Passive high-pressure safety injection of hybrid-safety injection tank

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Passive high-pressure safety injection system is developing to improve reliability of nuclear power plant during the Small Break-Loss of Coolant Accident (SB-LOCA). When the pressure of reactor coolant system remains high due to small break size, the core can be damaged even though sufficient cooling water is available in safety inject tank (SIT). By connecting SIT to pressurizer via pressure balance line (PBL), the coolant of SIT can be injected to RCS regardless of high pressure of RCS. The time of pressure equilibrium between pressurizer and SIT is dependent on direct contact condensation effect at interface in SIT. Substantial amount of injected steam into SIT condenses and cannot contributes build-up of pressure. It causes long delay time of safety injection after initiating a safety operation. To verify the exact time of passive high-pressure safety injection, the code simulation has been performed and compared with existing experimental data in this study. Code simulation shows less delay time of safety injection than experimental data. It means code simulation underestimates condensation effect than experimental data. The change of node number for SIT also affects the result. More nodes cause less condensation. Direct contact condensation has been investigated in terms of flow regime in this study.

I. Introduction

The simulation results produced by system codes such as RELAP5 and MARS have been utilized to identify success criteria in Probabilistic Safety Analysis. The system codes mostly provide very conservative results, which is sufficient to use as a guideline, when we newly propose success criteria [1]. However, when simulation includes certain complicated phenomena, the estimated results shows high discrepancy with realistic values. Condensation due to direct contact between steam and subcooled water is one of phenomena that induces many uncertainties [2]. Recently, the experiment for Hybrid-Safety Injection Tank (H-SIT) was performed by Korea Atomic Energy Research Institute (KAERI) to validate condensation phenomena inside H-SIT [3]. H-SIT has been proposed to mitigate combined accident of Small Break-Loss of Coolant Accident (SB-LOCA) and Station Black Out (SBO). When less than 2 inch of small break occurs, the system pressure in primary system remains above 10 MPa [4]. In this case, even though the sufficient water is in the SIT, the core can be damaged because SIT only can inject water into the reactor vessel when the primary system pressure goes below 40 bar. Thus, KAERI proposed H-SIT system connecting SIT with pressurizer by Pressure Balance Line (PBL) for passive high-pressure safety injection in the case of SB-LOCA and SBO. The pressure of SIT is increased by high-pressure steam provided from pressurizer, when valves of PBL open. However, only limited portion of steam contributes to increase the pressure of SIT because of condensation. Majority of steam condensates at interface between hot steam and subcooled water.

In this paper, we will investigate the effect of code uncertainty caused by complicated phenomena, which is direct contact condensation, and discuss how to predict condensation in most common nuclear system codes such as RELAP5 and MARS.

II. Experimental study on Hybrid Safety Injection Tank

The concept of H-SIT is proposed by KAERI to utilize the water of SIT in the condition of SB-LOCA and SBO. Conventional SIT can provide safety injection passively with depressurization of primary system below 40 bar. However, SIT become useless during SB-LOCA because the pressure in primary system remains high when the break size is smaller than 2 inch. H-SIT is a similar concept of Core Make Up Tank in AP1000 of Westinghouse with a different purpose. By connecting SIT with pressurizer as shown in Fig 1. (a), we can increase the pressure of SIT passively and provide safety injection into high pressure primary system. Being different from conventional safety injection, H-SIT requires certain delay time to inject water into the system. After an operator initiates H-SIT operation, high-pressure steam provide into SIT through PBL. It takes some time to get the pressure equilibrium between SIT and pressurizer. After the pressure of SIT reach to equilibrium, then the injection become available. The mass flow rate of SIT is dependent on driving force such as gravity head and pressure difference. If delay time of H-SIT is too long, the operator must initiate H-SIT operation early enough. It means the operator's response time also rely on delay time. Thus, delay time of H-SIT operation is important parameter to establish emergency operation procedure.

The delay time is determined by direct contact condensation. More condensation brings longer delay time. KAERI performed Separate Effect Test (SET) on H-SIT to see direct contact condensation effect on delay time of H-SIT operation. SET facility of H-SIT is illustrated in Fig.1.(b).

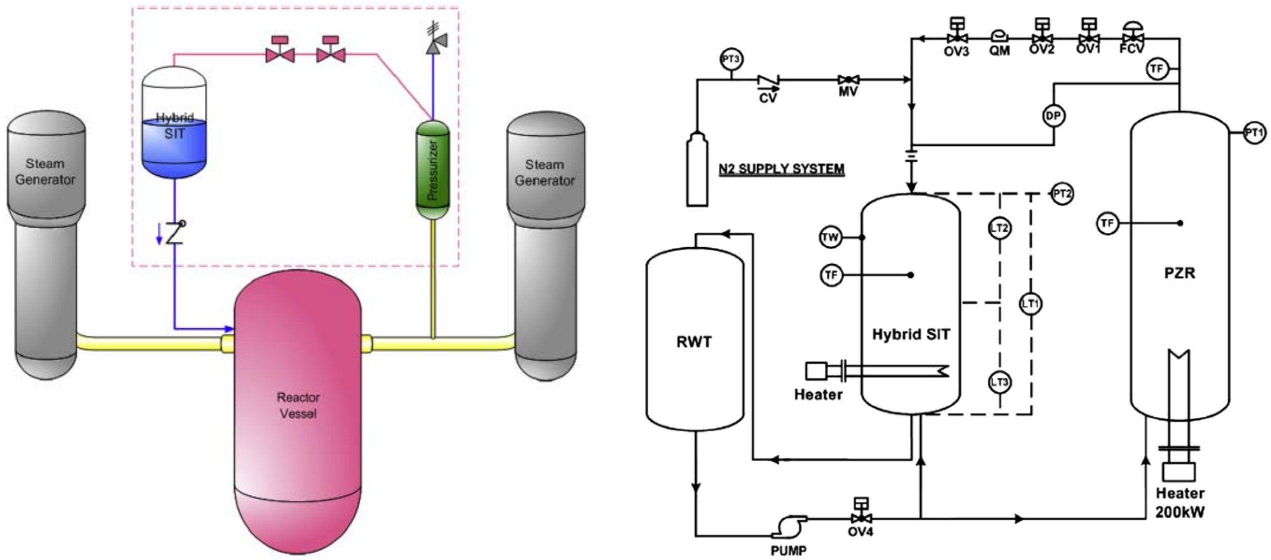


Fig. 1. (a) concept of hybrid SIT, (b) Schematic diagram of SET facility on H-SIT by KAERI [3]

II.A. Test Condition of SET facility on H-SIT

Ryu et al. have investigated the thermal-hydraulic phenomena in the H-SIT using a SET facility [3]. They performed four tests with different conditions to figure out parameter effects: steam flow rate effect, initial water level effect and steam injection velocity effect. For the steam flow rate effect, the steam flow from the pressurizer has been controlled by Flow Control Valve (FCV). The tests for 15% and 30% of FCV opening were performed. For initial water level effect, the level of SIT was changed from 2.38 meter to 2.44 meter. In addition, to change steam injection velocity, the size of H-SIT injection nozzle was changed from 2 inch to 1/2 inch. Before they start parametric study, the base case of test has been defined as following. The temperature and pressure of pressurizer set as 345.96 ^{o}C and 15.51 MPa, respectively. The temperature and pressure of H-SIT set as 30 ^{o}C and 4.21 MPa, respectively. Moreover, the water level of H-SIT determine 2.38 meter out of 3 meter height of H-SIT.

To observe the thermal-hydraulic phenomena, 33 of thermocouples were installed for measuring fluid temperature and 16 of thermocouples were also installed for measuring wall temperature. In addition, the level transmitter and DP sensor were added for measurement as shown in fig. 2.

II.B. Test Results of SET facility on H-SIT

The results provides us how much time it takes to reach the equilibrium pressure after an initiation of H-SIT operation. When we initiate H-SIT operation by opening a valve in PBL, high-pressurized hot steam injects into SIT. Considering the configuration of primary system, H-SIT is able to inject water into high-pressure system when the pressure difference between SIT and pressurizer become less than 0.07 MPa [3]. According to experimental results, the delay time from initiation to injection took 461 seconds with 30% opening of FCV and 759 seconds with 15% opening of FCV. During the first 50 seconds after initiation, almost 90 % of provided steam condensates and only 10 % of steam contribute to increase the pressure of SIT. Even the pressure reach to the equilibrium state after 600 seconds, 60 % of steam still condensate at the interface between water and steam while 40% of steam contribute to maintain system pressure.

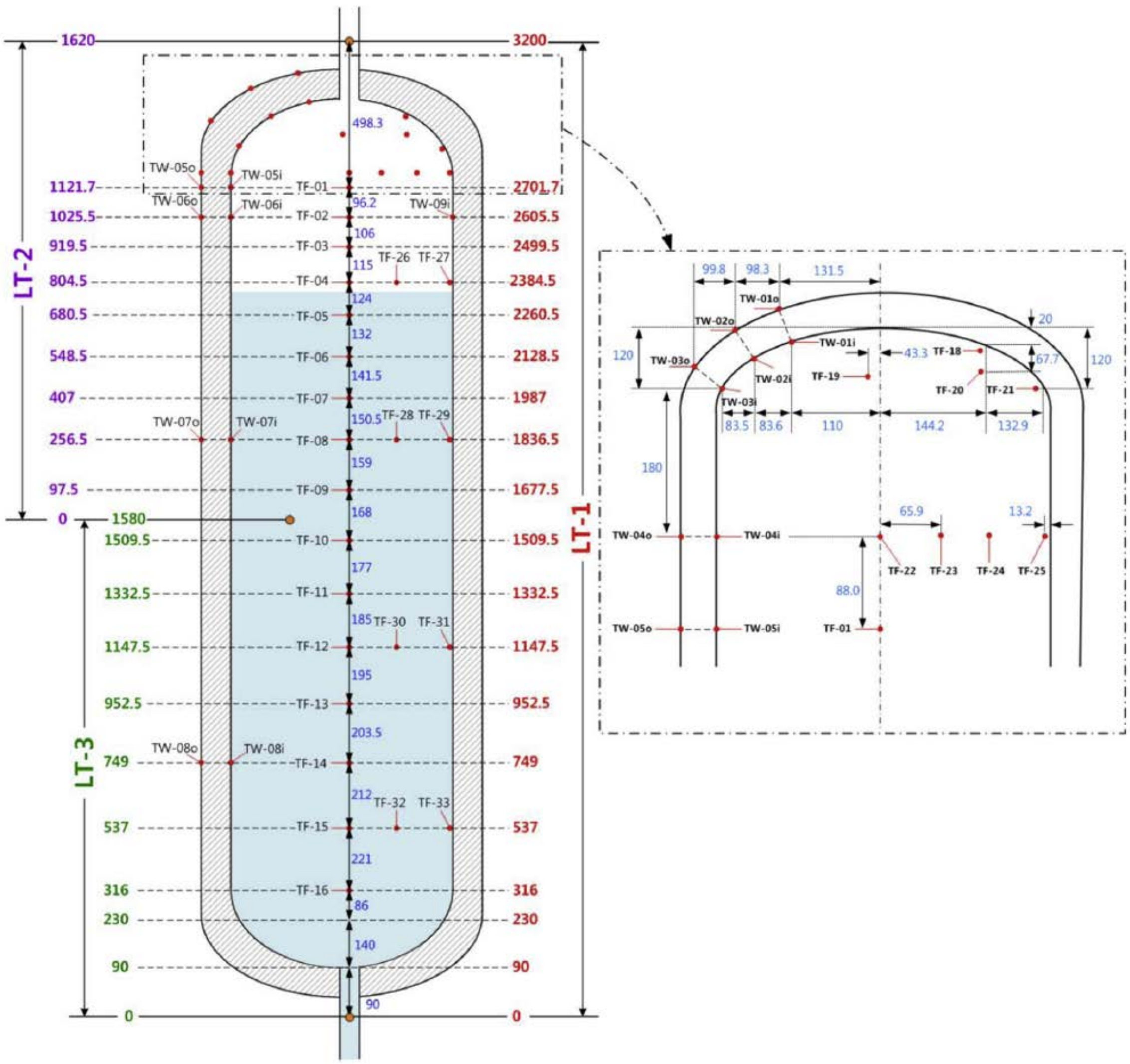


Fig. 2. Diagram of positions of the thermocouples and the level sensors installed in the Hybrid SIT. [3]
(TF: thermocouple of fluid, TW: thermocouple of wall, LT: level transmitter).

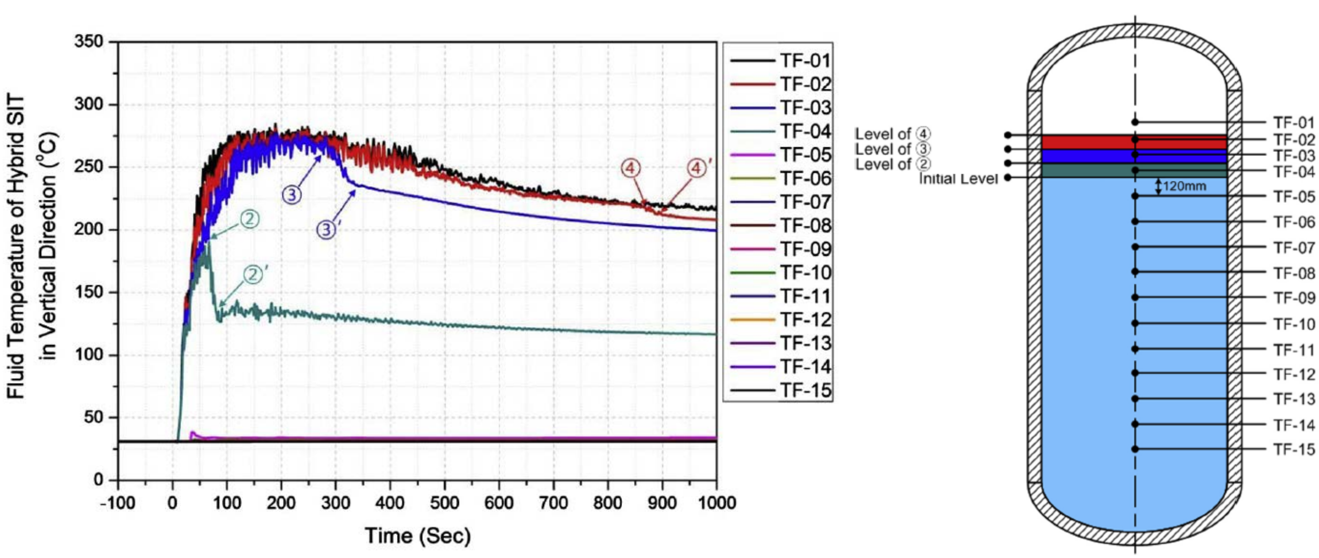


Fig. 3. (a) Fluid temperatures of Hybrid SIT in vertical direction, (b) the change of the water level in the Hybrid SIT.

This indicates that the pressure of primary system will be reduced somewhat and the equilibrium of pressure for injection of H-SIT can be lower than the assumption that Ryu et al provided.

Another important phenomenon is stratification at the interface. When hot steam injected into subcooled water, it could not penetrate water surface. It simply form layer of water with higher temperature. This cause more solid stratification effect as shown in Fig.3. After the steam forms the hotter water layer, then stratification reduce condensation and make more steam contribute to increase the pressure of SIT. The experimental result shows the fluid layer of stratification is relatively very thin. It means the coolant at the bottom of SIT still remain subcooled condition and provide more margin to extract heat from a reactor core.

III. System Code Analysis on H-SIT

Multi-dimensional Analysis of Reactor Safety (MARS) code has been utilized for code uncertainty comparison in this paper. MARS code has been developed by KAERI for the realistic multi-dimensional thermal-hydraulic system analysis of light water reactor transients. The backbones of MARS are the RELAP5/MOD3.2.1.2 and the COBRA-TF codes of USNRC. The RELAP5 code is a versatile and robust system analysis code based on one-dimensional two-fluid model for two-phase flows whereas the COBRA-TF code is based on a three-dimensional, two-fluid, three-field model. MARS consolidated two codes into a single code by integrating the hydrodynamic solution schemes, and unifying various thermal-hydraulic (T-H) models, EOS and I/O features [7]. However, even though MARS code is very conservative and robust system analysis code, the results of simulation can be different by user's expertise and experience as well as various T-H models. We will compare the effect of different nodes and discuss flow regimes that cause significant change in the results of simulation.

III.A. Nodalization of H-SIT system for MARS input.

The MARS input has been generated to comply with the specification of SET facility on H-SIT at KAERI. Pressurizer considered as time dependent volume that provide steam constantly. Flow control valve is located near to pressurizer as same as SET configuration at KAERI, it controlled steam flow by 15% opening and 30% opening. The inner diameter and length of PBL are 11.84 mm and 31.23 meter, respectively. The inner diameter and height of the SIT are 0.56 meter and 3 meter, respectively. The nodalization of H-SIT system is illustrated in Fig.4.

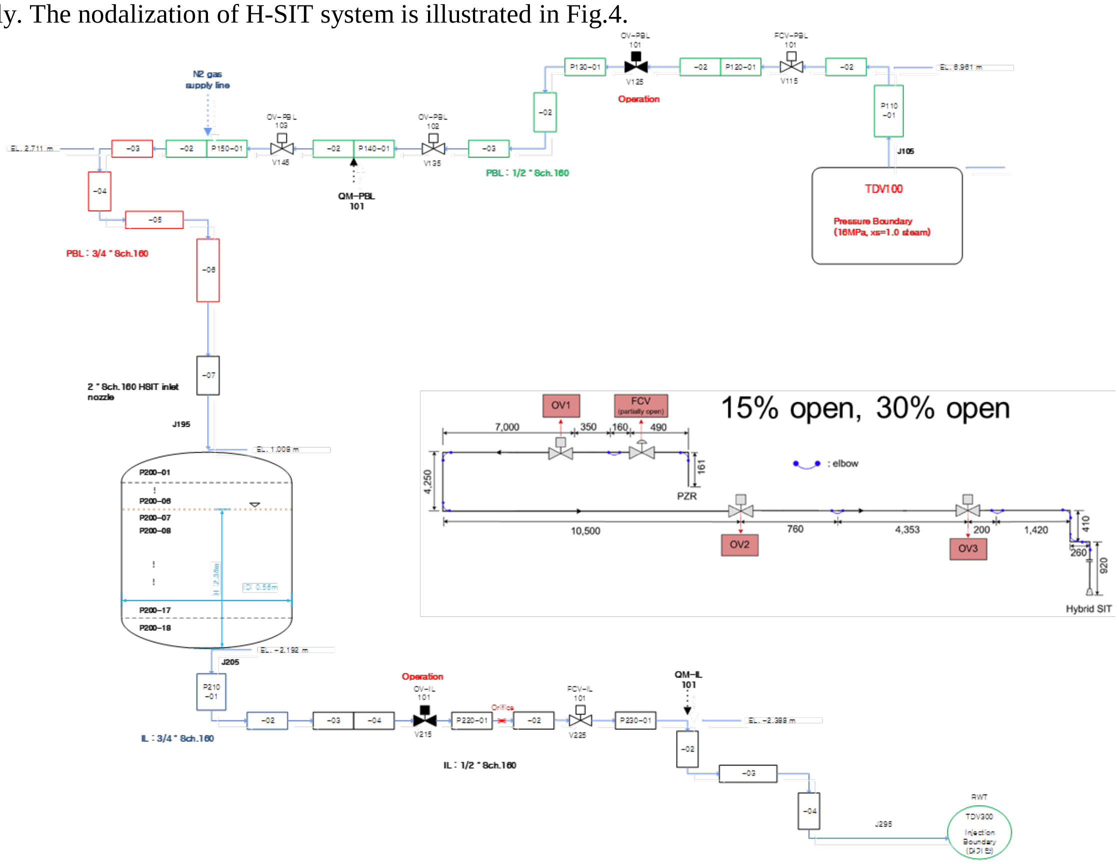
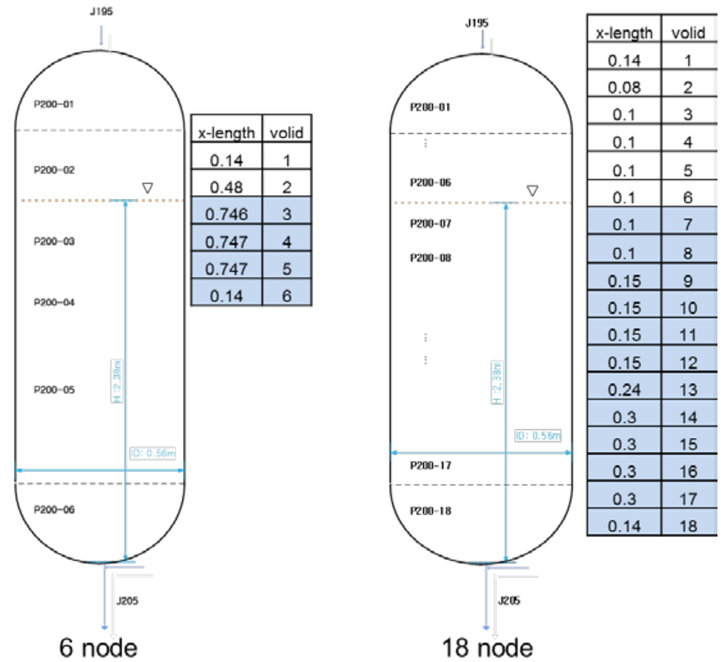


Fig. 4. Nodalization of SET facility on H-SIT at KAERI [3]



x-length	volid
0.14	1
0.48	2
0.746	3
0.747	4
0.747	5
0.14	6

x-length	volid
0.14	1
0.08	2
0.1	3
0.1	4
0.1	5
0.1	6
0.1	7
0.1	8
0.15	9
0.15	10
0.15	11
0.15	12
0.24	13
0.3	14
0.3	15
0.3	16
0.3	17
0.14	18

Fig. 5. Nodalization of Safety Injection Tank by 6 nodes and 18 nodes

We also prepared two different MARS inputs with 6 nodes and 18 nodes of SIT. We intentionally ignored the ratio of length over diameter (L/D ratio) for 18 nodes of SIT model. Length should be bigger than diameter for each nodes for averaged calculation in MARS simulation. However, to compare the code uncertainty by user, the results of 6 nodes and 18 nodes model has been compared.

III.B. Simulation results of H-SIT system with MARS code.

MARS simulation with two different node models has been performed and investigated in terms of equilibrium time of H-SIT system, level of SIT, fluid temperatures of H-SIT and flow regimes, then compare with experimental SET data from KAERI.

III.B.1. Equilibrium time of Pressure in H-SIT system after initiation of H-SIT operation

After the operator initiates H-SIT operation, actual injection will be occurred with certain delay time. In the case of 15% opening of FCV, the delay time of injection with 6 nodes was 373 seconds while the experimental data showed 759 seconds. Even the time with 18 nodes was shorter than that of 6 nodes. The code simulation estimate short time than experimental data. It means MARS code estimates less condensation effect than real case inside H-SIT. The results is summarized in table.1 and Fig.5.(a).

TABLE I. Time to reach equilibrium pressure in H-SIT

Controlled steam flow	Experimental value (sec)	6 Nodes (sec)	18 Nodes (sec)
15 % of opening	759	373	143
30% of opening	461	293	101

III.B.2. Level of SIT

Less condensation effect of code simulation also can be confirmed again with level change of SIT after steam injection into SIT as shown in Fig.5.(b). Level change of SIT indicates how much steam condensate in the safety injection tank. Level of SIT increases fast in the beginning of operation by more condensation effect. Then, the increase rate of level become less after the stratification forms at interface between fluid and steam. After initiation of H-SIT operation, almost 90 % of steam condensates by direct contact condensation, the rate of condensation became 60% when system pressure reach to equilibrium pressure.

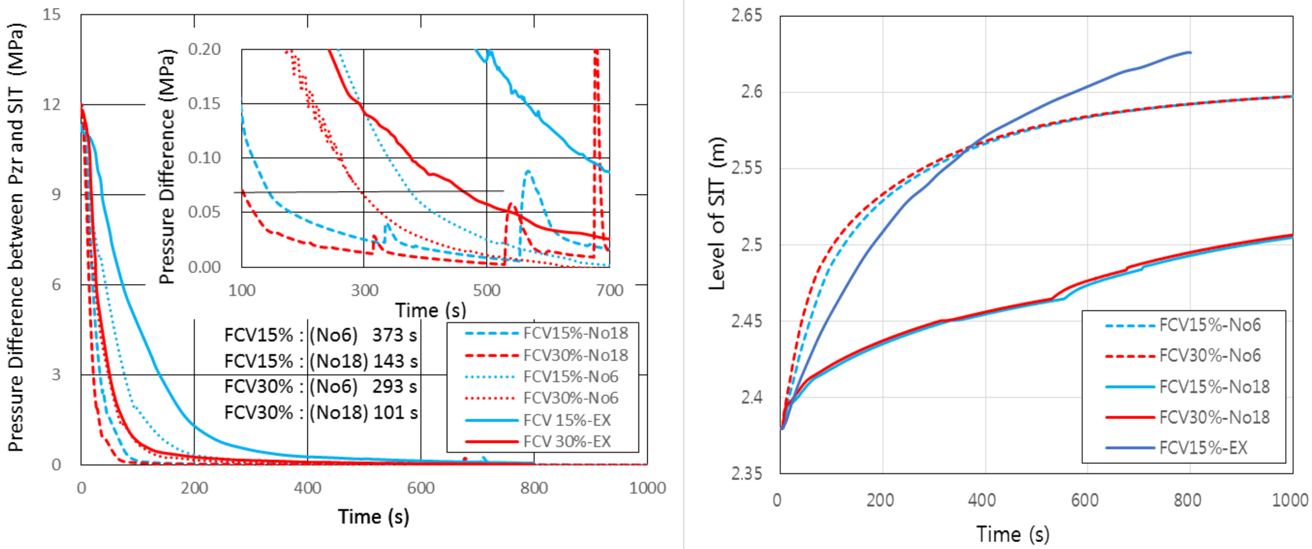


Fig. 5. (a) Pressure difference between Pressurizer and SIT, (b) level change of SIT after steam injection

III.B.3. Fluid temperatures of Hybrid SIT in vertical direction

Top two volume out of six volume were considered as a vapor condition at the beginning with 6 nodes MARS simulation while six volume considered as a vapor with 18 nodes simulation. 6 nodes simulation shows only two average temperature as shown in Fig.6.(a), while SET experimental data of KAERI showed very thin layer of stratification at the interface. Even though 18 node MARS simulation estimate less condensation, fluid temperature of 18 node simulation show similar temperature with experimental data at same vertical location as shown in Fig.6.(b). Vapor temperature of 18 nodes simulation was also compared with fluid temperature in vertical direction as shown in Fig.7. After 650 seconds, vapor temperature at volume 6 shows a drastic increase, while fluid temperature remains same. In the MARS code simulation, temperature change and condensation rate is determined by flow regime.

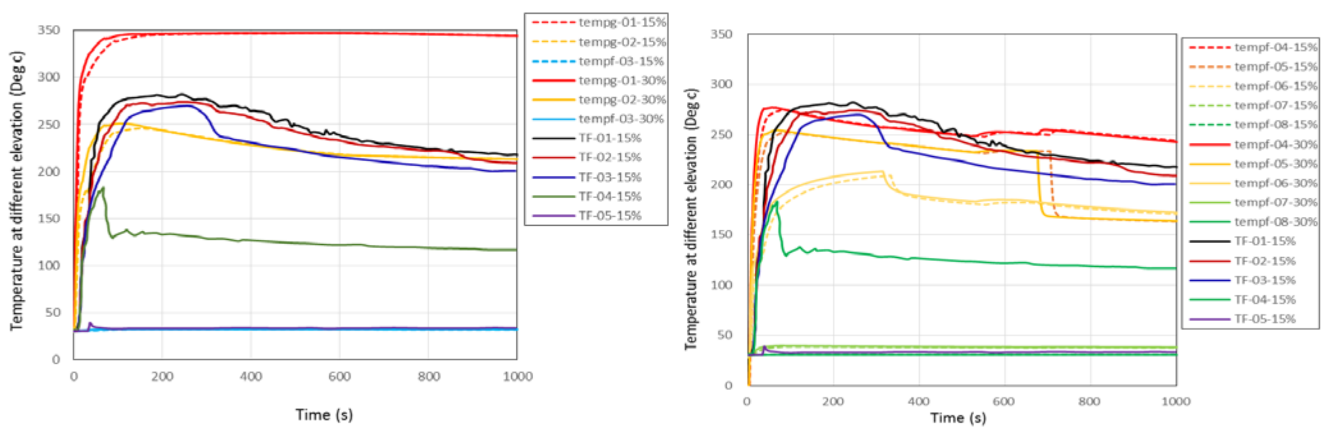


Fig. 6. Fluid temperatures of Hybrid SIT in vertical direction (a) with 6 nodes, (b) with 18 nodes

III.B.4. Flow regime

Fig.8 shows us flow regime of MARS simulation with 6 nodes and 18 nodes. When steam injected into H-SIT, flow regime of upper volume are considered as Annular mist and mist(pre-CHF) and flow regime at interface between steam and water assume vertically stratified condition. Flow regime of fluid region is simply considered as Bubbly flow condition. 6 nodes

MARS simulation shows very obvious flow pattern inside H-SIT, while 18 nodes simulation shows fluctuation behavior of flow pattern at interface. Flow regime of volume 5 maintains annular mist flow in the beginning, then turn into vertically stratified flow after 700 seconds. Flow regime of volume 6 is fluctuating between slug flow and vertically stratified flow in the beginning, then become bubbly flow. It means volume 6 is submerged under a fluid after 700 seconds.

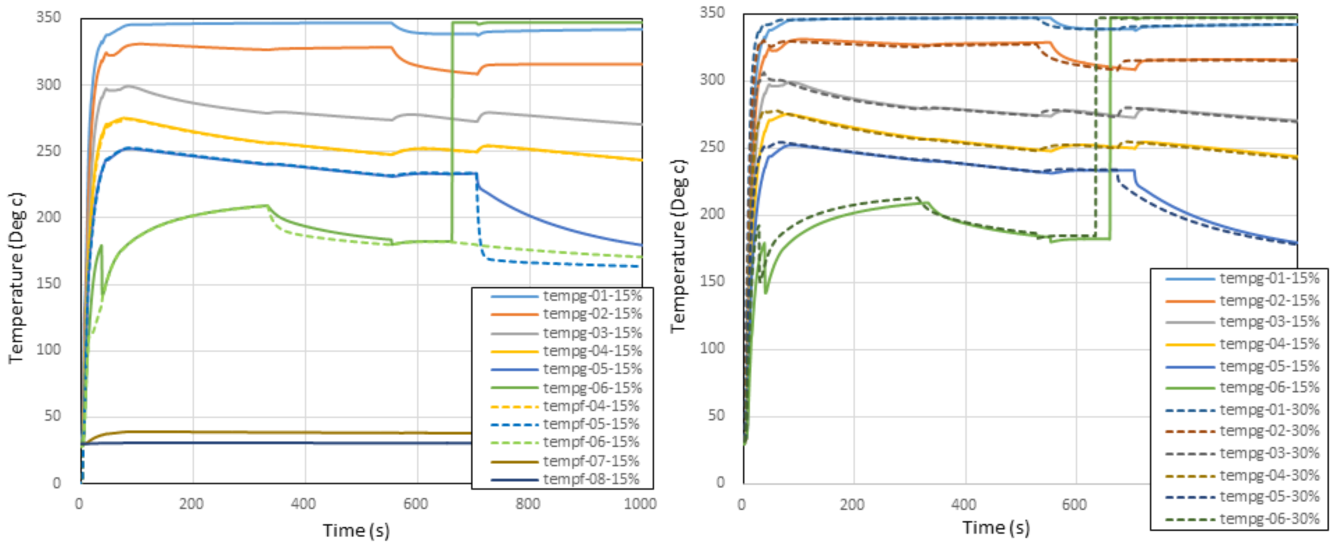


Fig. 7. Vapor temperatures of Hybrid SIT in vertical direction (a) with fluid temperature, (b) with 15% opening and 30% opening of FCV (18 nodes)

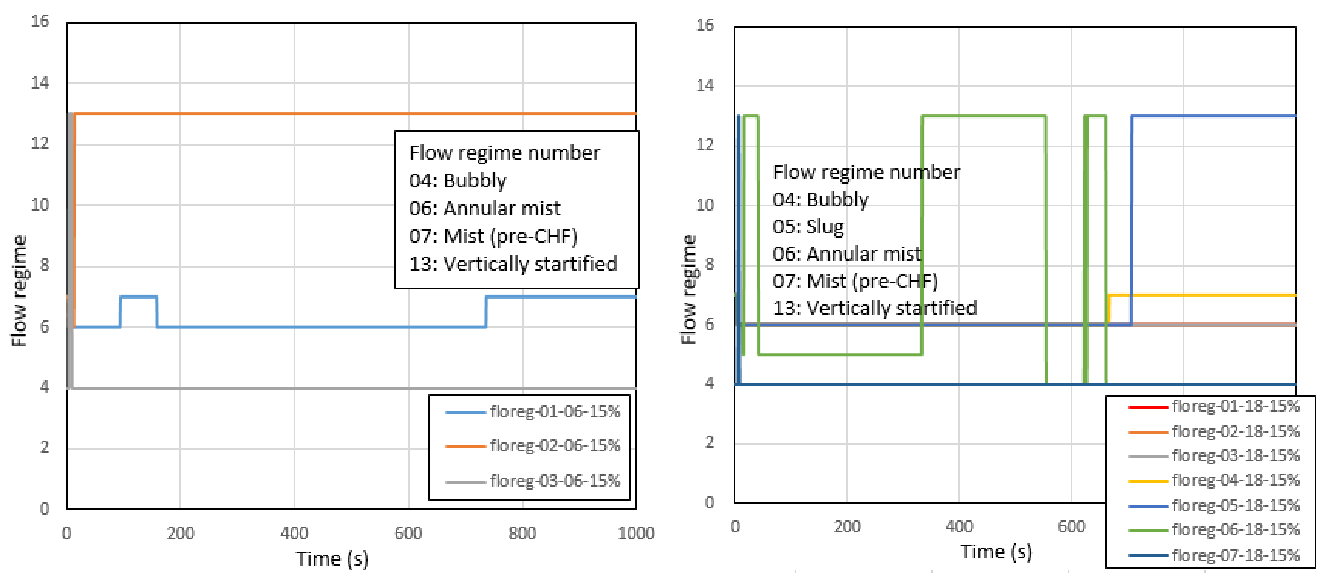


Fig. 8. Flow regime of Hybrid SIT (a) for 6 nodes, (b) for 18 nodes

III.C. Interface mass transfer rate (steam condensation rate) determined by flow regime

The hydrodynamic model of MARS code simulates transient flow behavior of thermal-hydraulic systems. The six conservation equations are numerically solved for the transient analysis. The two-fluid equations are formulated in terms of volume and time-averaged parameters of the flow. In the two-fluid model, two-phase mixture is divided into liquid and vapor phases. Conservation of mass, energy, and momentum is separately established for each phase. And, the conservation equations for two phases are interconnected by jump conditions at the liquid-vapor interface. For the jump condition, mass, momentum, and energy transfer at the liquid/vapor interface are considered.

The steam condensation rate is mainly determined by heat transfer at interface between liquid and vapor. When MARS code calculates the heat transfer at interface, it uses flow regime that define flow condition. The flow regime is also determined by three parameters; average flow velocity, void fraction, and the temperature difference between gas temperature and saturation temperature as shown in Fig. 9. The important findings from experimental data is that the vertical stratification is dominant at the L/V interface inside H-SIT. In the MARS code, to estimate steam condensation rate, energy jump condition at interface is considered which is expressed in equation (1). Condensation become dominant when interface gas enthalpy is same as saturated gas enthalpy and interface fluid enthalpy is same as fluid enthalpy ($h_{gi} = h_g^s$, $h_{fi} = h_f$), while evaporation become dominant when interface fluid enthalpy is same as saturated fluid enthalpy ($h_{gi} = h_g$, $h_{fi} = h_f^s$). To estimate exact condensation rate at interfacial area in H-SIT, flow regime map and interfacial heat transfer coefficient (H_{ig}, H_{if}) have to be well-modeled. In the condensation of HIT, the interfacial heat transfer coefficient of gas (H_{ig}) can be ignored because the steam temperature and saturated gas temperature is almost same in the equation (1). In this case, vertical stratification flow and bubbly flow became dominant, the interfacial heat transfer coefficient of fluid (H_{if}) mainly determines the amount of condensation. According to vertical flow map, the transient to vertical stratification flow initiates when average flow velocity (v_m) become smaller than Taylor buble rise velocity (v_{Tb}). The interfacial heat transfer coefficient with subcooled fluid is determined by McAdam correlation (2) when flow regime is the vertical stratification flow with slow average flow velocity, while the interfacial heat transfer coefficient with subcooled fluid is determined by modified correlation of Uanl and Lahey (3) when flow regime is the bubbly flow with small void fraction. Coefficient C is proportional to void fraction of vapor (α_g) in equation (3). In the transition between bubbly flow and vertical stratification flow, the interfacial heat transfer coefficient is calculated by extrapolation between correlation (2) and (3).

$$\Gamma_f = \frac{\frac{P_s}{P} H_{ig}[T^s(P_s) - T_g] + H_{if}[T^s(P_s) - T_f]}{h_{gi} - h_{fi}} \qquad (1)$$

$$H_{if} = Nu \frac{k_f}{D} \alpha_{af} \ \text{(McAdams)} \qquad (2)$$

$$H_{if} = \frac{C h_{fg} \rho_g \rho_f \alpha_g}{\rho_f - \rho_g} \text{(Modified Unal, Lahey) if } \alpha_g > 0 \qquad (3)$$

When we separate SIT with more volumes, it change the average flow velocity and void fraction, and leads change of flow regime. When we increase number of nodes from 6 to 18, the results shows the condensation rate become less. Fig.10. shows us the mass transfer rate per unit volume. The mass transfer rate includes both condensation and evaporation. Positive value means evaporation, while negative value means condensation. We can observe the evaporation at the beginning, and then it shows how much steam condensates later. We also find some peaks when flow regime changes. The condensation rate is also affected dependent on flow regime.

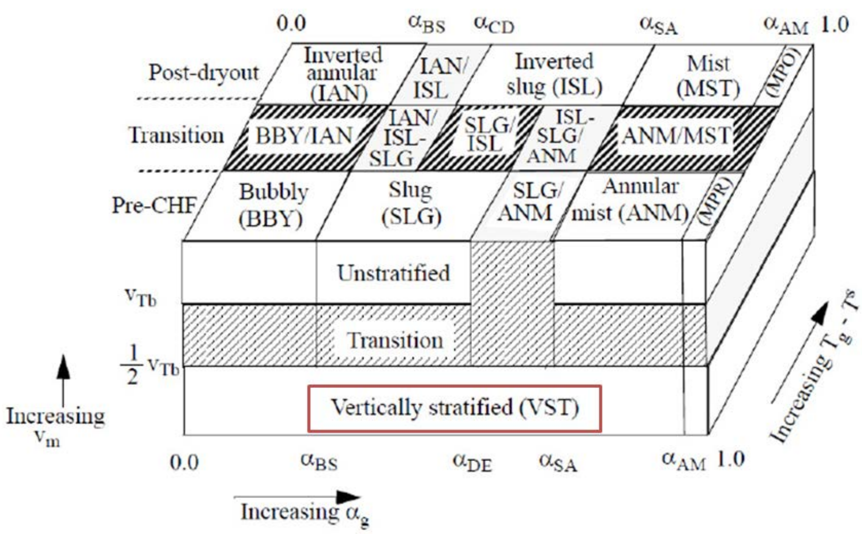


Fig. 9. Vertical flow regime map of MARS codes

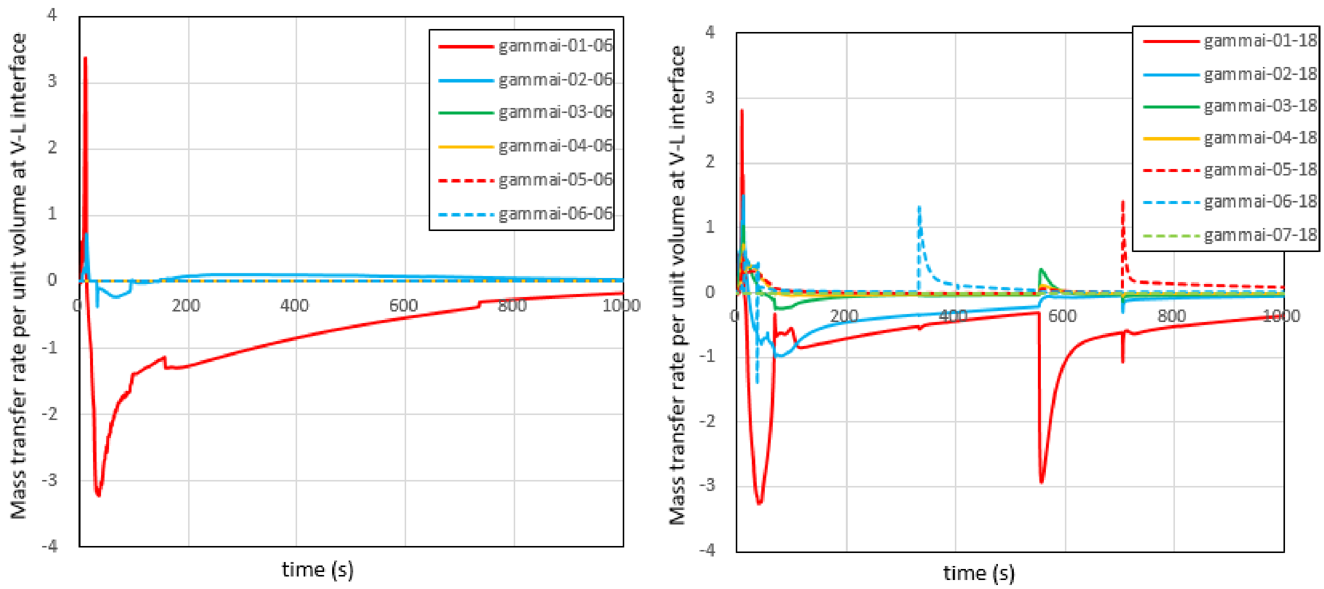


Fig. 10. Vertical flow regime map of MARS codes

IV. SUMMARY and CONCLUSIONS

The simulation results by system codes have been utilized when we propose success criteria of newly added safety component. In most case regarding an accident analysis, the code simulation gives us conservative and reliable guideline. However, the simulation involves some of complicated phenomena, the simulation results become unreliable. Thus, we must assume code uncertainty in this case. In this paper, we discussed direct contact condensation effect in hybrid safety injection tank to explain a code uncertainty that causes by code itself and user's effect with a nodalization. We compared the results of MARS simulation with experimental data from separated effect test by KAERI in terms of the equilibrium time, level of SIT and fluid temperature in vertical direction. Our discussions are summarized as follows:

1. Small Break Loss of Coolant Accident may lead to core damage even though SIT contain sufficient water.
2. Hybrid Safety Injection Tank has been designed by connecting Pressurizer to SIT with Pressure Balance line in the case of Total loss of Feedwater and SBO.
3. Separate effect test for the Hybrid SIT has been performed by KAERI. Tests conducted until the pressure of Pressurizer and SIT reach to equilibrium condition.
4. MARS simulation preformed with 6 node and 18 node input and compared with experimental data of SET.
5. Steam condensation rate in MARS calculation was lower than experimental data.
6. MARS calculation of 18 nodes showed less condensation rate and faster pressure increase than that of 6 nodes.
7. To estimate exact condensation rate at interfacial area in SIT, flow regime map and interfacial heat transfer coefficient (H_{ig}, H_{if}) have to be well-modeled.

We still do not have data to understand entire plant behavior for H-SIT because Integrated Effect Test (IET) of H-SIT that includes all components of plant has not performed yet. And, in many cases, we do not have a reliable experimental data to identify success criteria for newly propose safety system. Thus, code simulation is still very important methodology to produce a guideline. However, we must assume a code uncertainty that causes by code itself and user's expertise.

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