RESEARCH OF SCWR-M CHARACTER DURING LOSS OF FLOW TRANSIENT

Zhihong XU , Shengwei FU, Xiaojing LIU, Yanhua YANG

School of Nuclear Science and Engineering
Shanghai Jiao Tong University
Shanghai, China

Abstract

Based on a revised version of Relap5, a model of the mixed spectrum SCWR (SCWR-M) system is established. In order to optimize the SCWR-M system design, the Loss of Flow Transient (LOFT) is selected as a significant transient for the SCWR-M system safety analysis. To analysis the transient behavior of SCWR-M during LOFT, some important parameters, e.g. reactor coolant pump (RCP) coast-down time, Reactor Pressure Vessel (RPV) upper water volume and safety injection flow are chosen as the main parameters. The results achieved so far indicated that the SCWR-M system design is feasible and promising.

Keywords: Supercritical Water Cooled Reactor (SCWR), Mixed Core, Loss of flow transient

1. Introduction

The supercritical water cooled reactor (SCWR) is a Light Water Reactor (LWR) operating at higher pressure and temperature. Operation above the critical pressure eliminates coolant boiling phenomenon so that the coolant remains single-phase throughout the reactor. Recent research indicated that the flashing and water hammer phenomena can occur in the SCWR during pressure drop transient [1]. With high temperature in the outlet, the thermal efficiency of SCWR can dramatically increase to 44%. Based on the outstanding achievement of the water-cooled reactor and the supercritical fossil-fired plant, the SCWR can keep a smooth technical continuity [2].

In the last several years, extensive R&D activities have been launched covering various aspects of the SCWR development around the world. Several conceptual designs of SCWR have been proposed in the open literatures. Most of the concepts are based on thermal spectrum. Efforts were also made to design SCWR reactor cores with fast neutron spectrum [2].

A mixed spectrum SCWR core concept (SCWR-M) was proposed by Cheng et al.[3]. Some calculations of this new concept of SCWR system were completed with modified system code Relap5-SCWR, which indicate the SCWR-M system get a better safety character compared with other single spectrum supercritical water reactor.

Loss of flow Transient is a important event selected by some researchers for SCWR in the world [4][5]. Maintain coolant flow during LOFT is an important consideration in the SCWR system design. MacDonald et al. evaluated the effects of LOFT events in a thermal spectrum SCWR system. However, in his results, the peak

cladding temperature will exceed 840℃if the following requirements are not met: (1) auxiliary feedwater is initiated after 4.25 s of the LOFT (2) the auxiliary feedwater flow is less than 15% of the initial main feedwater flow rate [5].

Due to the innovative design of the SCWR-M, it can eliminate such limitation of safety injection delay and flow demand, which is benefit for the system design. This paper will investigate the main parameters, including the RCP coast-down time, RPV upper water volume and safety injection flow to evaluate SCWR-M system character. According to the results obtained, it shows that the new developed mixed spectrum SCWR (SCWR-M) system design is feasible and promising.

2. SCWR-M system model description

Fig. 1 schematically illustrates the flow channel of the SCWR-M system model. The reactor core is divided into two zones with a different neutron spectrum. In the outer zone the neutron energy spectrum is similar to that of a thermal reactor. In this zone the fuel assembly has a PWR-type structure but a co-current flow mode. The cold water entering the pressure vessel goes upward to the top dome and into both the moderator channels and the cooling channels of the thermal zone. It then exits the thermal zone in the lower plenum, from where it enters the fast zone of the reactor core (the inner zone). Table 1 summarizes the main parameters of the SCWR-M system.

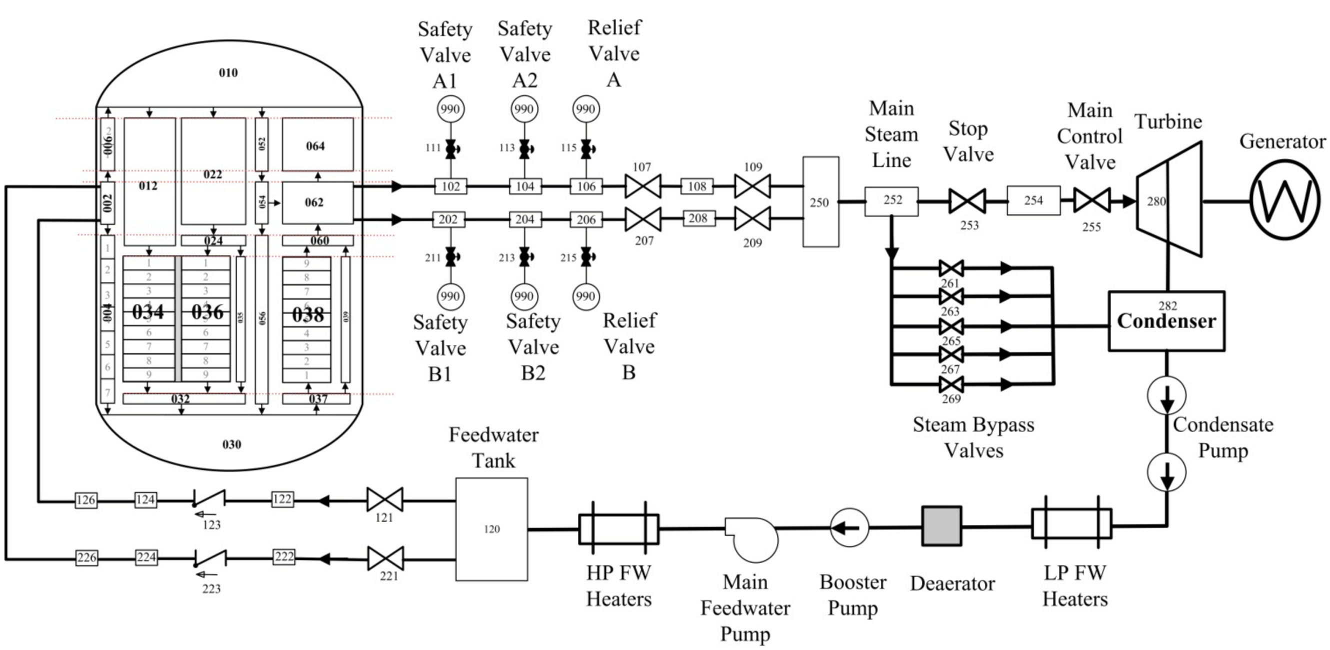


Fig. 1 SCWR-M system model node

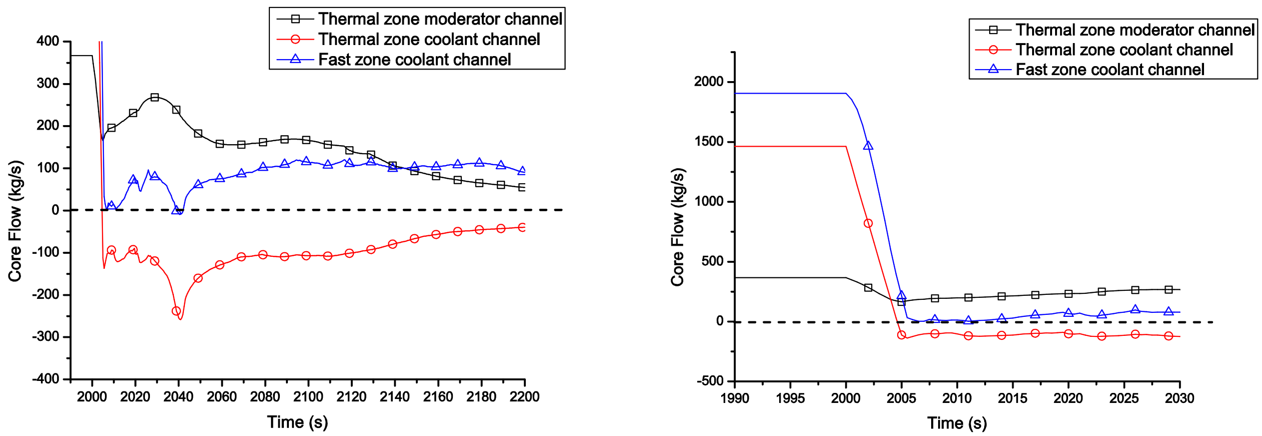
The water temperature is 280℃ at the inlet of the pressure vessel and 510℃ at the exit of the pressure vessel. We assumed that the water is heated to 400℃ through the thermal zone. The average linear power rate is 180 W/cm for both the thermal zone and the fast zone. The active height is 4.5 m for the thermal zone and 2.0 m for the fast zone. 2% of the coolant assumed to flow through downcomer (004) to the lower plenum. 98% of the total coolant flow through raising channel (006) into the top dome (010), and then divided into three parts at the upper plenum (012,022). 19% of the total mass flow rate goes through the moderator channels (034), 76% coolant flow through the thermal zone cooling channel (036). The other 3% of total coolant assumed flow through the control rod guide tubes as bypass flow (052,054,056). 1% of coolant is assumed leaking out to the outlet of RPV (062). 99% of total coolant flow through the fast zone (038) to cool the fuel assemblies from lower plenum (030). Detailed design of SCWR-M core concept can be found in reference [3][6][7][8][9].

Table 1 Parameters of the SCWR-M system

Parameters	Values
Thermal zone power, MW	2390.0
Fast zone power, MW	1400.0
System pressure, MPa	25.0
Coolant flow rate, kg/s	1926.0
Thermal zone coolant ratio	76.0%
Thermal zone moderator ratio	19.0%
Fast zone flow ratio	99.0%
Downcomer flow ratio	2.0%
Bypass flow ratio	3.0%
Bypass to outlet ratio	1.0%
Core diameter, m	3.2
Thermal zone core active height, m	4.5
Fast zone core active height, m	2.0
NO. of thermal zone fuel assemblies	164.0
NO. of fast zone fuel assemblies	120.0
Coolant inlet temperature,℃	280.0
Coolant Outlet temperature, ℃	510.0
Coolant density coefficient, pcm/cm^3	-638.00
Doppler coefficient, pcm/℃	-2.64
Ave. linear power, W/cm	18.0
RPV inner diameter, m	3.6
RPV wall thickness, m	0.4
Volume of top dome,m^3	14.4
Volume of upper plenum,m^3	13.0
Volume of downcomer,m^3	10.5
Volume of lower plenum,m^3	8.0
Number of feed-water lines	2
Number of steam lines	2

3. SCWR-M response during LOFT

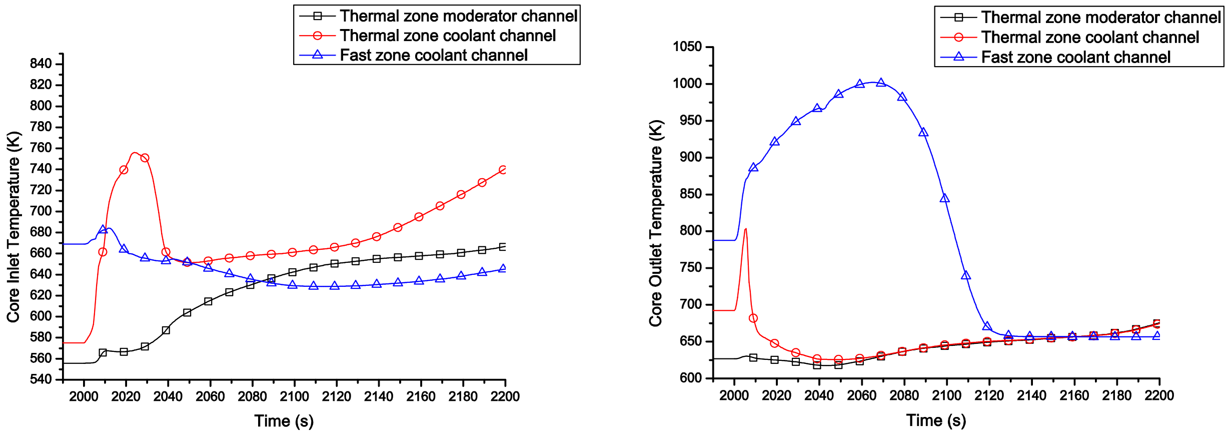
Loss of flow transient (LOFT) was selected as one of the most significant transient in SCWR design. This paper contains some calculations of this transient. The flow decreasing is the first response of the transient. Decreasing of inlet flow directly affects the flowrate in the core, especially there are two kinds of spectrum in the core. During LOFT, two RCPs are assumed to trip. The coast-down time is 5 seconds. Safety injection is assumed to start 20 seconds later after reactor trip. Main results indicate there are special phenomena in the core, which are different from PWR or BWR. System flow changing of SCWR-M during LOFT is shown in Fig. 2. Loss of flow transient is started by trip of two RCPs, after 2000 seconds steady calculation, start RCP trip, 5 seconds coast down later, the inlet coolant flow decreases linearly to zero. Fig. 2 shows the three flow channels in the core of SCWR-M system. Thermal zone coolant channel, thermal zone moderator channel, fast zone flow channel are the three main flow channels in the RPV of SCWR-M system. All the flowrate in these channels decreased quickly due to loss of inlet flow at the first few seconds. But the flowrate gradually increase to a relatively high flowrate in the next decades of seconds, especially in the thermal zone two channels. This is a very significant character of SCWR-M system. Thermal zone can establish nature circulation with enough flowrate after forced flow loss. The nature circulation can be established before safety injection start, which is effective to mitigate the fuel cladding temperature increasing at the first time after accidents. From Fig.2 (a), we can find the thermal zone coolant and moderator can maintain a higher flowrate than fast zone fluid in the first 150 seconds. The fast zone flow keeps low flowrate at the first decades of seconds because of short coast-down time and delay of safety injection. Fig.2 (b) shows that the inverse flow occurs in thermal zone coolant channel at the end of the RCP coast-down. The reason of the flow direction change in the thermal zone coolant channel is caused by the special design of down-flow in the thermal spectrum zone. In the normal operation, flow is forced by the RCPs, special mechanism design can maintain the most part of inlet flow go to the top dome, just little of the coolant flow through the downcomer for thermal isolation of RPV. The main flow to the top dome is divided into three parts to flow through the thermal zone coolant channel, thermal zone moderator channel and bypass channel to the lower plenum. Together with the downcomer flow, all the lower plenum coolant go through the fast zone channel to the outlet of RPV. Only a little flow in the bypass channel can directly leak to the outlet without cooling any part of the core. During LOFT, no forced flow exits to maintain the fuel cooling. Coolant in the thermal zone is heated by the fuel rods in the thermal zone coolant channel, buoyancy increasing with the coolant density change, the moderator channel keeps cooling the coolant channel with heat exchange, which establishes a nature circulation automatically. The coolant filled in the thermal zone can start to flow itself, so the demand of safety injection is mitigated. Of course the thermal zone is not isolated, flow loss or added by other flow channels in the top dome or the lower plenum occurs usually during the nature circulation. The nature circulation can be affected by the RCP coast-down time, the volume of top dome and the flow of safety injection, which will be discussed in the following sections.



(a) Flowrate after LOFT in the core (b) Flow change of flow in the core

Fig. 2 Core flow during LOFT

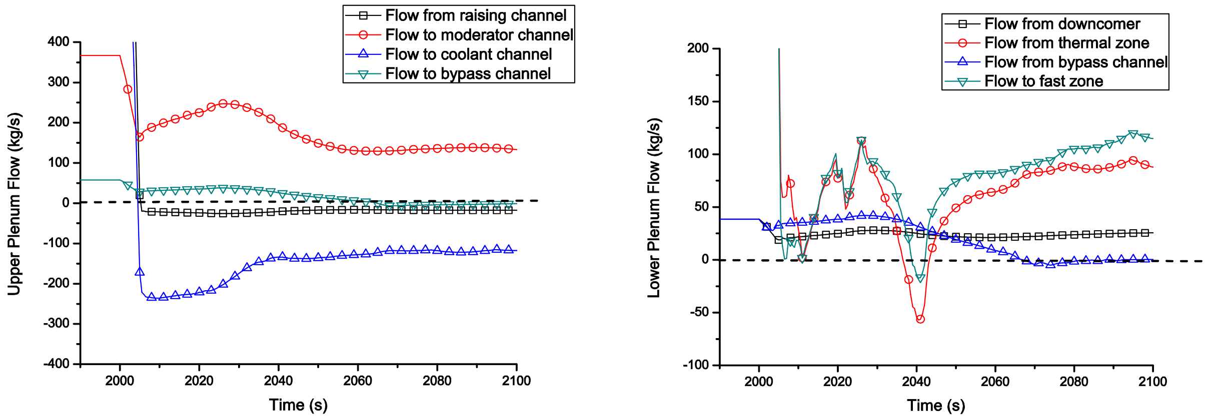
From Fig.3, the temperature change of inlet and outlet of three channels in the core indicate the inverse flow in the thermal zone coolant channel. The highest temperature of the three channels is fast zone, and the lowest temperature is thermal zone moderator channel in the steady state calculation, no matter inlet or outlet. After LOFT happens, there is peak temperature appear in thermal zone coolant channel and fast zone flow channel outlet nodes, while temperature in thermal zone moderator outlet node nearly keep steady. Lack of coolant flow leads to increase the temperature of fast zone outlet for a long time, while thermal zone outlet temperature decrease quickly after the nature circulation established. Nature circulation in thermal zone directly affects the temperature change of inlet and outlet node in thermal zone coolant channel. Inverse flow in the thermal zone coolant channel makes the node with highest cladding temperature become the lowest cladding temperature part, which is benefit to mitigate cladding temperature increasing. Thermal zone coolant inlet node is not a high temperature part during normal operation, but nature circulation makes it become the highest temperature part in the three zone inlet node. Outlet temperature of thermal zone two channels become the same and higher than the temperature of inlet node in fast zone, which means most of the coolant flow out of thermal zone moderator channel goes in to thermal zone coolant channel, little downcomer flow and bypass flow together with the flow left from thermal zone moderator channel go to the lower plenum, then go through the fast zone flow channel. Lower temperature coolant from downcomer and bypass channels together with part flow from thermal zone moderator channel, makes the inlet temperature of fast zone is lower than outlet temperature of thermal zone.



(a) Core zone inlet temperature (b) Core zone outlet temperature

Fig. 3 Core in-out temperature during LOFT

Fig.4 shows the flow changes in the top dome and lower plenum. One inlet from raising channel keeps flowrate at 1800kg/s during normal operation, but quickly changes the flow direction after LOFT and maintains a flowrate at 30kg/s, which means top dome coolant flow through raising channel to maintain downcomer flow. Even if it's no benefit to thermal zone coolant, but it maintains lower temperature coolant go to lower plenum, makes the inlet temperature of fast zone is lower than the outlet temperature of thermal zone and increases the cooling of fast zone. Three outlet of top dome are thermal zone coolant channel, thermal zone moderator channel and bypass channel. Thermal zone coolant channel flow direction changes quickly after LOFT happens. Flow in thermal zone moderator nearly decreases half but keeps flow direction. Flow in bypass channel gradually decreases to inverse flow but maintain very low flowrate. Fig.4(a) shows that inverse flow happens quickly in thermal zone coolant channel and raising channel. Bypass flow will change flow direction decades of seconds later after LOFT. No inlet flow to the RPV, but downcomer flow direction is not change, means even most part of the inverse flow from the thermal zone coolant channel go to the thermal zone moderator channel, part of it go to lower plenum though downcomer. Downcomer makes low temperature water direct go to lower plenum without heated by thermal zone fuel assembly, which is better to mitigate the temperature of coolant in the lower plenum increasing. Fig.4 (b) shows the inlet and outlet of lower plenum. Three inlets form downcomer, thermal zone and bypass. One outlet is to the fast zone channel. Only thermal zone to the lower plenum flow and lower plenum flow to fast zone flow change directions for a short time in some times, the four channels flowrate decrease but not keep inverse flow for a long time. The reverse flow occurs in the thermal zone between lower plenum and fast zone between lower plenum is effected by the safety injection flow. Safety injection by forced flow effects the nature circulation in thermal zone. Detailed discussion on it will be presented next.



(a) Flow change in top dome (b) Flow change in Lower plenum

Fig. 4 Flow change of RPV during LOFT

Fig.5 shows that fast zone fuel cladding temperature is higher than thermal zone fuel and decreases later than thermal zone. That's because the natural circulation established in thermal zone mitigates the cladding temperature increasing and make it decrease faster. If all the inverse flow of thermal zone coolant channel goes to thermal zone moderator channel, the inlet temperature of fast zone will increase with the inlet coolant in lower plenum increasing because no lower temperature coolant flow from top dome to lower plenum by downcomer. The cladding temperature decreasing by the decay heat decreasing faster than the coolant, but it will rise again without more coolant injection.

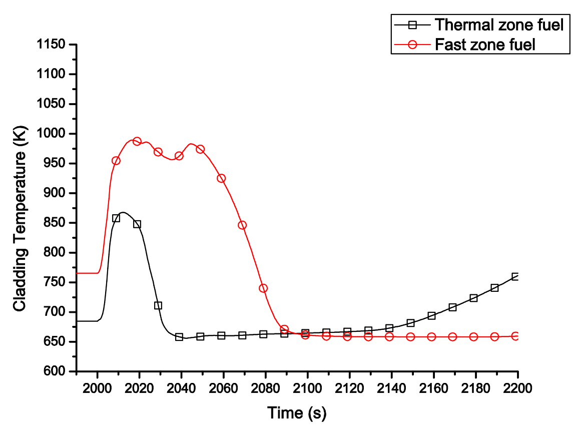
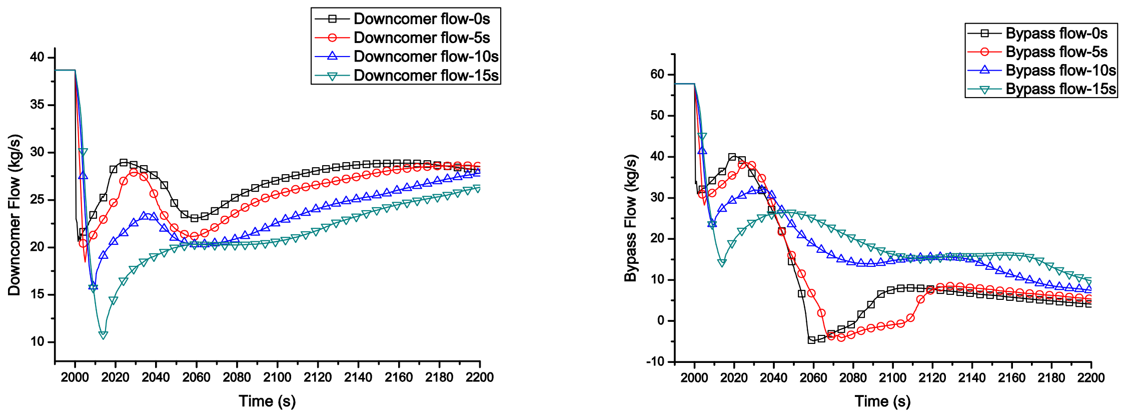


Fig. 5 Fuel cladding temperature during LOFT

4. Effect of RCP coast-down time

Assumed RPV upper water volume is $27m^3$, no safety injection, RCP coast-down time is selected as 0 second, 5 seconds, 10 seconds and 15 seconds. Compare 200 seconds results after LOFT together to analysis the effect of RCP coast-down time during LOFT.

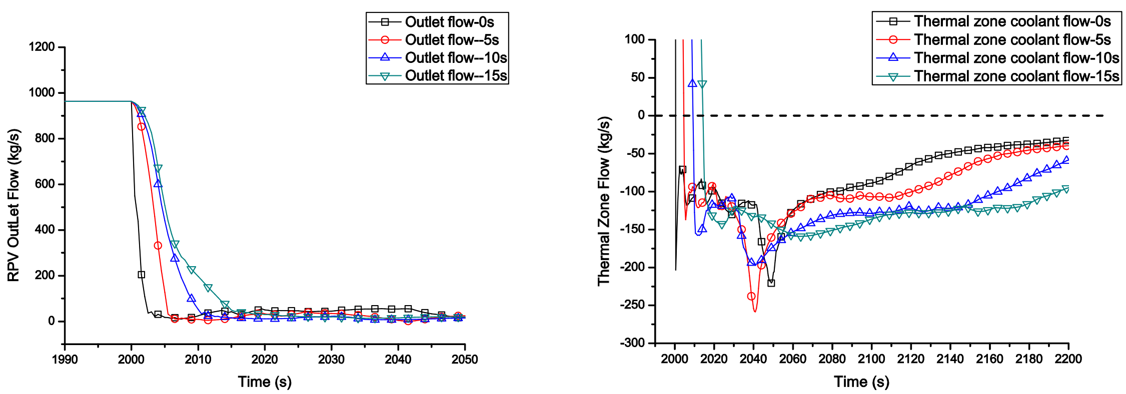
During LOFT, RCP coast-down time is an important parameter to mitigate the result of such transient. If RCP coast-down time is long, the decreasing of inlet flow to zero lasts long. From Fig.6, downcomer and bypass flow are obviously effected by RCP coast-time. Fig.6(a) shows that the RCP coast-down time is longer, the downcomer flow is lower. Fig.6(b) shows that the RCP coast-down time is longer, the bypass flow is lower at the first decades of seconds. The decreasing of downcomer and bypass flow is better to let more coolant form inlet go to top dome and flow passes the thermal zone.



(a) Downcomer flow (b) Bypass flow

Fig. 6 Downcomer and bypass flow change
with different coast-down time

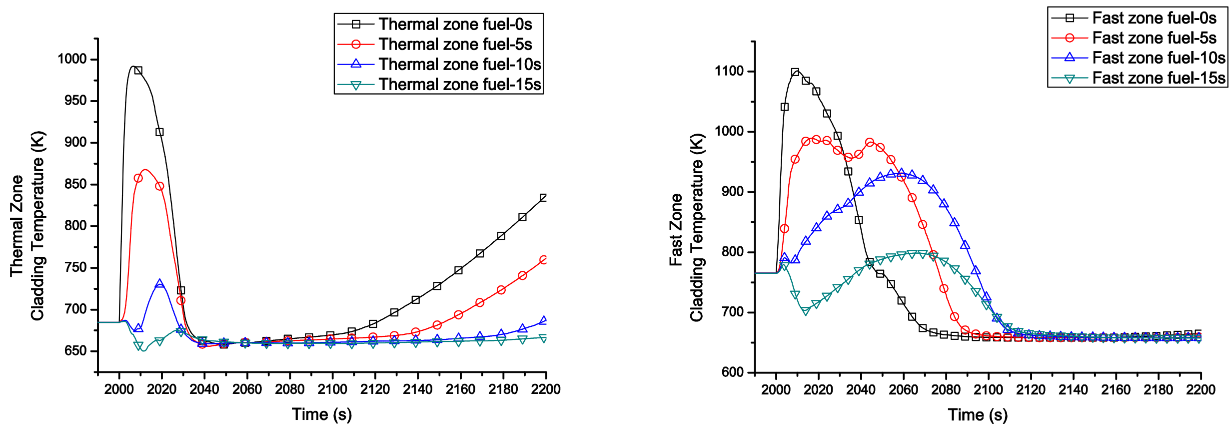
Flow change in the core is direct effected by inlet flow. Fig.7 shows the flow change in outlet of RPV and thermal zone coolant channel in the core. From Fig.7 (a), we can find outlet flow decrease to near zero when the RCP coast-down finish. Fig.7 (b) shows the thermal zone flow turning to inverse flow at the end of RCP coast-down time, and the longer of RCP coast-down time, the higher inverse flowrate of thermal zone coolant.



(a) RPV Outlet flow (b) Thermal zone coolant flow

Fig. 7 Outlet and thermal zone coolant flow change
with different coast-down time

RCP coast-down time effects the flow of the SCWR-M system after LOFT occurs. Different flowrate in the core leads to different fuel cladding temperature. Fig. 8 shows the cladding temperature in the core, including thermal zone and fast zone. The longer of RCP coast-down time, the lower cladding temperature. Because there is no safety injection, the temperature will rise again. Fig. 8(a) shows the cladding temperature rise again quickly is the coast-down time is too short. There is no temperature rising again in Fig. 8(b), because the fast zone inlet coolant temperature decreasing mitigates the cladding temperature increasing. But all the cladding temperature will rise again if there is no more coolant injection.



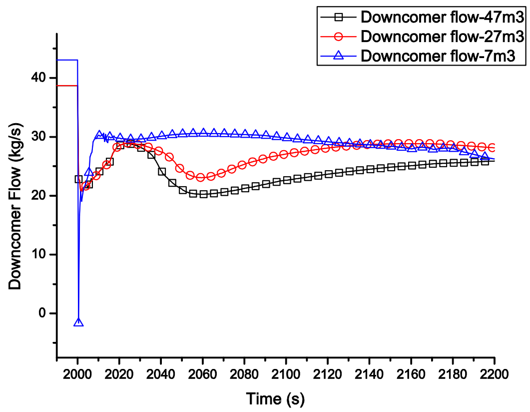
(a) Thermal zone cladding temperature (b) Fast zone cladding temperature

Fig. 8 Thermal and fast zone cladding temperature change
with different coast-down time

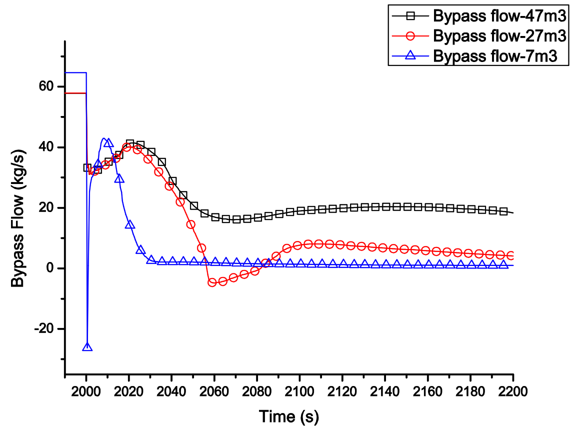
5. Effect of RPV upper water volume

Assumed RCP coast-time is 0 second, no safety injection, RPV upper water volume is selected as $47m^3$, $27m^3$, $7m^3$. Compare 200 seconds results after LOFT together to analysis the effect of RPV upper water volume during LOFT.

During LOFT, because of SCWR-M special core design, RPV upper water volume is an important parameter to mitigate the result. If RPV upper water volume is larger, the coolant stored in the RPV is more. After loss of forced flow, the coolant stored in the upper of RPV can help to maintain nature circulation flow in decades of seconds. Fig.9 shows the downcomer flow and bypass flow with different RPV upper water volume. The lager the RPV upper water volume is, the lower flow of in the downcomer is. Large RPV upper water volume can maintain high flowrate in the bypass channel.



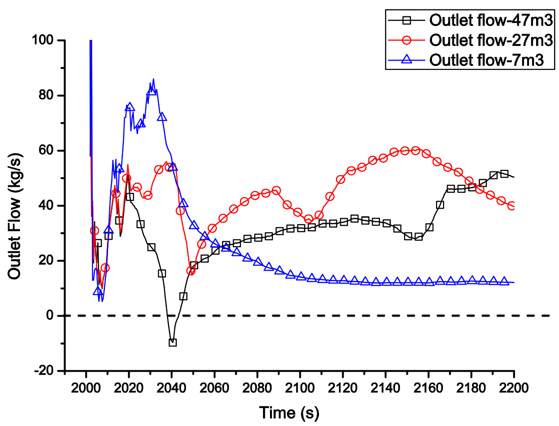
(a) Downcomer flow



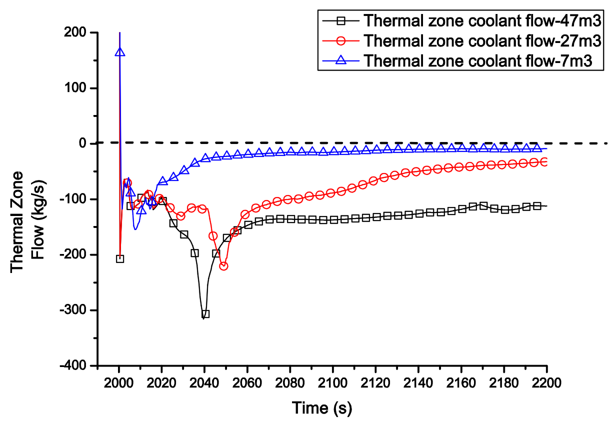
(b) Bypass flow

Fig. 9 Downcomer and bypass flow change
with different RPV upper water volume

RPV upper water volume affects the outlet flow of RPV and flow in the core. Fig.10 shows the outlet flow of RPV is affected by RPV upper water volume. If the upper water volume is too small, the outlet flow will decrease quickly to a very low flow. The small volume of RPV upper water will lead to very low inverse flowrate in the thermal zone coolant. Lager volume of RPV upper water can maintain high flowrate in the thermal zone, which means lager RPV upper water volume is benefit to establish nature circulation in thermal zone.



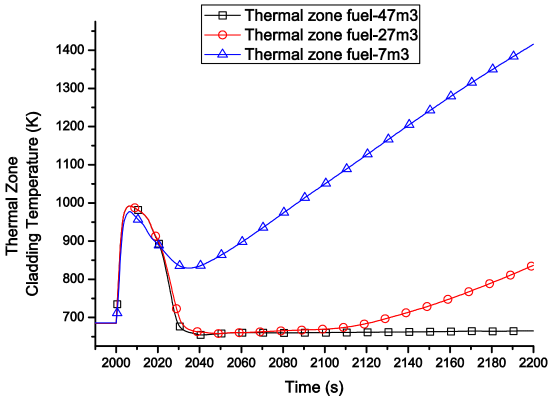
(a) RPV Outlet flow



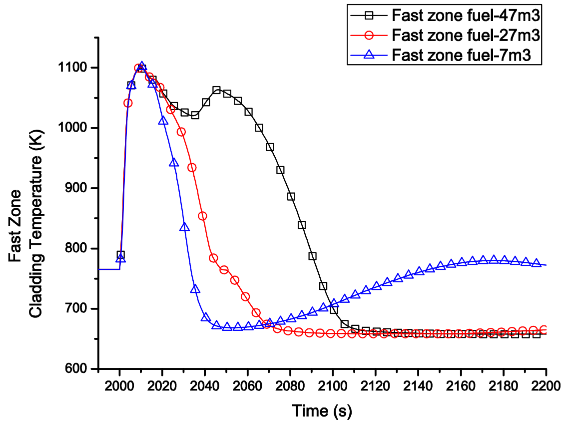
(b) Thermal zone coolant flow

Fig. 10 Outlet and thermal zone coolant flow change
with different RPV upper water volume

RPV upper water volume affects the flow in the core, which leads to different fuel cladding temperature. From Fig.11, results show that different RPV upper water volume just affects the cladding temperature decades of seconds later after LOFT, which means the first decades of cladding temperature rising is not affected by RPV upper water volume. The volume of water in the upper of RPV can mitigate the cladding temperature rising again, and let it rise later.



(a) Thermal zone cladding temperature



(b) Fast zone cladding temperature

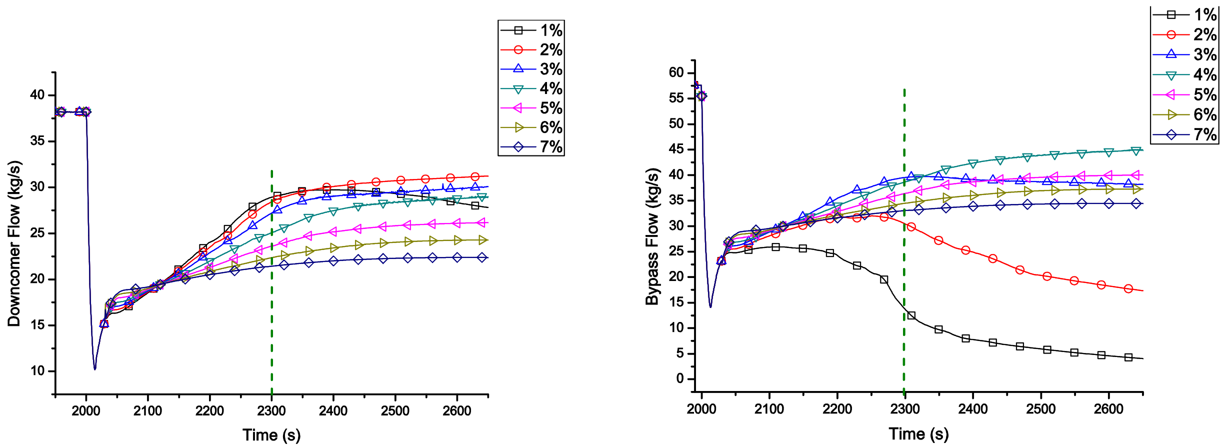
Fig. 11 Thermal and fast zone cladding temperature change
with different RPV upper water volume

6. Effect of safety injection flow

Assumed RCP coast-time is 0 second, RPV upper water volume is $27m^3$, safety injection delay is 20 seconds. Select safety injection flow is 1% to 7% of system design flow. Compare 500 seconds results after LOFT together to analysis the effect of safety injection delay during LOFT.

During LOFT, even SCWR-M design can provide RCP coast-down and RPV upper water volume to mitigate the result, but if there is no more coolant injection, the cladding temperature will rise and exceed the limitation of cladding material at last. Because the SCWR-M system can mitigate the LOFT result automatically at the first decades of seconds with enough RCP coast-down and RPV upper water volume, the delay of safety injection becomes not an important factor. The safety injection flow is selected as an important factor to analysis the LOFT of SCWR-M system.

Fig. 12 shows the downcomer and bypass flow change in the LOFT with different safety injection flow. The safety injection flow amount has not significant effect to downcomer flow. No matter the safety injection flow is, the downcomer flow can maintain nearly 30 kg/s. Downcomer is a circle around the RPV with large volume is an important reason that it will keep a relatively high flow after LOFT. The bypass flow increases with the safety injection flow.



(a) Downcomer flow (b) Bypass flow

Fig. 12 Downcomer and bypass flow change
with different safety injection flow

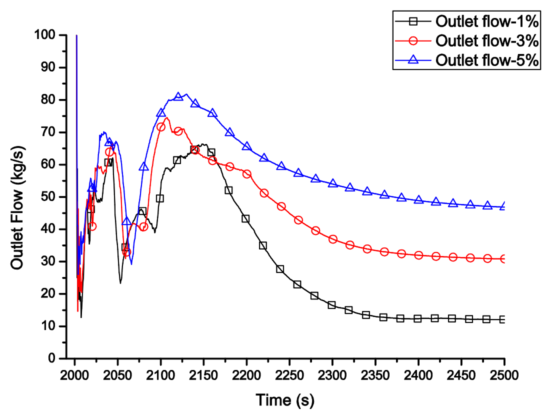
When 300 seconds after LOFT occurs, downcomer flow becomes steady. Compare different downcomer flow at 2300s in Table 2, we can find when the safety injection flow is higher than 5% of system design flow, the downcomer flow is less than 25% of the safety injection flow and the bypass is less than 40% of the safety injection flow. Even is only 35% of the safety injection flow goes through thermal zone (less than 2% of system design flow), the fuel in the thermal zone can be cooled by the nature circulation in thermal zone.

Table 2 Downcomer and bypass flow at different safety injection flow

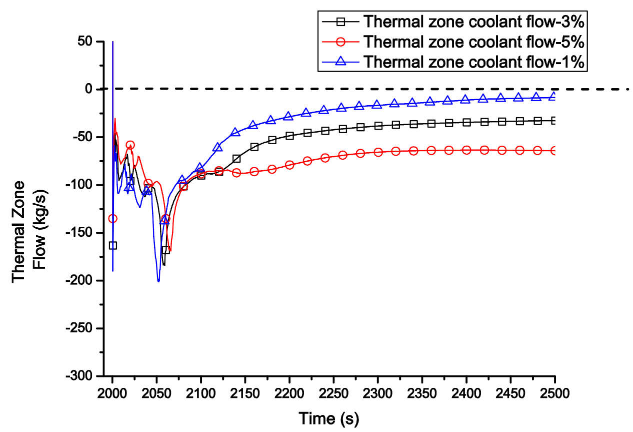
	Downcomer	Bypass	All Coolant flow	Downcomer percent	Bypass percent
Steady	38.05 kg/s	57.63 kg/s	1926.07 kg/s	1.98%	2.99%
1%	29.93 kg/s	3.61 kg/s	19.26 kg/s	155.39%	18.75%
2%	28.38 kg/s	16.93 kg/s	38.52 kg/s	73.67%	43.95%
3%	27.15 kg/s	38.11 kg/s	57.78 kg/s	46.99%	65.96%
4%	24.97 kg/s	45.18 kg/s	77.04 kg/s	32.41%	58.64%
5%	23.66 kg/s	37.67 kg/s	96.30 kg/s	24.57%	39.11%
6%	22.34 kg/s	31.14 kg/s	115.56 kg/s	19.33%	26.94%
7%	21.41 kg/s	20.44 kg/s	134.82 kg/s	15.88%	15.16%

From Table 2, the percent of downcomer and bypass flow is decreasing with the safety injection flow increasing. When the safety injection flow is 1% and 2%, most of the safety injection flow goes into the downcomer, even more than 100%, which means flow from back of top dome. Because the flow area limitation in downcomer and bypass, if more safety injection flow goes into the RPV, the percent of the flow goes through the thermal zone will increase, because the flow area there is larger than downcomer or bypass.

Without RCP coast-down, see in Fig. 13(a), the outlet flow decrease quickly after LOFT occurs, then increases by supply of water volume in RPV and nature circulation in thermal zone, which lasts only decades of seconds and decreases again. After safety injection flow into the core, the outlet flow increases and then maintains a relatively high flow rate. All the safety injection flow go to the outlet at last, so the outlet steady flow in the end is the same with the safety injection flow. Fig 13(b) shows that the first decades of seconds after LOFT occuring, thermal zone coolant inverse flow is unstable and not affected by safety injection flow. The steady natura circulation flow of thermal zone coolant is affected by safety injection obviously. Safety injection flow supports the nature circulation flow in the thermal zone and maintains it with enough flow.



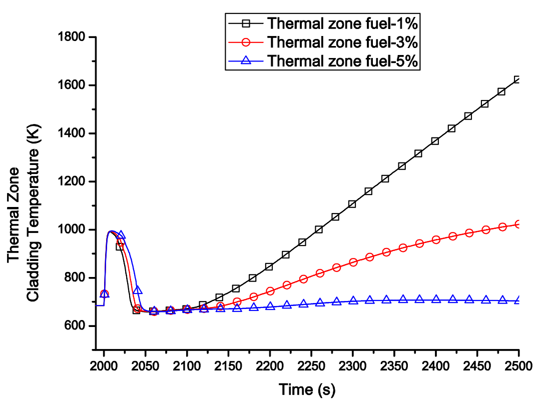
(a) RPV Outlet flow



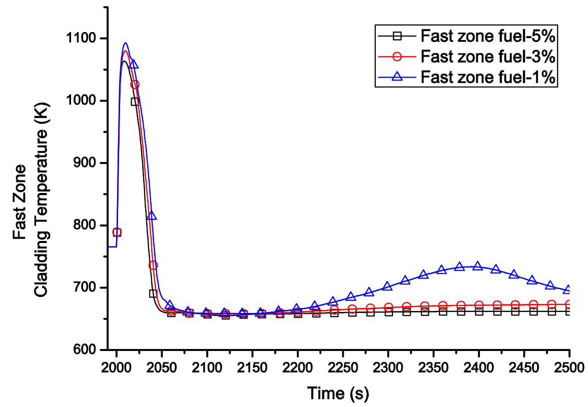
(b) Thermal zone coolant flow

Fig. 13 Outlet and thermal zone coolant flow change with different safety injection flow

From Fig. 14, the first decads of seconds results are not affected by safety injection flow at all. Because the RCP coast-down time is too short, the cladding temperature rise quickly after LOFT occurs. About 100 seconds later, the thermal zone cladding temperature rises again to a very high temperature when the safety injection flow is not enough. If the safety injection flow is more than 5% of design system flow, the cladding temperature will not rise again, which shows the safety injection flow is the effective method to mitigate the loss of flow transient in the later period.



(a) Thermal zone cladding temperature



(b) Fast zone cladding temperature

Fig. 14 Thermal and fast zone cladding temperature change
with different safety injection flow

7. Discussion

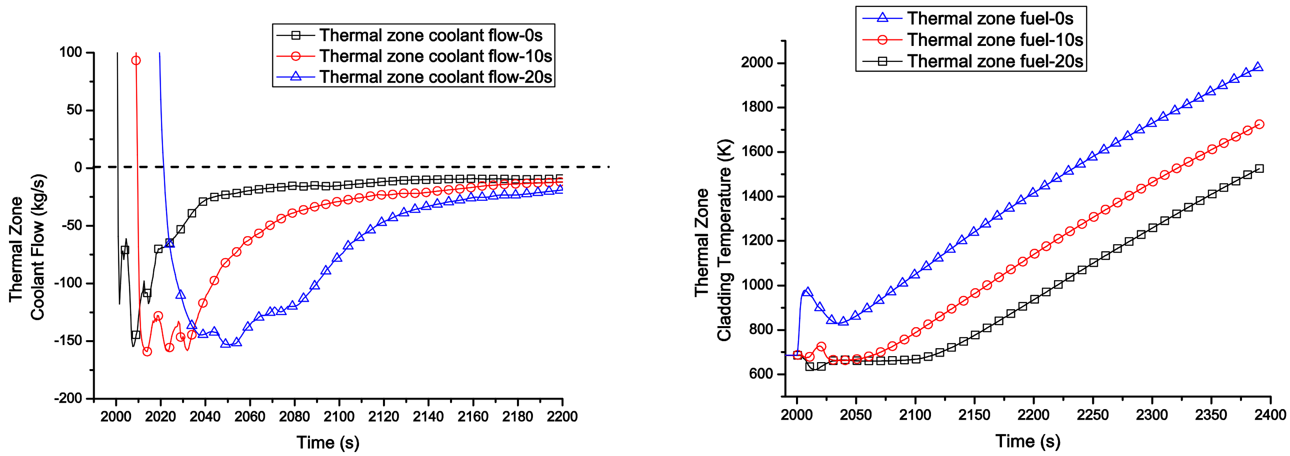
Special flow design of SCWR-M system leads to some special character during LOFT. Flow from upper plenum to lower plenum in thermal zone is the key factor for the system character during LOFT.

RCP coast-down is the most effective method to mitigate the fuel cladding temperature rising at the first decades of seconds after LOFT occurs, but it only mitigates the first seconds result. Because RCP coast-down just make the feedwater decrease slowly, but it can't supply any more water to the RPV. Without other measures to supply water to the RPV, the fuel cladding temperature will rise again quickly.

The RPV upper water volume is a special design of SCWR-M, which is benefit to mitigate the LOFT result after RCP coast-down complete. Fig.15 shows the result of small upper water volume. Even if the RCP coast-down is 20 seconds, without enough water in the upper of RPV, the flow established by natural circulation is not sufficient and cladding temperature will rise quickly.

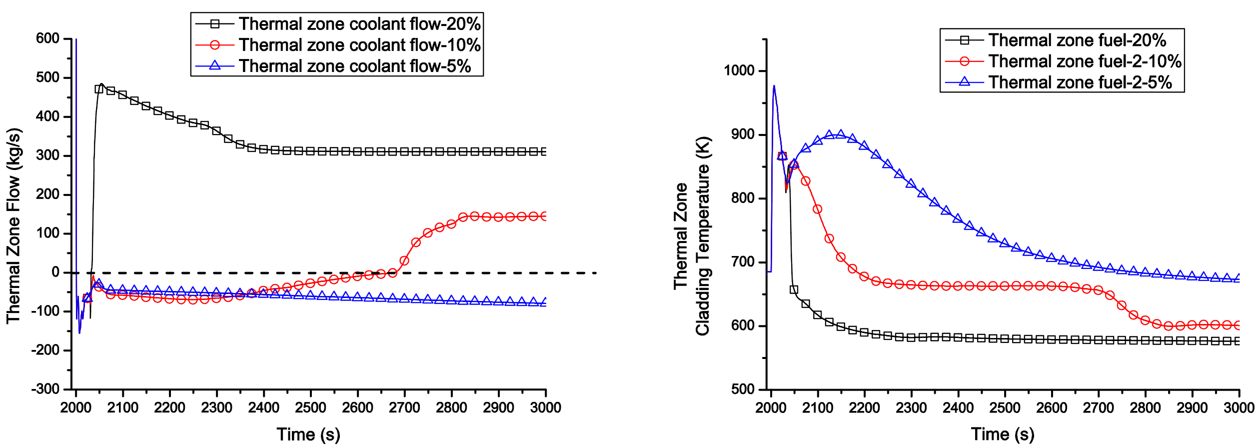
The safety injection flow requires a relatively long time to go to the core. Therefore, it cannot be used as the first method to mitigate the result of LOFT. It just can be used as a support method to mitigate the result of LOFT. Fig.16 shows the result of small RPV upper water volume (7 m3) and short RCP coast-down time (0.1 s). When the safety injection flow is high enough to force the thermal zone coolant flow turning back from the upper plenum to the lower plenum, the rise of cladding temperature during the first decades can't be mitigated.

The flow in the downcomer takes a small fraction feedwater directly to the lower plenum, which cause a decrease of the coolant flow in the thermal zone. Of cause, less flow pass thermal zone is not benefit for cooling thermal zone, but after carefully optimization of flow in moderator and coolant channel, the outlet temperature of thermal zone can be maintained below the safety limited. During LOFT, natural circulation in the thermal zone will cause relatively high flow to cool the fuel. So if the nature circulation is established and enough nature circulation flow is maintained, little flow from top dome go to lower plenum can be ignored. Reversely, lower temperature coolant from downcomer to the lower plenum can mitigate the inlet temperature of fast zone rising, which is benefit to cool the fast zone fuel.



(a) Thermal zone coolant flow (b) Thermal zone cladding temperature

Fig. 15 Small upper water volume results
with different RCP coast-down time



(a) Thermal zone coolant flow (b) Thermal zone cladding temperature

Fig. 16 Small upper water volume and short RCP coast-down time results
with different safety injection flow

8. Conclusions

The SCWR-M has some special design of spectrum and flow path, which gets some good character to mitigate the loss of flow transient.

The RCP coast-down time should be more than 15 seconds, then the cladding temperature rising at the first decades of seconds after LOFT can be mitigated.

The RPV upper water volume should be more than 27 m^3 in order to mitigate the rise of cladding temperature during the first decades of seconds after RCP coast-down.

Safety injection should be more than 5% of the system design flow in order to mitigate the rise of cladding temperature during the later period.

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9. Reference

[1]. A.R. Imre, Theoretical study of flashing and water hammer in a supercritical water cycle during pressure drop, Nuclear Engineering and Design ,2010,240:1569-1574
[2]. Y. Oka, Review of high temperature water and steam cooled reactor concepts, Proc. of SCR-2000, Tokyo, (2000).
[3]. X. Cheng, X.J. Liu, Y. H. Yang, A Mixed Core for Supercritical Water-cooled Reactor, Nuclear Engineering and Technology, 2008, 40(2):117-126.
[4]. Yuki ISHIWATARI, Safety of Super LWR, (II) Safety Analysis at Supercritical Pressure, Journal of Nuclear Science and Technology, Vol. 42, No. 11, p. 935–948 (November 2005)
[5]. Supercritical Water Reactor (SCWR), Progress Report for the FY-03 Generation-IV R&D Activities for the Development of the SCWR in the U.S. September 30, 2003
[6]. X.J. Liu, T. Yang, X. Cheng, Core and Sub-channel Analysis of SCWR With Mixed Spectrum Core, 2010, Annals of Nuclear Energy,2010,37: 1674-1682
[7]. X.J. Liu, X. Cheng, Coupled Thermal-hydraulics and Neutron-physics Analysis of SCWR with Mixed Spectrum Core, Progress in Nuclear Energy, 2010, 52(7),640-647.
[8]. X.J. Liu, X. Cheng, Thermal-hydraulic and Neutron-physical Characteristics of a New SCWR Fuel Assembly, Annals of Nuclear Energy, 2009, 36:28-36.
[9]. X.J. Liu, X. Cheng, Core and Sub-channel Evaluation of a Thermal SCWR, Nuclear Engineering and Technology, 2009, 41(5):677-690.