Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 18-19, 2017

Improved Safety Injection Flow Model Associated with Target Depressurization during Severe Accident Management

Joongoo Jeon[a], Wonjun Choi[a], Nam Kyung Kim[a], Yongjae Lee[a], Sung Joong Kim[a,b*]
[a] *Department of Nuclear Engineering, Hanyang University,*
[b]*Institute of Nano Science & Technology, Hanyang University*
222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea
[*] *Corresponding author: sungjkim@hanyang.ac.kr*

1. Introduction

In Korea, the accident management phase shifts from the Emergency Operation Procedure (EOP) to Severe Accident Management Guidance (SAMG) when a certain criterion is reached [1]. Among 7 mitigation strategies envisioned, the third management strategy, injecting coolant into Reactor Coolant System (RCS) is a key strategy to fortify the in-vessel retention capability. In this regard, it is necessary to estimate accurate heat generation and accumulation in the core to determine reasonable injection flow rate. During LWR severe accident, not only the decay heat but also a large amount of oxidation heat occurs in the reactor core. Thus, developing an accurate model to predict the total heat generation including the oxidation heat is essential for the effective applications of SAMG

For this reason, through a previous study, Lee et al. developed a safety injection (SI) flow model to predict the sum of the decay heat and the oxidation heat as the accident sequences were progressed. The mechanistic SI flow model adopted the CET increase rate and core water level decrease rate, which were obtained from MELCOR code simulation. It was believed that the SI model estimated the total heat reasonably by considering the expected amount decay heat and the accumulated heat in the core based on the RCS pressure [2.3].

However, it was confirmed that the SI model developed by Lee et al. could not represent the total heat removal especially since start of oxidation. Under transient conditions, the heat sources accumulated in the heat structures (fuel, cladding, supporting structures) should be embarked in the model for accurate contribution to the total heat source. Therefore, the objective of this study is to improve the previous SI flow model predicting the total core heat associated with target RCS depressurization to satisfy the in-vessel coolability during severe accidents. Additional terms were developed to reflect accurate heat accumulation and included in the previous model. Resulting SI flow model led to an improved SI flow map including the target RCS depressurization, which enables to figure out discharge of the required flow rate by utilizing the flow rate-pressure curve with operation of two high pressure safety injections (HPSIs). Also the accuracy of the improved map was verified by the recent MELCOR simulation results of postulated severe accident such as small break loss of coolant accident (SBLOCA).

2. Modeling

2.1 Limitation of previous model

Fig. 1 shows a water level in reactor pressure vessel (RPV) during severe accident. The RPV is divided into upper head, core, and lower plenum. In core region, L_o is core total height and L is height of the uncovered core. During severe accidents, the total heat generated in the core is calculated by the sum of the latent heat of the water and sensible heat of the vapor in previous model as shown in Eq. (1). Because the amount of evaporated water with time can be inferred from the water level change, the latent heat was calculated by Eq. (2). A is cross sectional area of upper head. Also, the sensible heat of the vapor can be calculated using the total amount of steam in the RPV and CET increase rate as shown in Eq. (3). The ideal gas equation was used to estimate the total amount of steam in the RPV. P_{RCS} is RCS pressure and V_o is volume of the upper head.

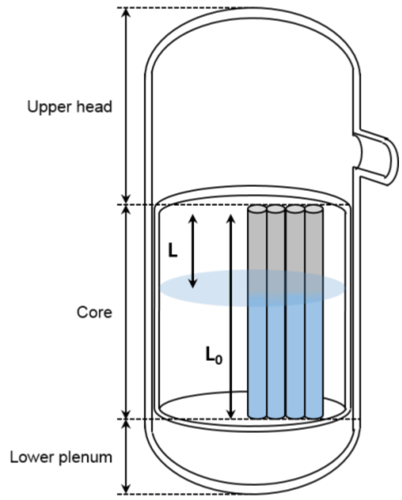

Fig. 1. A simplified RPV for SI flow model

$$\dot{q}_{tot} = \dot{q}_{decay} + \dot{q}_{oxidation} = \dot{q}_{latent} + \dot{q}_{sensible} \quad (1)$$

$$\dot{q}_{water} = (\rho_f A \frac{dL}{dt}) h_{fg} \quad (2)$$

$$\dot{q}_{steam} = M_g c_p \frac{dT_{CET}}{dt}, \quad M_g = \frac{P_{RCS}(V_0 + AL)M_{H_2O}}{RT_{CET}} \quad (3)$$

To verify the accuracy of the SI model, Fig. 2 compares the total heat estimated by the model using the core water level and CET values in the simulation and the same heat computed from the MELCOR code for SBLOCA without SI. It predicts similar values to the MELCOR results in the beginning. However, as accident sequence continues, the old model estimates a lower heat compared to the results. Especially after oxidation, the difference becomes larger and the credibility of the model is dramatically decreasing.

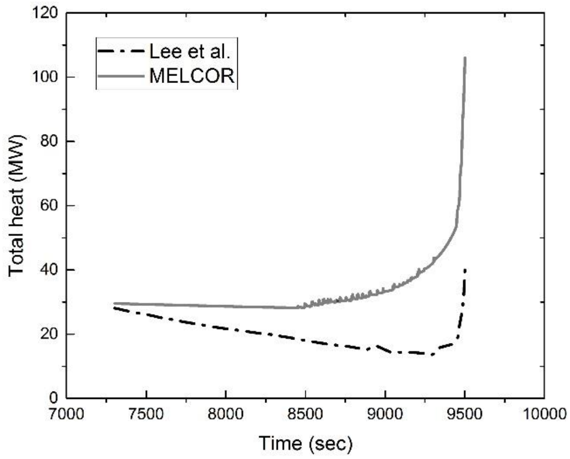

Fig. 2. Total heat by the SI flow model and MELCOR results during SBLOCA

2.2 Improvement of the SI model

The major reason for underestimating the heat generation in the previous model is because the heat sources accumulated in the heat structures (fuel, cladding, supporting structures) was not properly taken into consideration. Once the core is uncovered, a large amount of oxidation heat builds up in the structures, which causes such big differences. Therefore the accumulated heat in the heat structure was included in the improved model for accurate prediction of total heat as shown in Eq. (4).

Fig. 3 compares the fuel, cladding temperatures, and CET over time during SBLOCA. The actual temperature of the heat structure is different from the CET. However, it was observed that rate of change of the temperatures was similar from 500 seconds after the CET rise (Phase 2). Although the CET increase rate is higher during Phase 1, this period is relatively short and the slope is too small to generate sizable errors. Therefore, the accumulated heat can be represented reasonably through CET increase rate like the sensible heat of the vapor. Because the heat structure consists of a fuel, a cladding, and a supporting structure, Eq. (5) combines each accumulated heat. The mass of each structure was determined through the Final Safety Analysis Report (FSAR) [4]. This resulting model led to an improved SI flow map including the target RCS depressurization, which enables to figure out discharge of the required flow rate by utilizing the flow rate-pressure curve with operation of two high pressure safety injections (HPSIs).

The minimum injected flow rate was estimated through the amount of estimated total heat. Assuming that all injected water is evaporated, the minimum flow rate can be calculated as shown in Equation (6). $h_{sat,g}$ is the saturated steam enthalpy and h_{inj} is the injected water enthalpy. Finally, additional injection flow rate is required to restore the core water level as well as to eliminate the total heat. Thus, the final required flow rate for maintaining the core coolability is given in Eq. (7), where t_{fill} is the time taken for refilling the core inventory (0.66 hr). The calculated required flow rates were converted to target RCS depressurization through a characteristic pump curve. The characteristic pump curve determines the amount of injection flow by the high-pressure pump.

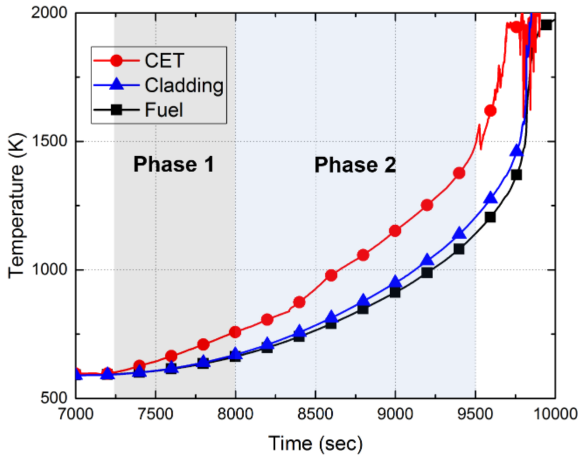

Fig. 3. Comparison of changes in fuel, cladding temperatures, and CET during SBLOCA

$$\dot{q}_{tot} = \dot{q}_{decay} + \dot{q}_{oxidation} = \dot{q}_{water} + \dot{q}_{steam} + \dot{q}_{hs} \quad (4)$$

$$\dot{q}_{hs} = M_{hs} c_p \frac{dT_{CET}}{dt}$$
$$= (M_{fuel} c_{p,fuel} + M_{clad} c_{p,clad} + M_{st} c_{p,st}) \frac{dT_{CET}}{dt} \quad (5)$$

$$\dot{m}_{\min} = \frac{\dot{q}_{tot}}{h_{sat,g} - h_{inj}} = \frac{\dot{q}_{water} + \dot{q}_{steam} + \dot{q}_{hs}}{h_{sat,g} - h_{inj}}$$
$$= \frac{(\rho_f A \frac{dL}{dt}) h_{fg} + (M_g c_p + M_{hs} c_p) \frac{dT_{CET}}{dt}}{h_{sat,g} - h_{inj}} \quad (6)$$

$$\dot{m}_{req} = \dot{m}_{\min} + \frac{\rho_f AL}{t_{refill}} \quad (7)$$

3. Results and Discussion

3.1 Verification of improved SI model

The accuracy of the improved SI model was verified by comparing computed value of the MELCOR code. Also, not only SBLOCA by MELCOR code, but also simulation results of station black out (SBO) and total loss of feed water (TLOFW) were used for more accurate verification. Figs. 4-6 show the calculated total heat by the previous and modified models using the core water level and CET values in the simulation. Unlike the previous model, the modified model predicts the heat without significant difference even after oxidation. It is confirmed that the added terms for accumulated heat in the heat structure contribute to reducing the difference between the Lee et al.'s model and the MELCOR results.

Nevertheless there exist slight differences between the model and MELCOR simulation. At first, errors appearing initially are caused by the overestimated temperature increase rate of heat structures at Phase 1. On the other hand, errors after the initial phase 1 are due to coolant discharge through opening of pressurizer safety relief valves (PSRV) and uncertainty of the core water level decrease rate. The RCS pressure was fluctuated due to the repeated valve openings, resulting in large fluctuation on the various thermos-physical properties of coolant determined by pressure in the model. Since the values of the properties are calculated according to specific pressure range, this large fluctuation might result in some errors. This is the reason why more errors could occur in the SBO and TLOFW, which inherently exhibit high pressure condition compared to SBLOCA. If the pressure ranges are calculated in more detail, the error is expected to diminish. As the severe accident progresses, the core water level decrease rate varies considerably from time to time because water evaporation is very active. This uncertainty of the core water level also can produce some errors.

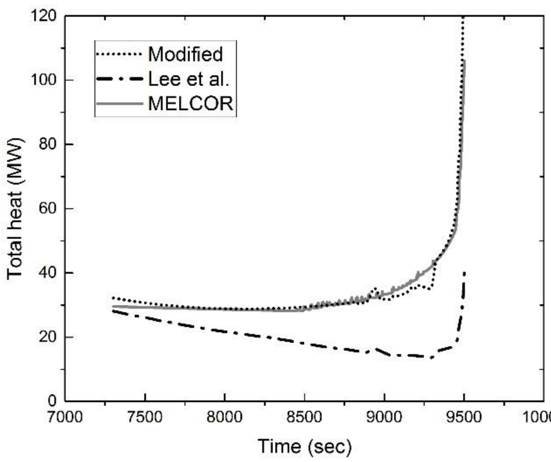

Fig. 4. Total heat by the SI flow models and MELCOR results during SBLOCA

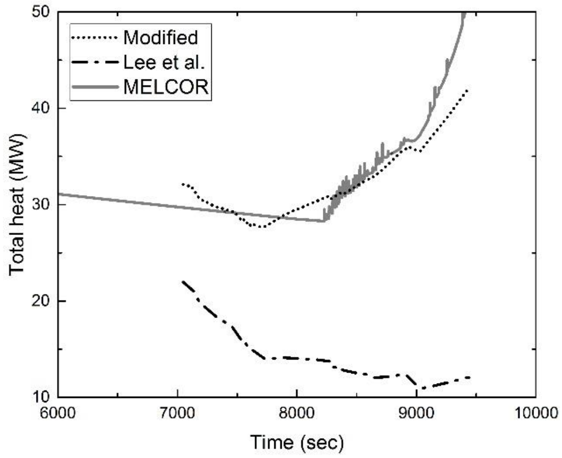

Fig. 5. Total heat by the SI flow models and MELCOR results during SBO

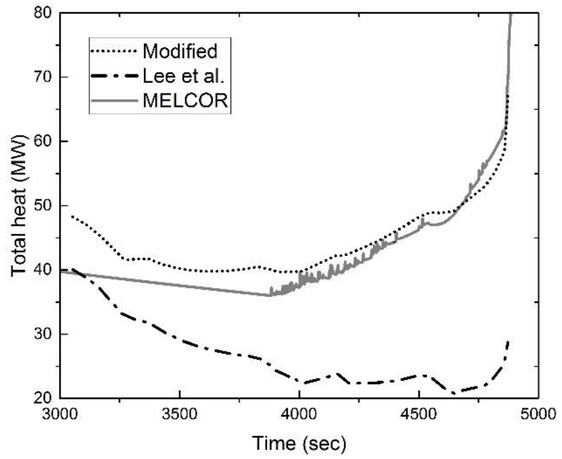

Fig. 6. Total heat by the SI flow models and MELCOR results during TLOFW

3.2 Improvement of SI flow map

As the improved SI model was validated, a RCS SI flow map assisted by two HPSIs for the postulated SBO accident was developed as shown in Fig. 7. After the required flow rate was estimated from the amount of calculated total heat by the equations listed above, the flow rate was converted to target RCS depressurization through the characteristic pump curve. This map was also verified using the MELCOR simulations. When the CET was 923 and 1023 K, the coolant was injected into the core by two HPSIs. The target depressurizations for injecting coolant were selected as 10.3, 10.4, and 10.5 MPa in two cases as shown by symbols. Circle symbols indicate success and X symbols indicate failure for core recovery within an hour. In all cases, the core water level was recovered within an hour only with the lower minimum pressure predicted by the SI flow map. When the target depressurizations were greater than the pressure map indicated, core recovery takes much longer or even fails. Fig. 8 shows, at the same time the pressure is reduced, the core water level begins to recover, and is completed in about an hour in case of 923 K-10.3 MPa. The core water level of 1.0 indicates that the core is completely filled with water. Therefore, the improved SI flow map reasonably predicts the injection flow rate to recover the in-vessel coolability.

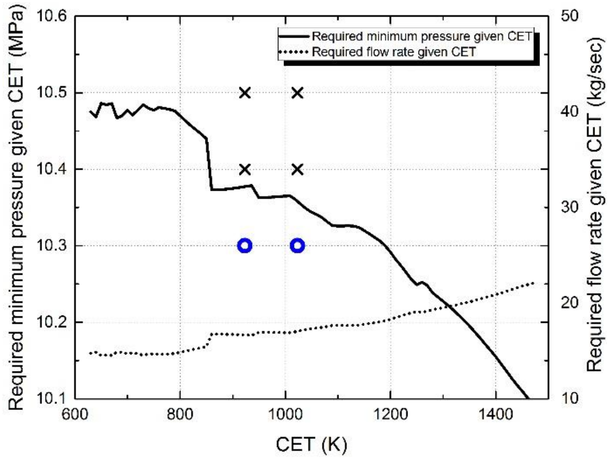

Fig. 7. RCS SI flow map for SBO accident

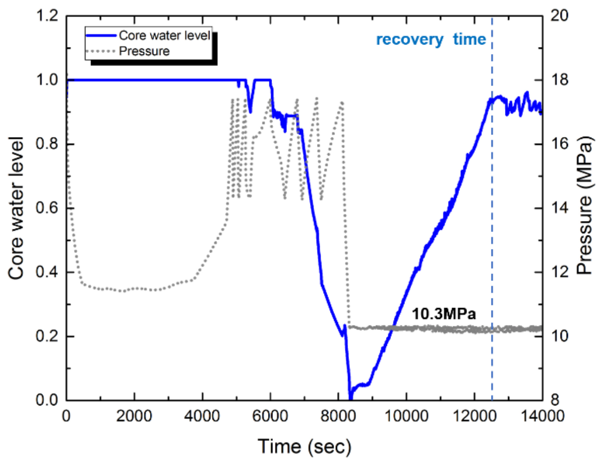

Fig. 8. RCS pressure and total HPSI injection flow in 923 K-10.3 MPa case

4. Conclusions

In this study, the previous SI flow model was improved by adding the terms for heat accumulating in heat structures to predict the injection flow rate enabling the core water level to restore. The accuracy of the improved SI model was verified by comparing computing results of SBLOCA, SBO, TLOFW by MELCOR code. Resulting SI flow model led to an improved SI flow map including the target RCS depressurization. This study contributes on improving the current SAMG by providing accurate quantitative calculation of required flow rate. Major findings can be summarized as follows.

(1) The accumulated heat can be represented reasonably through CET increase rate like the sensible heat of the vapor.
(2) The added terms for accumulated heat could reduce the difference between the model and the MELCOR results
(3) In all test cases, the core water level was recovered within an hour only with the lower minimum pressure predicted by the SI flow map. Therefore, the improved SI flow map reasonably predicts the injection rate to recover the in-vessel coolabiltiy

ACKNOWLEDGEMENT

This work was supported by the Nuclear Safety Research Program through the Korea Radiation Safety Foundation (KORSAFe), granted financial resource from the Nuclear Safety and Security Commission (NSSC), Republic of Korea (No. 1403002) and National Research Foundation of Korea (NRF) grants funded by MISP, grant numbers NRF - 2012M2A8A4025885

REFERENCES

[1] Kim HC, Evaluation of the status of the accident management guidelines in Korea and foreign countries, Korea Institute of Nuclear Safety, Daejeon, 2013
[2] Lee Y, Choi W, Seo S, Kum H-Y, Kim SJ, Development of safety injection flow map associated with target depressurization for effective severe accident management of OPR1000, Journal of Nuclear Science and Technology, Vol. 53, p.1502-1512, 2016
[3] Lee S, Ha KS, Kim H-Y, Kim SJ, Validation of RCS depressurization strategy and core coolability map for independent scenarios of SBLOCA, SBO, and TLOFW, Journal of Nuclear Science and Technology, Vol. 51, p.181-195, 2013
[4] Korea Hydro & Nuclear Power, Shin kori 1&2 final safety analysis report, Seoul, Korea Hydro & Nuclear Power, 2008.