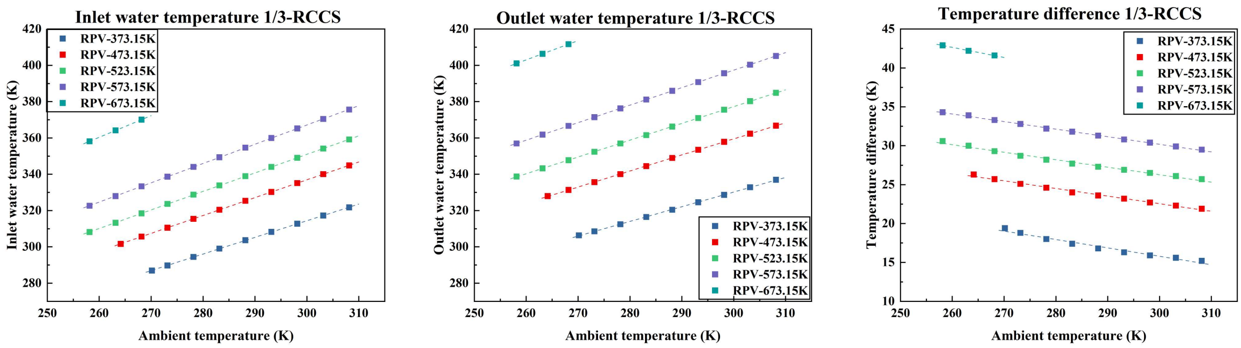


Figure 4. b_p / k_P under Different Boundary Conditions

3.2.2. Cooling water temperature

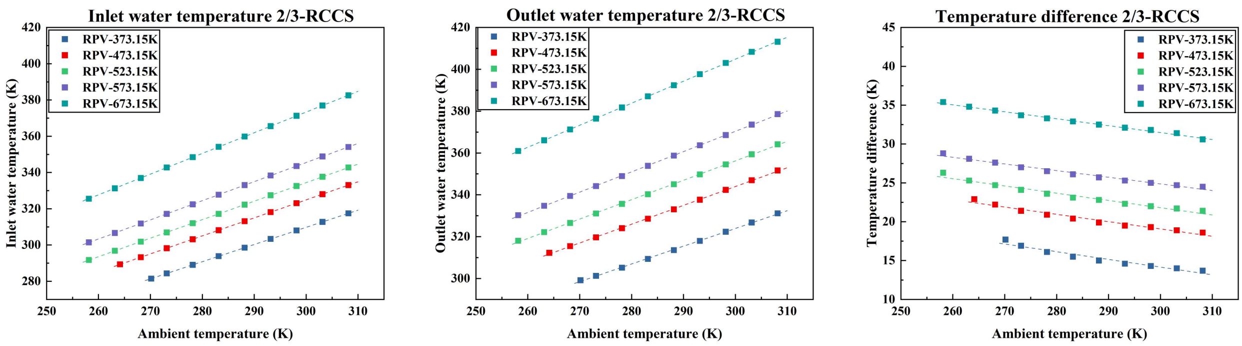
Figure 5-7 illustrate how the inlet and outlet water temperature in the water-cooling pipe vary with different ambient temperature for different numbers of RCCS sets working and different RPV temperatures. It is evident that the inlet and outlet temperatures of the cooling water are positively correlated with the ambient temperature and RPV temperature. The trend of temperature changes in cooling water is the same as that of temperature changes in cold and heat sources (RPV and ambient temperature increase, cooling water temperature increases; RPV and ambient temperature decrease, cooling water temperature decreases) Besides, inlet and outlet water temperatures are negatively correlated with the number of RCCS sets.

The temperature difference between inlet water and outlet water is negatively correlated with the ambient temperature and number of RCCS sets and positively correlated with RPV temperature. It can be inferred that the temperature difference increases with the increase of heat carrying capacity of each set.



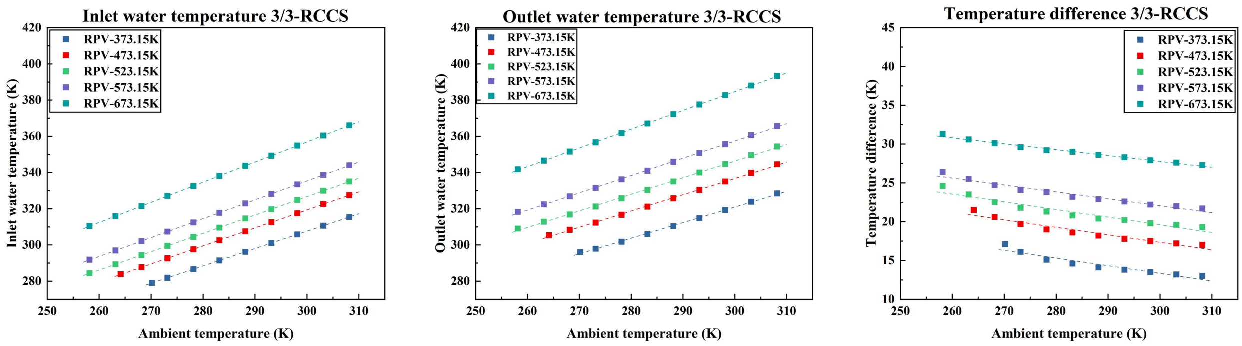
(a) Inlet Water Temperature under One Set of RCCS (b) Outlet Water Temperature under One Set of RCCS (c) Temperature Difference under One Set of RCCS

Figure 5. Cooling Water Temperature under One Set of RCCS



(a) Inlet Water Temperature under Two Sets of RCCS (b) Outlet Water Temperature under Two Sets of RCCS (c) Temperature Difference under Two Sets of RCCS

Figure 6. Cooling Water Temperature under Two Sets of RCCS



(a) Inlet Water Temperature under Three Sets of RCCS (b) Outlet Water Temperature under Three Sets of RCCS (c) Temperature Difference under Three Sets of RCCS

Figure 7. Cooling Water Temperature under Three Sets of RCCS

3.2.3. Temperature limit

Figure 8 shows the ambient temperature limits of the system at different working numbers of RCCS sets and RPV temperatures, with Table 2 provides the fitting formula for the curves. The results indicate that, at a constant RPV temperature, the greater the number of operating RCCS sets, the higher the temperature limit. This finding is consistent with the conclusion that the more RCCS sets are operated, the lower the average cooling water temperature, making it easier to reach zero (freezing point) and less likely to reach boiling point at the same ambient temperature. In addition, it was observed that higher RPV temperatures lead to lower temperature limits for the same number of operating sets. This is because as the RPV temperature increases, the average cooling water temperature also increases, reducing the possibility of freezing and increasing the possibility of boiling at the same ambient temperature, thereby lowering the temperature limit.

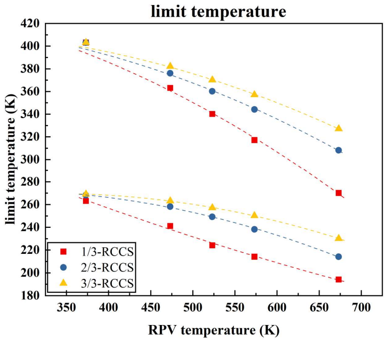


Figure 8. Limit Temperature of RCCS

Table 2. Equation between Limit Temperature and RPV Temperature

Set of RCCS	Equation	
1	$T_{freezing} = 0.000114T_{RPV}^2 - 0.354T_{RPV} + 379.903$	$T_{boiling} = 0.000416T_{RPV}^2 - 0.0199_{RPV} + 444.231$
2	$T_{freezing} = -0.000352T_{RPV}^2 - 0.187T_{RPV} + 247.845$	$T_{boiling} = 0.000370T_{RPV}^2 - 0.0889T_{RPV} + 415.496$
3	$T_{freezing} = -0.000343T_{RPV}^2 + 0.228T_{RPV} + 231.553$	$T_{boiling} = 0.000335T_{RPV}^2 - 0.112T_{RPV} + 403.750$

The calculation results also reveal that when the RPV temperature is 673.15K and only one set of RCCS operates, boiling phenomenon occurs in the cooling water when the ambient temperature exceeds 268.15K; under other operating conditions, no boiling occurs.

3.3. Discussions

In HTR-PM, the RCCS is designed as that, two sets working normally can guarantee the heat carrying capacity of 1.2 MW, so to keep the RPV and cavity safe in accident condition. The working pressure of the cooling water in the water-cooled pipes is 0.3MPa.

The calculation results introduced in Chapter 3.2 show the influence of ambient temperature, RPV temperature and number of working sets on the operating characteristics and safety features of the RCCS, which can benefit for the future design optimization, and also the operation and management optimization of the system. Below in this section, based on the design of HTR-PM RCCS, the possible failure of the system due to boiling or freezing of the water, as well as the possible measure are further discussed. The heat carrying capacity of the HTR-PM RCCS is also discussed.

3.3.1. High Temperature Failure Analysis

The cooling water temperature of RCCS will increase with the increase of ambient temperature and RPV temperature, and it will also increase with the decrease of RCCS operating sets. According to the HTR-PM design, the RPV temperature limitation for normal operation and design basis accident (DBA) is 350℃ and 425℃ respectively. Analysis indicates that in all DBA and most beyond design basis accident (BDBA), the RPV temperature would not exceed the 400℃. The calculated results show, if two or three sets of the RCCS can work normally and ambient temperature is below 35℃, the outlet water temperature would not exceed the boiling point at 0.3MPa, which means the RCCS would not fail due to the heat transfer deterioration. HTR-PM meets the design criteria of 3 × 50% redundancy during operation.

According to the working principle of the RCCS, as well as the above analysis, when HTR-PM is operating in the hot summer, it is important to avoid RCCS failure caused by cooling water boiling and heat transfer deterioration. Therefore, it is necessary to monitor the RPV temperature, RCCS working pressure, ambient temperature and outlet water temperature. If the outlet water temperature is close to boiling point, increasing the working pressure is also a practical measure.

Besides, analysis results show that if only one set of RCCS works, it might easily fail due to the higher RPV temperature or higher ambient temperature. Therefore, the reactor should not be allowed to operate with only one set working. In addition, in some special condition that only two sets work normally and the third set is in maintenance or repair, the reactor should be shut down if the maintenance or repair could not be completed with the specified time.

3.3.2. Low Temperature Failure Analysis

According to above analysis, it can be found that, compared to system failure caused by water boiling, the phenomenon of cooling water freezing in HTR-PM RCCS is more likely to occur and need more focus. This was also confirmed by HTR-PM operation experience. The freezing of cooling water can cause water-cooling pipe rupture, affecting the circulation of cooling water in RCCS.

When the reactor is operating in the winder, it is important to monitor the inlet water temperature and take some measures in advance when it is near freezing point, for example shut down part or all sets of RCCS, close the inlet door of the air-cooling tower, or even insulate the water pipe of the air cooler.

3.3.3. System Heat Carrying Capacity

The actual heat carrying capacity of the system is influenced by the RPV temperature, ambient temperature, and the number of RCCS sets. The heat carrying capacity increases with the increase of RPV temperature, decreases with the increase of ambient temperature, and increases with the increase of RCCS operating sets. According to the calculation results, the heat carrying capacity is mainly affected by the RPV temperature, while the ambient temperature and the number of RCCS sets have a relatively small impact on the system's heat carrying capacity. The heat carrying capacity is linearly related to the ambient temperature, and when the RPV temperature is high and more RCCS sets are operating, the heat carrying capacity is less affected by changes of ambient temperature. In addition, there is a positive correlation between the heat carrying capacity and the temperature difference between the inlet and outlet of the cooling water.

When the fluctuation of ambient temperature is large, the number of RCCS put into operation can be appropriately increased to reduce the impact of ambient temperature changes on heat carrying capacity, reduce the temperature fluctuation of cooling water, and reduce the impact of thermal stress on pipelines.

In HTR-PM, the design requirement for the heat carrying capacity of RCCS is 1.2MW with two sets of operation. According to the calculation results, it can be found that the heat carrying capacity of the two sets of RCCS can even greater than 2MW if the RPV with an average temperature of higher than 400℃ (that may not happen in reality). The analysis results indicate that the design of RCCS of HTR-PM meets, or even better than the requirements.

In actual operation of reactor, the RPV temperature is also affected by the operating characteristics of the RCCS. Therefore, in order to reasonably determine the design capability of the RCCS so as to optimize the cost, the reactor behaviour and RCCS behaviour need to be further analysed in coupling.

4. CONCLUSION AND DISCUSSION

The paper analyzes the impact of ambient temperature, RPV temperature and the number of RCCS operating sets on the system's heat carrying capacity and cooling water temperature. In addition, the limit of ambient temperature for the system operating normally corresponding to different RPV temperatures and RCCS operating sets were also analyzed. Based on the calculation results, the following conclusions can be concluded.

(1) When the HTR-PM operates normally and RPV temperature is kept at a lower temperature, only one set of RCCS can keep the reactor cavity safe. Under some accident conditions of the reactor emergency shutdown, the core temperature and RPV temperature will increase due to the decay heat. However, two sets of RCCS can effectively export residual heat and keep the RPV and reactor cavity safe.

(2) RCCS may experience boiling or freezing of cooling water during operation, which may cause the heat transfer deterioration or even the system failure. During normal operation of the reactor, the cooling water will not boil according to the calculation results. But in some accident conditions, if the RPV temperature is higher, it is necessary to ensure the operating number of RCCS sets to prevent boiling of the cooling water. Compared to boiling, the freezing of the cooling water and the resulting pipe rupture need more attention. In cold winter, especially when the RPV temperature is lower, it may need to consider shutting down parts or all of the RCCS sets to avoid cooling water freezing. Closing the air inlet door of the air cooler to increase the temperature of the cooling water is also a feasible measure.

(3) The heat carrying capacity is mainly determined by the temperature of the RPV and is positively correlated with the difference between inlet cooling water and outlet water temperature. Based on the analysis and operation, it is found that the heat carrying capacity of the RCCS of HTR-PM exceeds the design requirement, 1.2 MW with two of three sets operating normally.

(4) However, because the RPV temperature is also affected by the operating characteristics of the RCCS, further study should be carried out with coupling simulation of reactor, RPV and RCCS behaviour, so as to further understanding of the RCCS characteristics and design optimization of the system.

Acknowledgements

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