PERFORMANCE EVALUATION OF SAFETY INJECTION TANK FOR APR1400 PLANT

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ABSTRACT

Safety Injection Tank (SIT) with Fluidic Device (FD) has been installed in APR1400 nuclear power plants. It was designed to provide a longer passive safety injection than the existing accumulator to improve the safety for Large Break Loss-of-Coolant Accident. The present paper discusses the major concerns related to SIT/FD hydrodynamics and the directions to resolution recently concerned. Modeling of SIT/FD by total hydraulic resistances, potential of nitrogen intrusion, and effect of initial pressure of SIT testing are included. Based on the discussion, a table of the important phenomena of the SIT/FD was proposed with the relevancy of the calculation models applied. The following conclusions are obtained:
(1) Uncertainty due to the assumption of the total K-factor as constant for high flow, transition phase, and low flow phase should be considered.
(2) Nitrogen intrusion phenomena during the transition phase should be considered with a conservatism, especially considering the current situation of non-measuring the standpipe level,
(3) Similitude between different initial pressures in plant SIT testing does not exist. Therefore, SIT testing should be conducted as close to the design condition.

1. Introduction

Safety Injection Tank (SIT) with Fluidic Device (FD) has been used in several APR1400 nuclear power plants [1]. It was designed to provide a longer passive safety injection than the existing accumulator to improve the safety for Large Break Loss-of-Coolant Accident (LBLOCA) by changing the injected flow through the FD and the standpipe of the SIT. The FD has a vortex chamber to combine the flow through the standpipe and the one from the connecting holes, in which the hydraulic head and the flow rate of each flow path are balanced with interaction. Fig. 1 shows structure of the flow controlling safety injection tank with fluidic device and the illustration of a typical flow pattern inside the vortex chamber: (a) high flow phase and (b) low flow phase [2].

As a result, high flow injection phase and the subsequent low flow one can be achieved as longer than the existing accumulator.

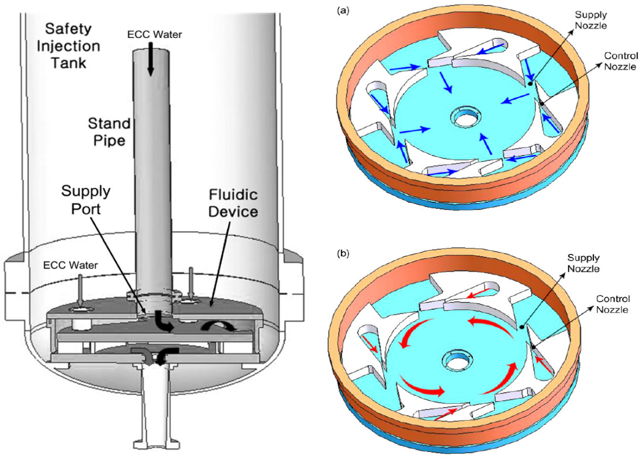

Fig. 1. Structure of safety injection tank with fluidic device and the illustration of typical flow pattern inside the vortex chamber: (a) high flow phase and (b) low flow phase [2].

In the course of design and licensing reviews of several APR1400 plants, extensive studies to resolve the several concerns related to the SIT hydrodynamics have been conducted [2, 3, 4, 5]. The present paper discusses the major concerns related to SIT hydrodynamics and the directions to resolution recently concerned. Modeling of SIT/FD by total hydraulic resistances, potential of nitrogen intrusion, and effect of initial pressure of SIT testing are included. Based on the discussion, a table of the important phenomena of the SIT/FD was proposed with the relevancy of the calculation models applied.

2. Hydrodynamic Concerns

To address SIT/FD phenomena in the LBLOCA calculation, licensee used a simple model using the RELAP5 code and the ‘accum’ component and two valves having the different hydraulic resistances (loss factors) [6]. A scheme was imposed such that the first valve was dedicated for the high flow phase and the second one for the low flow phase [7]. The following concerns were raised regarding the licensing model:

(1) Two constant values were assumed for the total loss factor, one for high flow phase and one for low flow phase, respectively. Concerns were if the assumption is applicable to this problem and if it inevitably induces additional uncertainty in determining the constant value. Due to this approach, the transition phase from high-flow to low-flow could not be considered. Also, the water level in standpipe cannot be measured in the actual plant testing, therefore, only the water level outside the standpipe was used in the determination of K-factor for the low flow phase. It may have an effect on overall K-factor in transition phase and low flow phase.

(2) The potential of nitrogen intrusion during the transition phase was not considered in the ‘accum’ model. The VAPER experiment has shown that the standpipe water level rapidly dropped to the bottom and then recovered a little and the flow stopped during the transition phase [8]. It may imply that nitrogen can be intruded to vortex chamber. This phenomena may be true in the actual plant although the standpipe water level could not be measured. Therefore, a conservative approach is recommended on this concern.

(3) All sources of uncertainty induced by the SIT/FD phenomena including nitrogen intrusion should be considered in the LBLOCA calculation. Currently four parameters including SIT initial level were considered.

(4) The pre-operational test of SIT is conducted to confirm the SIT performance as designed. Concerns regarding the initial pressure of the test and the criteria in terms of K-factor for acceptance of the test [9] were discussed. Estimation of the K-factor from the measured data may involve additional uncertainty. Reasonable criteria in terms of physical parameters and less uncertainty is recommended.

3. Discussions

3.1 Loss Factor

Fig. 2 shows a behavior of overall loss factor estimated from the pressure and water level measured from the SKN Unit 3 test [8].

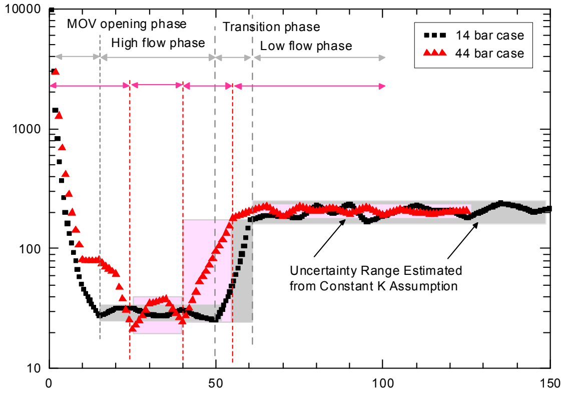

Fig. 2. K-factor estimated from the test data

The interval of raw data was 0.01 seconds for 14 bar test and 1 second for 44 bar test, respectively. For a stable estimation of K, the measured data was averaged over every 0.5 seconds interval for the 14 bar test, while the data averaged for 7 seconds with overlapping was used for the 44 bar test. It was found that the total loss factor was changed dynamically from the high flow phase, through the transition phase, to the low flow phase. From this figure, it can be reasoned that the assumption of constant K-factors during high flow phase and low flow phase may involve a significant uncertainty (shaded regions). The early phase which the SIT motor operated valve was being open for was not included in this estimation. Especially during the transition phase, significant uncertainties may be involved for duration and value of K-factor.

3.2 Nitrogen Intrusion

The nitrogen discharge behavior was evaluated using MARS-KS code with both the ‘accum’ model and the ‘pipe’ model. The latter has two flow paths to represent the standpipe and the FD. Both models were applied to the simulation of the test in 44 bar (Fig. 3).

Fig. 4 presents the nitrogen mass within the SIT. In case of the ‘accum’ model, the nitrogen was only released at the end of low flow phase and the discharge was finished at once. However, in case of the ‘pipe’ model, a certain portion of the nitrogen was firstly discharged at the transition phase through the standpipe and the rest of the nitrogen was finally released at the end of low flow phase. The discharged nitrogen at the transition phase may have an important effect on the PCT during the reflood phase because the nitrogen can intrude the core at the early refill or reflood phase and can consistently impede the core heat transfer for a long term. It was recognized the nitrogen release during transition phase was not negligible and should be precisely modeled.

The nitrogen intrusion was known to be complex phenomena affected by the gas pressure, the water level of the gas penetration, the water flow rate, the geometric configuration, etc. Although the calculation above has shown the nitrogen more than 100 kg was intruded from the SIT, accuracy and/or reliability of the result was not validated. And the specific evaluation on how much gas can be intruded may be beyond the system code capability. In the present study, therefore, the parameter of the system thermal-hydraulic code affecting the amount of nitrogen intruded was investigated. Vertical stratification model and interfacial drag of the MARS-KS code were studied, which indicated the vertical stratification model did not have any significant effect. For the interfacial friction model, multiplier ranging 0.7 to 1.3 was introduced to the model for the component standpipe and SIT vessel.

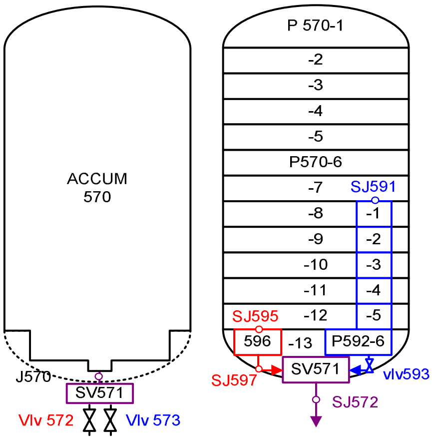

Fig. 3. SIT models for MARS-KS calculation

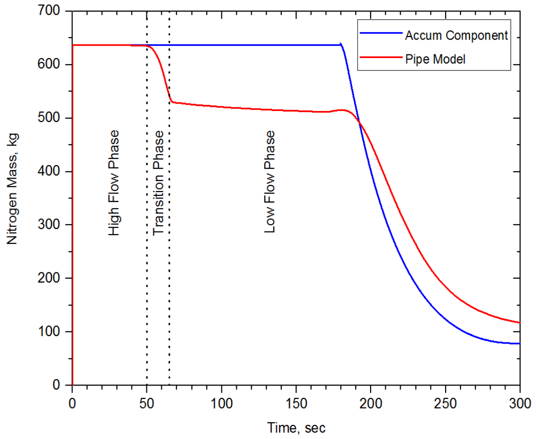

Fig. 4. Calculated nitrogen mass in SIT

Fig. 5 shows the sensitivity results for the interfacial friction. As the interfacial friction increased from 10% to 30%, the discharged nitrogen during transition phase remarkably increased from 116 to 174 kg. It implies the discharged nitrogen mass is sensitive to the interfacial friction.

Fig. 6 presents the non-condensable gas mass fraction at SIT discharge. As the interfacial friction increased, nitrogen was discharged earlier and nitrogen was released not only during transition phase and the end of low flow phase but also during low flow phase for the case that the interfacial friction multiplier was 1.3.

Fig. 7 shows the discharged mass flow rates. There were not significant deviations of discharged flow rates for different interfacial friction cases. Although the discharged flow rates were similar, the amount of nitrogen intruded into the reactor core and the timing of nitrogen intrusion were different and it may influence the heat transfer phenomena during LBLOCA.

Interfacial friction can be used as a controlling parameter for nitrogen concern. Also, it can be pointed out that nitrogen intrusion should be carefully evaluated using the modeling scheme to match the measured data well or should be treated by uncertainty method.

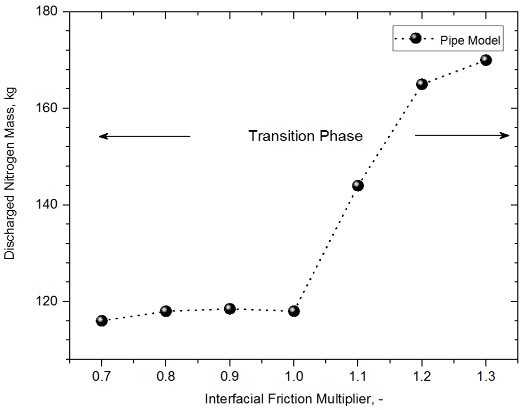

Fig. 5. Calculated nitrogen mass discharged during transition phase for the range of interfacial drag

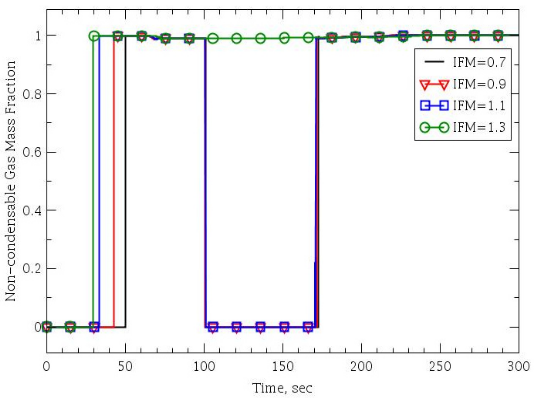

Fig. 6. Calculated Non-condensable gas fraction at discharge for the range of interface drag

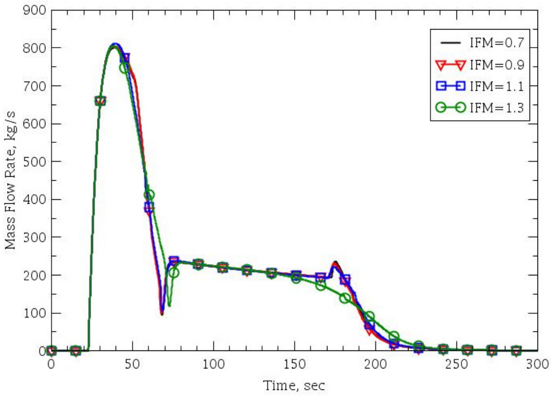

Fig. 7. Discharged coolant mass flow rates for the range of interfacial drag

3.3 Initial Pressure of SIT Test

Regulatory Guide 1.79 [10] allows any initial filling pressure up to the normal SIT pressure can be adopted in the test and requires the test result of the flow rate should be adjusted for the design condition. It means a specific scaling law to extrapolate the result of the test conducted at low pressure to the performance at design condition.

To evaluate the scaling law pertinent to SIT flow, a model from Reyes [11] was applied in this study. The model was based on mass conservation equation and Bernoulli equation with isentropic assumption. The final non-dimensional differential equation has a term of exit pressure normalized by initial pressure, thus, a unique solution in non-dimensional form cannot be obtained. Numerical solution of the Reyes model was plotted in Fig. 8, which shows the non-dimensional pressure versus the non-dimensional time. The pressure was normalized by the initial pressure and the time was normalized by the time needed to discharge all the gas volume in the maximum flow rate.

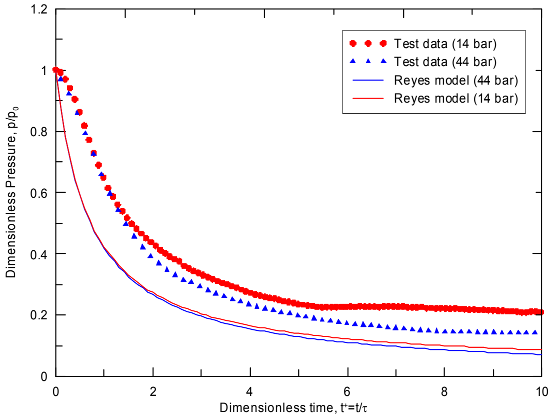

Fig. 8. Dimensionless pressure behaviors

In this figure, the measured pressures from the tests conducted at 14 bar and 44 bar were compared with the numerical solution of Reyes model, respectively. The numerical solution was obtained assuming that the gravitational head can be neglected when compared to the other terms. The difference during the initial phase between the test data and the numerical solution was due to the non-modeling of the valve opening period in the numerical solution. The figure shows that the non-dimensional pressure of 14 bar case is deviated from the one of the 44 bar case with time. Such a deviation was significant in the test data. It means that isentropic process is valid only in the short term period and that the similarity between two different initial pressures does not exist. Therefore, the adjustment of the result of low pressure test to the design condition, as required by the regulatory guide, cannot be achieved using this kind of simple method. It means that the initial filling pressure for SIT test should be close to the pressure which was assumed for the design basis LBLOCA.

Evaluating the K-factor from the measured data to confirm the range of K-factor which was specified as the acceptance criteria for the SIT test may involve an additional uncertainty in the data processing, as discussed above. Accordingly, the upper bound and the lower bound of SIT level and pressure should be used. They should be determined by using the SIT modeling and the range of uncertainty parameters consistent with the LOCA calculation and any influence from the factors involved in the test including valve opening time should be considered.

3.4 Important Phenomena

Based on the experience of analysis and experiment and plant test, the phenomena important to the safety criteria, peak cladding temperature (PCT), were listed in Table 1. All the phenomena discussed above were included and were categorized for high flow phase, transition phase, low flow phase, and empty state Heat transfer to SIT cylinder metal is still listed although less important to the PCT than others. The phenomena at the vortex chamber are quite complex, but were simply expressed in two items; flow interaction and mixing in vortex chamber, for simplicity.

In this study, the analysis using RELAP5 [7], one using MARS-KS [4], CUPID [5], and CFD [3] were reviewed and the capability of each analysis model was listed in four categories; a model using ‘accum’ component of system code (such as RELAP5), one using general ‘pipe’ component of system code, one by component code (such as CUPID), and one using CFD. The table is read that all the phenomena can be simulated by CFD code in general sense, but it should be reminded the specific model used in CFD calculation was not fully tested. System code with general ‘pipe’ component, can be used, however, a special modeling is needed to capture the ‘partial water level recover and flow stop’. Such a condition is the same as the CUPID code.

4. Conclusions

The present paper discussed the SIT hydrodynamics including the modeling of SIT/FD by total hydraulic resistances, potential of nitrogen intrusion, and effect of initial pressure of SIT testing. Also a table of the important phenomena of the SIT/FD was proposed with the relevancy of the calculation models applied. The following conclusions are obtained:

(1) Uncertainty due to the assumption of the total K-factor as constant for high flow, transition phase, and low flow phase should be considered.

(2) Nitrogen intrusion phenomena should be considered with a conservatism, especially considering the current situation of non-measuring the standpipe level,

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ACKNOWLEGEMENT

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Part	Important phenomena	Sub-phase				Model			
		High flow	Transition	Low flow	Empty	System code (RELAP5)		Component code (CUPID)	CFD code
						accum	pipe		
Gas space	Isentropic expansion	√				OK	OK	OK	OK
	Isenthalpic expansion		√	√	√	OK	OK	OK	OK
	Nitrogen intrusion		√		√	OK[3]	OK	OK	OK
	Heat transfer to metal				√	OK	OK	OK	OK
Standpipe	Rapid level decrease		√				OK[1]	OK[1]	OK
	Flow stop		√	√	√		OK[2]	OK[2]	OK
Outer-Standpipe	Level decrease	√	√	√			OK[1]	OK[1]	OK
Vortex Chamber	Interaction between 2 flows	√	√				OK[1]	OK[1]	OK
	Flow mixing with vortex	√	√	√					OK

Table I: Important phenomena and analysis model

Note

1. Needs input of hydraulic resistances for the flow path through standpipe and the one through connecting holes from the experiment data and/or CFD level analysis result
2. Needs specific form of hydraulic resistance on the flow path through standpipe as a specific function of flow
3. OK only for SIT empty