

Assessment of Molten Pool Cooling Characteristics During LBLOCA for Advanced Passive PWR

Lili Tong, Ge Shao

School of Mechanical Engineering, Shanghai Jiao Tong University,
No. 800, Rd. Dongchuan, Shanghai, 200240, China
lltong@sjtu.edu.cn, sealmodel@sjtu.edu.cn

ABSTRACT

Molten pool cooling by external reactor vessel cooling (ERVC) strategy, which is designed as a severe accident mitigation strategy for advanced passive pressurized water reactor (PWR), can prevent reactor vessel failure and decreases the containment failure possibility. Previous studies about ERVC strategy mostly focus on the heat transfer behavior of molten pool and lower head after the molten pool is already exists. Therefore, it's necessary to analyze the formation process of the molten pool coupled with the ERVC strategy. Cavity natural circulation cooling capability is analyzed by SCDAP/RELAP5 code, which is validated with the KOREA experiment for APR1400. The reactor coolant system (RCS) model combined with engineering features systems of the advanced passive PWR for molten pool cooling capability assessment is built coupled with ERVC structure. The major portions of the model include the reactor core, primary system, secondary system and passive core cooling system. The lower head of reactor vessel is modeled by COUPLE module. One severe accident sequence induced by large break loss of coolant accident (LBLOCA) at cold leg with failure of internal refueling water storage tank is chosen to analyze molten pool cooling characteristics during core damage progression and heat remove capability by the natural circulation after cavity injection strategy is implemented. The key events of the accident shows good agreement with the probabilistic risk assessment (PRA) report, and the wall temperature distribution of the lower head is obtained. The results indicate that molten pool in the lower head can be effectively cooled by cavity flooding after core exit temperature exceeds 923K during LBLOCA accident, and the integrity of reactor pressure vessel (RPV) can be maintained.

KEYWORDS

Molten pool cooling, EVRC strategy, LBLOCA, Advanced passive PWR;

1. INTRODUCTION

Molten pool cooling by ERVC strategy can prevent reactor vessel failure and decreases the containment failure possibility, which is designed as a severe accident mitigation strategy for advanced passive PWR. Molten pool cooling capacity during direct vessel line break was analyzed for AP1000 [1]. However, the detail structure of the cavity was not taken into account in the analyses. SCDAP/RELAP5 code can analyze reactor vessel wall temperature distribution with accident progression [2], and it can simulate two phase flow instability at a more detail level when external cooling is considered [3]. Flow analyses using the RELAP5/MOD3 were performed for OPR1000 [4]. The value of corium mass and decay heat were quoted from the SCDAP/RELAP5/MOD3.3 simulation results [5]. Previous studies about ERVC strategy

mostly focus on the heat transfer behavior of molten pool and lower head after the molten pool is already exists. Therefore, it's necessary to analyze the formation process of the molten pool coupled with the ERVC strategy.

In this study, cavity natural circulation cooling capability is analyzed by SCDAP/RELAP5 code, which is validated with the KOREA experiment for APR1400. The RCS model combined with engineering features systems of the advanced passive PWR for molten pool cooling capability assessment is built coupled with ERVC structure.

2. SIMULATION METHOD

2.1. Experiment Validation

A 1/21.6 scaled experiment facility was established by KAERI utilizing the results of a scaling analysis to simulate the APR1400 reactor vessel and insulation system. The Schematic of the experiment facility is shown in Fig. 1 [6]. The radius of the vessel was 119mm, and the annular gap size was 31mm. Due to the conical configuration of the insulation, the minimum gap region with the size of 19mm was located at 56.6° on the vertical axis of the vessel. The lower water inlet consisted of one hole with a diameter of 20mm. Heating elements were installed in the reactor vessel, which provided a maximum average heat flux of 173kW/m² at the vessel outer surface.

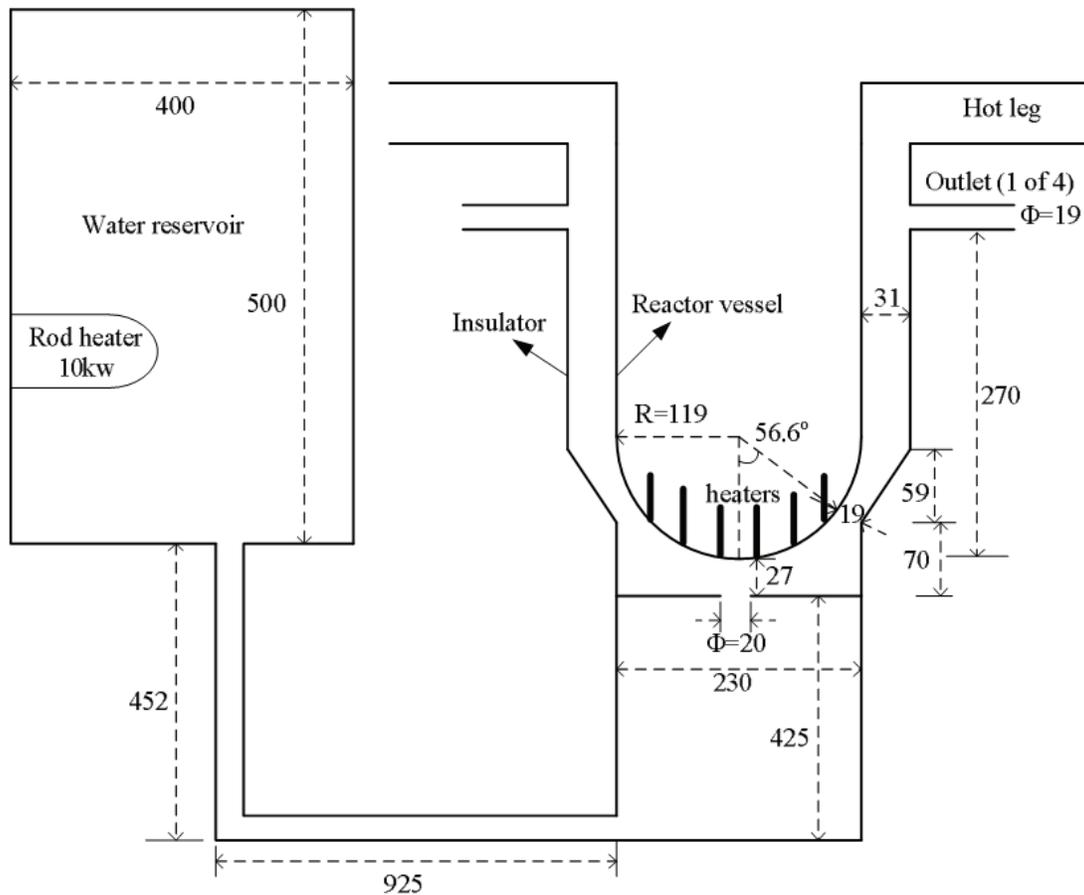


Fig.1 Schematic for experiment facility

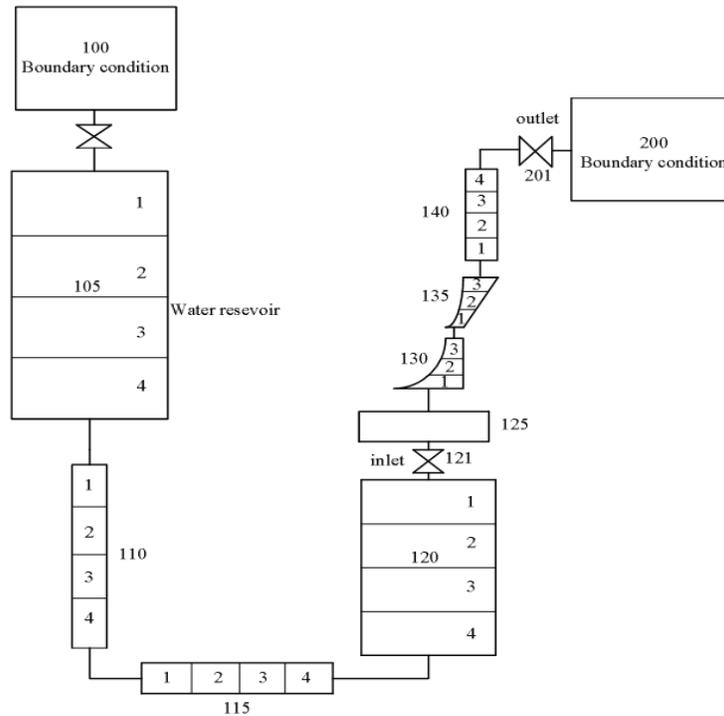


Fig.2 Nodalization for code calculation

Simulation model is established by SCDAP/RELAP5 code, and the model nodalization is shown in Fig.2. The flow paths from water reservoir to reactor cavity are simulated by node 110 and 115. The reactor cavity is simulated by node 120. The water inlet into the insulation gap is simulated by node 121. The free volume between the water inlet and lower head bottom is simulated by node 125. The heating parts are simulated by node 130 and 135. The flow path from heating parts to coolant outlet is simulated by node 140. The coolant outlet is simulated by node 201.

Table I. Comparison of flow rate between code calculation and experimental results

Heat Flux (kW/m ²)	Outlet Area(mm ²)	Water Head(mm)	Circulation Flow Rate (kg/s)		Error
			Experiment	Simulation	
56	284	270	0.0086	0.010	16%
95	284	270	0.0119	0.013	9%
56	568	270	0.0088	0.011	25%
95	568	270	0.0207	0.023	11%

The experiment results and the simulation results are compared as shown in Table 1. The natural circulation flow mass increases with the increase of the heat flux outside the lower head and the outlet

flow area. The calculation results are in agreement with the experiment results. It can be concluded that the SCDAP/RELAP5 code is applicable for analyzing the natural circulation flow under ERVC.

2.2. Plant Model

The RCS model combined with engineering features systems of the advanced passive PWR for molten pool cooling capability assessment is built coupled with ERVC structure as shown in Fig. 3. The major portions of the model include the reactor core, primary system, secondary system and passive core cooling system. The lower head of reactor vessel is modeled by COUPLE module with 448 nodes and 405 elements. The thickness of stainless steel lining is 0.0056m, and the thickness of RPV lower head carbon steel is 0.158m. The wall of lower head which temperature does not exceed 900K should be thicker than 0.022cm referring to the PRA report [7]. The carbon steel is modeled as 10 layers and each layer thickness is 0.0158m to analyze reactor vessel wall temperature distribution with accident progression. The stainless steel lining is modeled as one layer, and the layer thickness is 0.0056m.

The cavity structure is modelled in detail to analyse the cavity flooding coupled with the accident progression. The steam generator compartment is simulated by node 760. The flow path from steam generator to reactor cavity is simulated by node 755. The reactor cavity is simulated by node 720. The water inlet into the insulation gap is simulated by node 710. The free volume between the water inlet and lower head bottom is simulated by node 765.

The COUPLE code is a two-dimensional, finite element, steady-state and transient heat conduction code. The code was developed to solve both plane and axisymmetric type heat transfer problems with anisotropic thermal properties. COUPLE can model the following phenomena and conditions: spatially varying porosity; thermal conductivity of porous material; a debris bed whose height grows sporadically with time; radiation heat transfer in a porous material and the melting or freezing of debris. Node 115 which represents lower head is connected to node 720 through COUPLE code. Node 115 gives the boundary conditions which represent the lower head inside heat flux. Node 720 gives the outside lower head boundary conditions. COUPLE model simulates the molten core behavior in Node 115. Convective heat transfer coefficients and radiation sink temperature are determined at the surfaces of the COUPLE finite element mesh through interfaces with the RELAP5 code. The boundary conditions are as follows:

$$\left(-K_{et}\right) \frac{\partial}{\partial n} T(z_b, r_b) = h_c(z_b, r_b) [T(z_b, r_b) - T_c(z_b, r_b)] + q_{rad}(z_b, r_b) \quad (1)$$

Where $T(z_b, r_b)$ is temperature of external surface of node on COUPLE finite element mesh with coordinates of (z_b, r_b) ; z_b is elevation of node on external surface of finite element mesh; r_b is radius of node on external surface of finite element mesh; n is coordinate in direction normal to external surface; $h_c(z_b, r_b)$ is RELAP5 calculated convective heat transfer coefficient for node on external surface with coordinates (z_b, r_b) ; $T_c(z_b, r_b)$ is RELAP5 calculated temperature of the fluid at surface coordinates (z_b, r_b) ; $q_{rad}(z_b, r_b)$ is radiation heat flux.

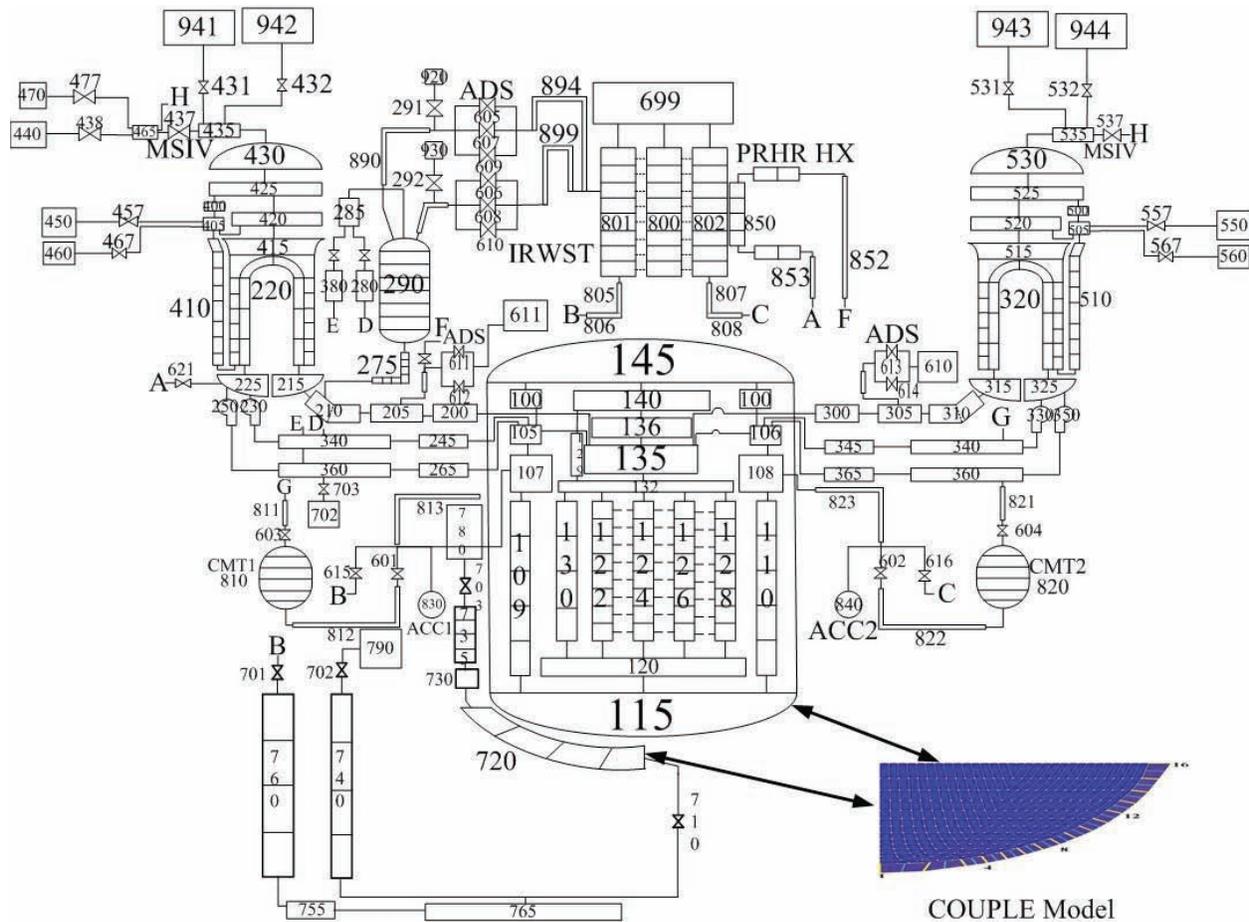


Fig.3 The nodalization of Plant Model

2.3. Molten Pool Model

The calculation is completed assuming steady-state natural convection within molten regions of the corium pool. This is a somewhat conservative assumption because transient natural convection is lower than steady-state natural convection and because a finite period of time is required before the transition from transient to steady-state convection will occur [2].

The correlation calculates a mean upward heat transfer coefficient to the upper crust covering the molten pool and a mean downward heat transfer coefficient:

$$h_u = \frac{k}{R} 0.36Ra^{0.23} \tag{2}$$

$$h_d = \frac{k}{R} 0.54Ra^{0.18} f(\theta) \tag{3}$$

Where k is thermal conductivity of the melt in the boundary layer adjacent to the phase change interface; R is effective radius of the molten region.

The Rayleigh number Ra is defined as:

$$Ra = \frac{g\beta QR^5}{\alpha \nu k} \quad (4)$$

Where g is gravitational constant; Q is volumetric heat generation rate; β is coefficient of volumetric expansion; α is thermal diffusivity; ν is kinematic viscosity of the molten materials.

3. MOLTEN POOL COOLING CAPACITY ANALYSIS

3.1. Thermal Hydraulic Analysis

The following assumptions are made for LBLOCA at cold leg: failure of passive residual heat removal (PRHR) system, accumulators, and the in-containment refueling water storage tank (IRWST) gravity injection to the core. Core makeup tank (CMT) and automatic depressurization system (ADS) stages 1-4 are assumed to be available. The accident progression is shown in Table 2. At time zero, large break loss of coolant accident at cold leg happens and large quantity of coolant blows down to the containment. The reactor scrams at 6s, and the reactor coolant pumps coast down at 7s. CMTs are actuated at 7s. When CMT reaches the low water level setpoint, the ADS stage 1 activates at 280s. Then ADS stage 2 and 3 activate at 400s and 520s, respectively. With the decrease of CMT water level and RCS pressure, ADS stage 4 activates at 1039s. Due to the failure of IRWST gravity injection, the core starts to melt down. The melted core relocates to the lower head plenum at 5102s and the lower head plenum dry out at 7300s. The calculation results are in agreement with PRA results as shown in Table 2.

Table II. Key events of accident

Key Event	Time (s)	
	PRA report	Simulation
Large break at cold leg	0	0
Reactor scram	0.2	6
RCP coastdown	0.7	7
CMT activation	0.7	7
ADS stage 1 activation	372.3	280
ADS stage 2 activation	492.3	400
ADS stage 3 activation	612.3	520
ADS stage 4 activation	1 131.5	1 039
Corium relocation to lower head	5 157	5 102
Lower head dryout	7 000	7 300

3.2. Calculation Results under ERVC

The couple code nodalization of the lower head is shown in Fig. 4. Node 1 is located at 0° on the vertical axis of the vessel; Node 4 is located at 22.5° on the vertical axis of the vessel; Node 8 is located at 45° on the vertical axis of the vessel; Node 12 is located at 77.5° on the vertical axis of the vessel. When the core exit temperature exceeds 900K, operator activates cavity flooding with 20 minutes' delay. The heat of molten pool is removed by natural circulation as shown in Fig. 5. Relocated constituents are as follows: 113990 Kg UO₂, 3079.7 Kg ZrO₂, 259.11 kg stainless steel, 1931.3 kg Ag. The decay power of molten pool is 51.92 MW as shown in Fig. 6. With the increase of natural circulation heat removal, the lower head wall is cooled down effectively. The thickness of lower head wall which temperature does not exceed 900K is 3.16 cm, greater than 0.022cm as shown in Fig. 7. The calculation results indicate that molten pool relocated into the lower head can be cooled down effectively after cavity flooding, and the integrity of RPV can be maintained.

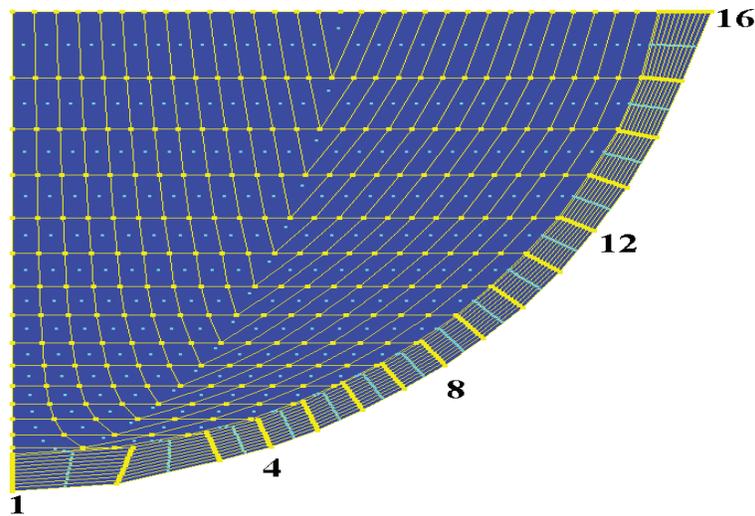


Fig.4 Couple code nodalization of the lower head

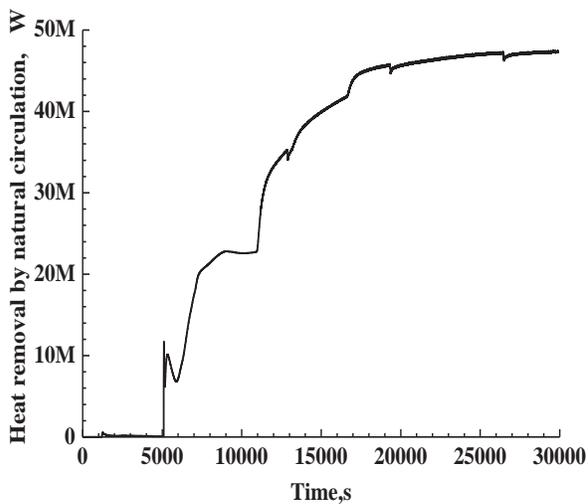


Fig. 5 Heat removal by natural circulation

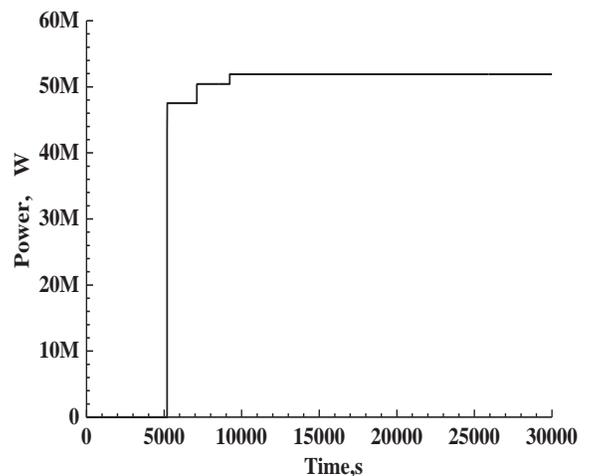
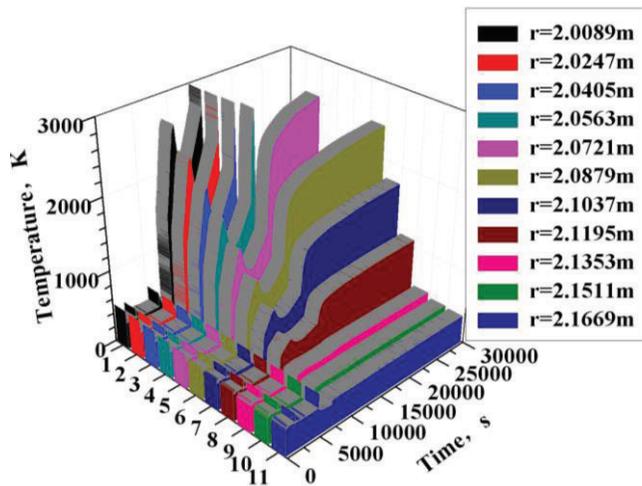
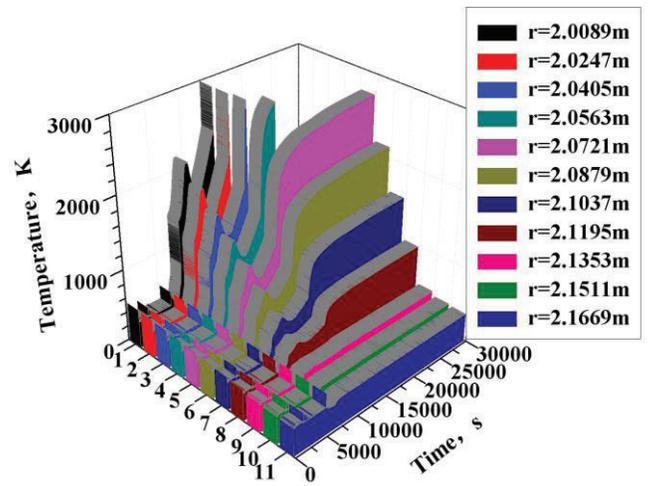


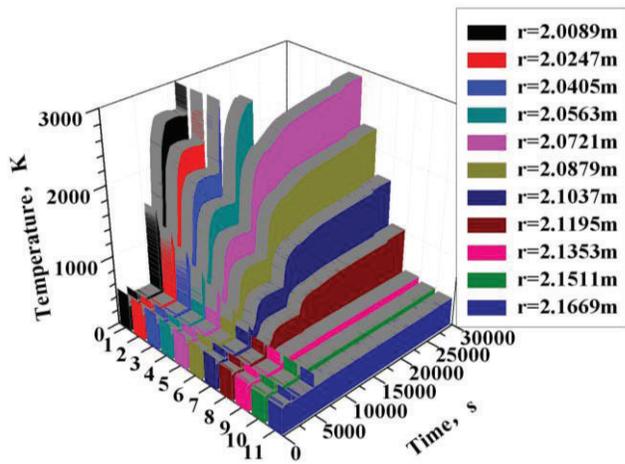
Fig. 6 Total power of molten pool



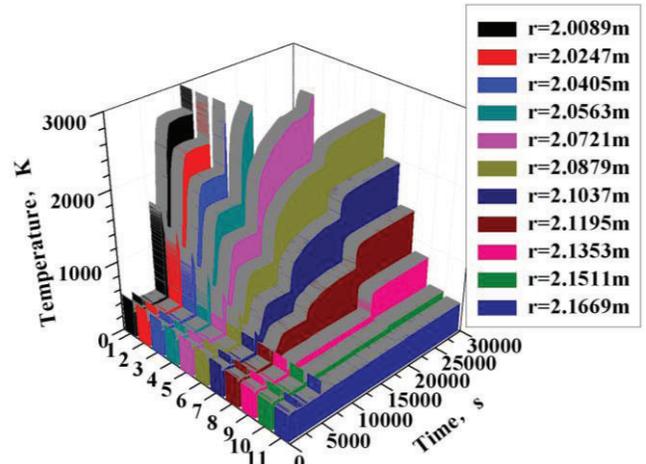
Node 1



Node 4



Node 8



Node 12

Fig. 7 Wall temperature distribution at different nodes

3.3. Sensitivity Analysis

One of ADS stage 4 inadvertent actuation is selected to analyze the influence of molten pool decay heat to the natural circulation, and the LBLOCA is the base calculation. The accident assumptions are as follows: failure of IRWST gravity injection to the core; ADS stage 1-3, CMTs and accumulators are available. The decay power of molten pool is 48.63MW. Cavity flooding starts earlier and the natural circulation mass flow of LBLOCA is larger than one of ADS stage 4 inadvertent actuation as Fig.8, because the decay power of molten pool for LBLOCA is larger than that for one of ADS stage 4 inadvertent actuation. With the increase of the molten pool decay power, the lower head carbon steel temperature increases more rapidly, and the peak temperature at the same location is also higher. The thickness of carbon steel which exceeds 900K is also increases. The temperature of carbon steel at node 4($r=2.1195\text{m}$) is shown in Fig. 9. The carbon steel temperature increases more rapidly for LBLOCA than one of ADS stage 4 inadvertent actuation.

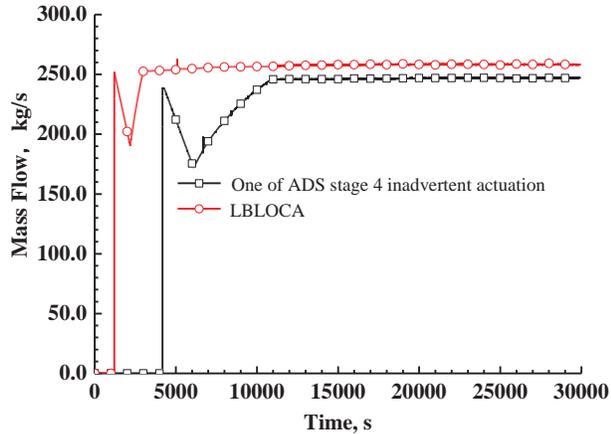


Fig. 8 Natural circulation mass flow

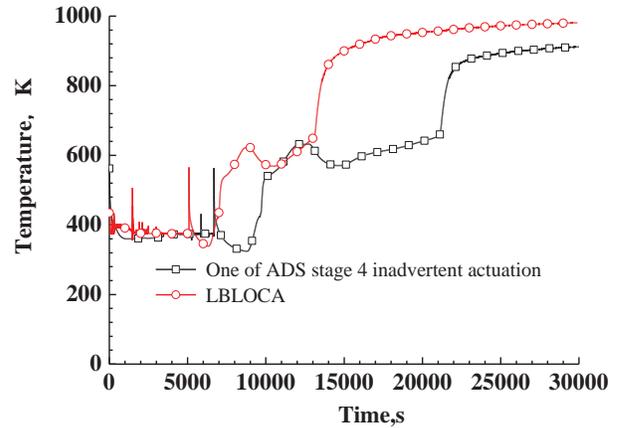


Fig. 9 Temperature comparison at node 4

4. CONCLUSIONS

One severe accident sequence induced by large break loss of coolant accident (LBLOCA) at cold leg with failure of internal refueling water storage tank is chosen to analyze molten pool cooling characteristics during core damage progression and heat remove capability by the natural circulation after cavity injection strategy is implemented. The key events of the accident show good agreement with the PRA report, and the wall temperature distribution of the lower head is obtained. The results indicate that molten pool in the lower head can be effectively cooled by cavity flooding after core exit temperature exceeds 923K during LBLOCA accident, and the integrity of RPV can be maintained. Sensitivity shows that the natural circulation mass flow will increase with the increase of the molten pool decay power.

ACKNOWLEDGMENTS

This work was supported by National Natural Science Foundation of China (11205099).

REFERENCES

1. J.L. LI, G.F. HUANG, L.L. TONG, et al. "Analysis on IVR in severe accident induced by DVI line break," *Atomic Energy Science and Technology*, **44**(Suppl), pp.238-241(2010, in Chinese).
2. J. L. REMPE, K. Y. SUH, F. B. CHEUNG, et al. "In-vessel retention strategy for high power reactors," Idaho National Engineering and Environmental Laboratory, USA(2005).
3. AHN Kwangii, KIM Dongha. "A state-of-the-art review of the reactor lower head models employed in three representative U.S. severe accident codes," *Progress in Nuclear Energy*, **42** (3), pp. 361-382(2003).
4. K. H. KANG, R. J. PARK, S. B. KIM, et al. "Flow analyses using RELAP5/MOD3 code for OPR1000 under the external reactor vessel cooling," *Annals of Nuclear Energy*, **33**,pp. 966-974(2006).
5. R. J. PARK, S. B. KIM, H. D. KIM. "Detailed analysis of in-vessel melt progression in the LOCA of the KSNP using SCDAP/RELAP5," *Korean Nuclear Society Fall Meeting*, Yongpyung, Korea,(2004).
6. K. S. HA, P. J. PARK, H. Y. KIM, et al. "A study on the two-phase natural circulation flow through the annular gap between a reactor vessel and insulation system," *Int Comm Heat Mass Transfer*, **31**, pp. 43-52(2004).

7. Westinghouse, “AP1000 probabilistic risk assessment report, Rev.1”, APP-GW-GL-022. USA(2003).