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

Analysis of the Nitrogen Entrainment in a Safety Injection Tank with a Small Scaled Experiment

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1. Introduction

The Korean large pressurized water reactor APR1400 applied passive flow controller for the emergency core cooling system to correspond to the increase of concerns about passive safety.

The passive flow controller in the APR1400, which is called fluidic device, controls the flow rate of emergency core cooling (ECC) water from the safety injection tank (SIT).

The vortex chamber in the fluidic device controls flow rate. ECC water get into the vortex chamber and discharged without forming vortex inside of the chamber during the high flow mode. However, in low flow mode, vortex is formed in the chamber. The vortex builds up high flow resistance through the fluidic device and therefore, the discharge flow rate decreases.

The performance of the fluidic device was evaluated by experiments with the valve performance evaluation rig (VAPER) facility in the KAERI. The discharge mass flow rate from the SIT over time was demonstrated as expected [1]. However, the experiment did not focus on the nitrogen entrainment phenomena which has been issued recently.

Accumulators or safety injection tanks which utilize pressurized nitrogen as a flow driving source have possibility of the nitrogen injection into the primary loop of the nuclear reactor during the ECC process. There were several researches which tried to figure out the exact effect of the entrained nitrogen during the SBLOCA and LBLOCA situation, but the results remained quite arguable.

The effect of the nitrogen and water volume ratio in the SIT was measured by the computational fluid dynamics (CFD) and RELAP5/MOD3.3 and concluded that the decrease of nitrogen volume ratio in the SIT results in lower pressure drop within low-flow mode and delayed start of the flow mode transition [2]. Also, Li, Y et al brought out the expectation that the nitrogen entrainment may affect the performance of the safety injection [3]. Mitsubishi Heavy Industries topical report ranked the effect of nitrogen entrainment is low because the nitrogen entrainment starts with the reflood phase when the peak cladding temperature has already occurred [4]. Nuclear regulatory guide (NUREG) stated that the injection of nitrogen into the primary loop enhance the core cooling temporally [5].

Although the effect of the nitrogen entrainment on the nuclear reactor safety is not totally uncovered, injection of the nitrogen into the primary loop may harm the nuclear reactor safety. Therefore, nitrogen entrainment phenomena within safety injection should be analyzed.

The first step of preventing malfunction of the ECCS is to design SIT which does not allow nitrogen intake. To achieve this, the study focused on figuring out the nitrogen entrainment criteria.

2. APPARATUS AND EXPERIMENTS

2.1 Experimental facility

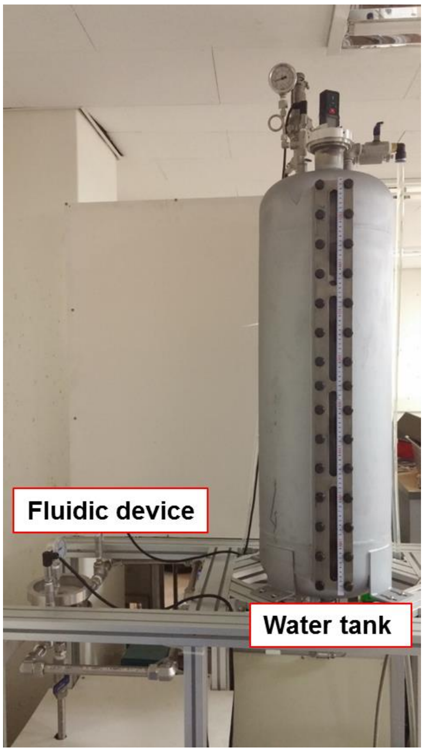

Fig. 1. Small scale SIT experimental facility

Small scale SIT was designed as 1/10 size of the APR1400 SIT to adjust to the laboratory scale. Several structures were modified to observe and collect data of the flow in the SIT.

First, a vertical window was installed at the side of the SIT to measure the water level inside the SIT.

Second, the fluidic device was simplified as a two pipes connected with a round shaped vortex chamber, which described a supply nozzle and a control nozzle of the APR1400 fluidic device.

Third, the fluidic device, which is originally located in the SIT, was taken out of the water tank. Also, the transparent windows were installed at the top and the bottom of the fluidic device to observe inside of the fluidic device.

Visualization of a fluidic device is a key feature of the experimental apparatus to check the time of the vortex flow formation, the direction of the vortex, and nitrogen entrainment start and end time and how the nitrogen entrainment affects the flow in the fluidic device.

Fig. 1 is a small scale SIT which was installed in the laboratory. There is a pressure gauge, a thermocouple, a water inlet line, a gas inlet line, a safety relief valve at the top of the SIT. The water inlet and the gas inlet is controlled by the valve. A circular window is installed at the top to observe inside of the SIT. A vertical window is at the side of the SIT to measure the water level inside the SIT.

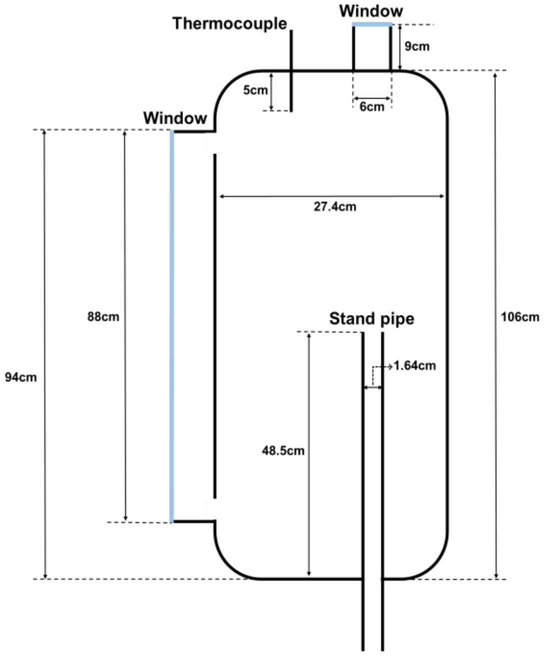

Fig. 2. Schematics of the water tank

Fig. 2 shows the important dimensions of the small scale SIT experimental facility. The SIT vessel has total height of 106 cm, inner diameter of 27.4 cm, and has 9 cm height column at the top. The top-side column has a window to observe inside of the vessel. There is a thermocouple at the top of the vessel which measures the temperature at the point of 5 cm below the top of the vessel. The stand pipe inside the vessel has 48.5 cm length from the bottom and has inner diameter of 1.64 cm

Fig. 3 is a simplified fluidic device. Simplified fluidic device has structure to describe the high flow mode and low flow mode well and adequate to visualization. The one pipe is connected to the bottom of the SIT and another pipe is connected to the stand pipe. And both pipes connected to the vortex chamber with opposite direction.

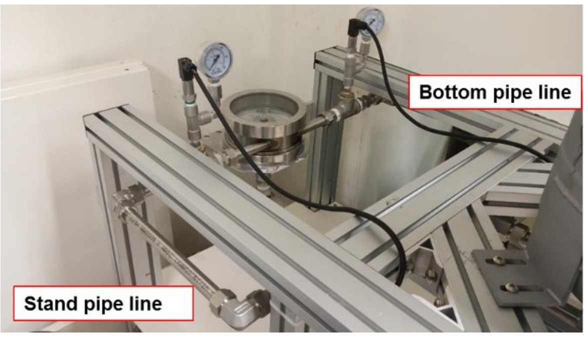

Fig. 3. Side view of the fluidic device

The simplified fluidic device has same scailing ratio with the SIT. The diameter of both pipes is identical to the 1/10 of the supply nozzle thickness. The inner diameter of the simplified fluidic device is identical to the 1/10 of the vortex chamber of the APR1400 fluidic device.

The fluidic device has inner diameter of 13.4 cm. The stand pipe line and the bottom pipe line have identical inner diameter of 1.64cm. The discharge pipe line has inner diameter of 1.6cm.

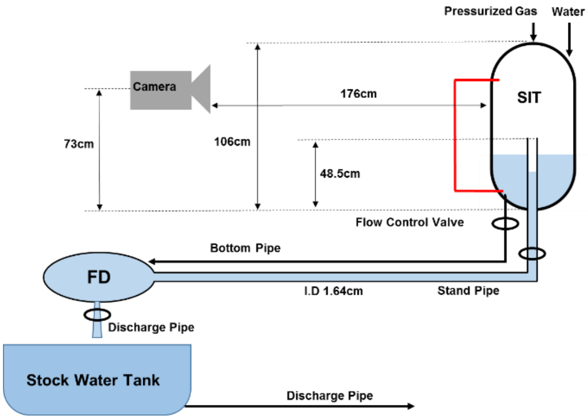

Fig. 4. Schematics of the small scale SIT

Fig. 4 shows the schematics of the experiment. There are SIT, fluidic device, and the camera to measure water level through the time. The camera is settled at the identical position for the entire experiments to eliminate the error in the water level measurement. All the valves are maintained as opened between each experiment to maintain room temperature and humidity inside the facility.

2.2 Equilibrium water level

The concept of equilibrium water level was defined in this experiment to analyze the results.

After the start of nitrogen entrainment, there is no water flow through the stand pipe but the water keep flowing through the bottom pipe. The pressure loss in the control pipe should be compensated by the pressure difference between the inside of stand pipe and the outside of the stand pipe. Therefore, the water level inside of stand pipe is lower than the outside of the stand pipe during the low flow mode. Equilibrium water level is the water level in the stand pipe when the water level difference between the inside and outside of the stand pipe is enough to balance the pressure loss at the control pipe. Therefore, if equilibrium water level is positive, the SIT water is driven into the stand pipe and the nitrogen passage is blocked.

2.3 Procedures

1. Set the water level of SIT as 89 cm.
2. Pressurize the SIT by the nitrogen gas. (range: 5 ~ 10 bar)
3. Open the valve at the discharge pipe.
4. Records pressure, temperature, water level in the SIT through the time.
5. Records fluid behavior in the fluidic device.
6. Calibrate the water level.
7. Interpolate the water level where the water level is invisible.
8. Derive discharge mass flow rate of the water with the equation (1)

$$W(t) = \rho_{water} A_{SIT} \frac{(H(t)-H(t+\Delta t))}{\Delta t} \qquad (1)$$

9. Calculate the pressure at the bottom of the tank.
10. Deduce the pressure loss through the bottom pipe
11. Deduce the equilibrium water level during the nitrogen entrainment

3. Results and Discussion

The water level in the 10 bar pressurized SIT was measured. Fig. 5 is a water level – time graph. The water level was measured in millimeter resolution. Test 1 to 3 shows almost identical data. The water level decreases fast when the top water surface is above the stand pipe. After the top water surface passes through the stand pipe, which occurs at the 20 sec, water level decreases relatively slow.

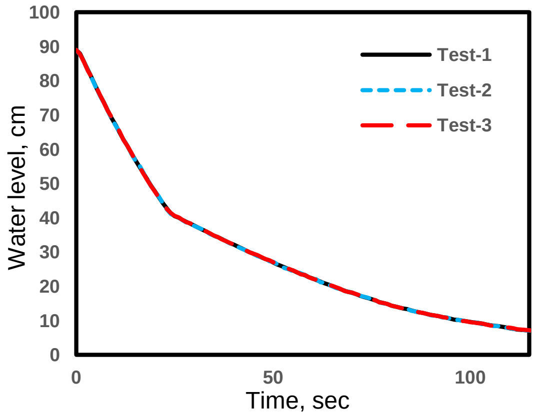

Fig. 5. Water level in the tank with initial pressure of 10 bar

According to the Fig. 5, water level passed the stand pipe at 19.58 sec. Fig. 6 shows the fluidic device at the start of the nitrogen intake. Nitrogen started to get into the fluidic device at 20.31 sec. Bubbles in the fluidic device moved about 5cm during 0.034 sec. The bubble velocity is about 1.5 m/sec. With the nitrogen velocity and total nitrogen passage length, nitrogen bubbles took 1.17sec from the top of the stand pipe to the fluidic device. Thus, nitrogen entrainment started at 19.13 sec after the discharge.

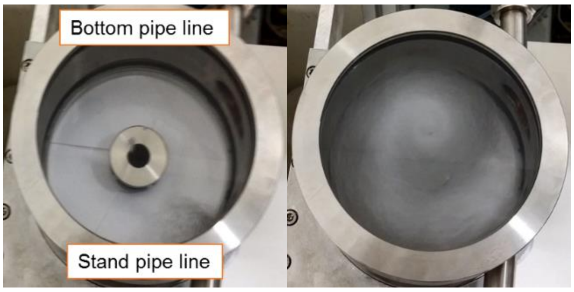

Fig. 6. Flow behavior in the fluidic device of 10 bar nitrogen pressurized SIT during the discharge (Left: 20.4 sec, Right: 21 sec)

The water level at 19.13 sec is 49.26 cm by interpolation. This is 0.76 cm above the top of the stand pipe. With the same process, the nitrogen entrainment ends at 37.91 sec with the water level of 33.26 cm.

Identical processes were performed to the 5 bar to 9 bar initial conditions. The results were listed in the Table I.

Table I: Nitrogen entrainment start and end time

Pressure (bar)	Start (sec)	End (sec)
10	19.13	37.91
9	21.65	40.07
8	24.91	42.62
7	29.03	45.64
6	34.38	49.81
5	41.77	55.82

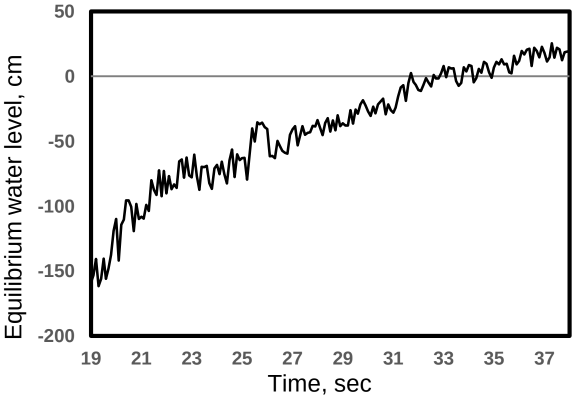

Fig. 7. Equilibrium water level at initial pressure of 10 bar

Fig. 7 is the equilibrium water level – time graph with initial pressure of 10 bar. The data fluctuates a lot so equilibrium water level at the end of the nitrogen entrainment was calculated by the mean of 9 values near the point.

Equilibrium water level is lower than 0 during the entrainment. This means the pressure loss at the control pipe cannot be able to be compensated and the nitrogen kept flow into the vortex chamber. Therefore, unlike APR1400 case, nitrogen was entrained over 15 seconds until the equilibrium water level exceed 0 and water starts to surge into the stand pipe.

Equilibrium water levels for the initial condition of 5 bar to 10 bar cases were deduced and listed on the table Ⅱ.

Table II: Equilibrium water level in the stand pipe at the end of the nitrogen entrainment

Pressure (bar)	Equilibrium water level (cm)
10	19.50
9	17.58
8	14.14
7	11.71
6	7.96
5	5.62

Equilibrium water level increases through the initial pressure increase. This means that SIT needs more driving force to get back the water level in the stand pipe and block the nitrogen intake when the initial pressure is higher.

4. Conclusion

The concept of equilibrium water level was brought to analyze the nitrogen entrainment phenomena and to figure out the criteria of the nitrogen entrainment. Deduced equilibrium water level is 19.5 cm for the initial condition of 10 bar. The level increases through the initial pressure increases.

The longer stand pipe which can provide enough water level difference between stand pipe and SIT will decrease the amount of entrained nitrogen. The large, short and simple-shaped control pipe which lowers the pressure loss at the pipe will decrease the amount of entrained nitrogen.

The results can be used to design a SIT with no nitrogen entrainment to the primary loop of the nuclear reactor.

5. Further Works

- Validate the results with various stand pipe geometry.
- Validate the gas intake model in the system code MARS by describing the small scale SIT facility with the model.

6. Acknowledgements

This research was supported by the KUSTAR-KAIST Institute, Korea, under the R&D program supervised by the KAIST.

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