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Research Article

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RELAP5 code investigation on operational characteristics of passive siphon breaker line in research reactors under LOCA conditions

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HIGHLIGHTS

- The heterogeneous solution approach has fewer errors and is more accurate than the homogeneous solution.
- The amount of UH is increased with the increase of break size or the decrease of the size of the siphon breaker line.
- The RELAP5/Mod3.2ai thermohydraulic code is capable of modeling this kind of accident on a large scale.
- The simulation results showed an acceptable degree of conformance with the experimental data.

ABSTRACT

Currently, passive safety systems are critical for enhancing nuclear reactor safety and dependability. To limit the chance of the core being uncovered in pool-type research reactors, a siphon pipe with a penetration in the pool wall higher than the core level can be used as the pool outlet pipe. Using a siphon breaker as a passive safety system is vital. The hydraulic study of the siphon breaker line passive safety system for a pool-type research reactor is carried out using the RELAP5 code. The hydraulic analysis and modeling are carried out on a 16-inch coolant outlet siphon pipe, taking into account 16-inch and 8-inch break diameters, as well as siphon breaker line diameters of 2, 2.5, 3, and 4 inches. As a consequence, the undershooting height for a 16-inch break and a 4-inch siphon breaker line is -36.7 cm. The undershooting height is -51.4 cm when using an 8-inch break and a 2-inch siphon breaker line. Compared with the findings to the reference experimental data, the largest difference is -3.1 cm and the smallest difference is -0.1 cm. The findings obtained indicate a substantial agreement between the simulated and experimental results.

KEYWORDS
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RELAP5
SBL
LOCA

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1 Introduction

Since the first nuclear power plants went into operation, scientists and activists in this field have been examining the safety of nuclear reactors utilizing passive technology. Furthermore, the system's stability and ability to maintain the core of research reactors cooled and protect against radiation after an accident resulting in coolant loss improve the reactor's level of safety. According to the International Atomic Energy Agency's recommendations in the field of research reactor safety, the cooling piping should not be left at the bottom of the pool to reduce the risk of draining the reactor pool coolant in the event of an accident or coolant loss. Instead, it should be left through a siphon tube by creating a hole in the pool wall at a height higher than the core. The siphon breaker line is employed as a passive safety mechanism to prevent the coolant from draining completely in the case of a break in the outlet pipe, as well as to restrict the outflow from the pool to keep the pool water level higher than the core. A LOCA (Loss of Coolant Accident) condition occurs when an outlet pipe in a pool-type research reactor's cooling system fails. However, if the water level in the reactor pool remains above the level of the core and the emergency shutdown mechanism trip the reactor, the decay heat of the reactor core can be removed by natural convection flow, avoiding the repercussions of a Loss of Coolant Accident.

In 1991, there was consideration of passive safety systems (IAEA, 1991), in the International Atomic Energy Agency's conference titled "Nuclear Energy Safety: Future Strategy." The use of passive systems can result in system simplicity and overall cost benefits, as well as a

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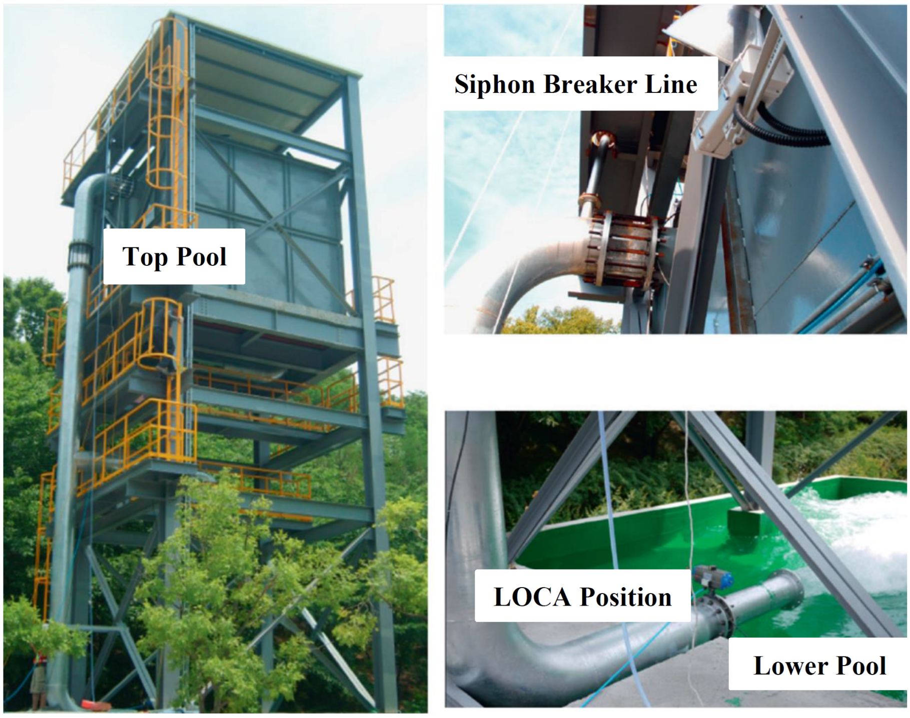

Figure 1: Siphon break experimental facility.

reduction in human error as compared to active systems. As a result, passive safety systems have been studied for several kinds of research reactors. In 1993 (Neill and Stephens, 1993), Neil et al. evaluated the siphon breaker line on a small scale and modeled the system with the RELAP5 safety analysis algorithm. However, they were unable to obtain satisfactory findings, so they abandoned modeling and merely presented the results of experiments. In 1999 (Sakurai, 1999), Sakurai et al. conducted an experimental and numerical evaluation of a small-scale siphon breaker line with a pool height of approximately 6.5 m and a break distance to the pool top of 19.5 m. The numerical findings were satisfactory in terms of accuracy when compared to the experimental test results using the SBAP (Siphon Breaker Analysis Program) software.

From 2011 until 2017 (Kang et al., 2011; Seo et al., 2012; Lee and Kim, 2016, 2017b), Lee et al. conducted experimental and simulation studies on the siphon breaker line for a real-scale research reactor, as shown in Fig. 1. In these studies, the break diameters ranged from 6 to 16 inches, the siphon breaker line sizes varied from 2 to 6 inches, and the pool outlet pipe size was 16 inches. As a consequence, UH (Undershooting Height) were measured in two experimental and simulation modes at various break sizes, with a maximum error of 13 cm and a minimum error of 1 cm.

In 2018 (Ji et al., 2018), Kim et al. conducted an experimental examination of a small-scale siphon facility and numerical analysis by using SBSP (Siphon Breaker Simulation Program). According to the obtained findings, in the size of the siphon breaker line of 0.375 inches and 0.5 inches, the tank sweeping mode was relatively small and partially, while in the size of 0.25 inches, the tank was completely empty and the change of the air sweeping mode was not easy. Furthermore, the simulation UH differed from the practical test results by decreasing the diameter of the siphon breaker line, with a minimum average error of 16 mm and a maximum relative inaccuracy of 48%. In the lower diameters of the siphon breaker line, the difference grows with an increase in the C factor equation mentioned in reference (Ji et al., 2018), and the SBSP program is appropriate for usage in the design range of 100,000 to 420,000.

In 2022 (Sengupta et al., 2021), Samiran et al. investigated the siphon breaker line on a small scale using both experimental and numerical methods. The numerical solution was performed using the RELAP5/Mod3.2 code, and experimental and numerical analysis were performed with various break diameters. The numerical and experimental findings were in satisfactory compliance, demonstrating that RELAP5 is capable of modeling the siphon breaker line in a small-scale facility.

According to the literature and what was mentioned about the significance of passive systems, as well as the complexity of the two-phase behavior of the flow in this phenomenon, the two-phase phenomenon of this system has been studied experimentally in many countries since 1993. Several numerical analyses have been carried out using diverse programs and codes, such as: RELAP5, CFD, OpenFOAM (Park et al., 2011, 2014; Ramajo et al., 2017), and special codes have also been developed (Lee and Kim, 2017a; Park and Park, 2020). However, in real-scale pool type research reactors, the simulation and validation of two-phase flow in siphon pipe have not been provided in a valid manner by RELAP5 code, therefore in the present work, the mentioned simulation and analyses are performed and validated with the reference experimental results (Lee and Kim, 2016) in real-scale.

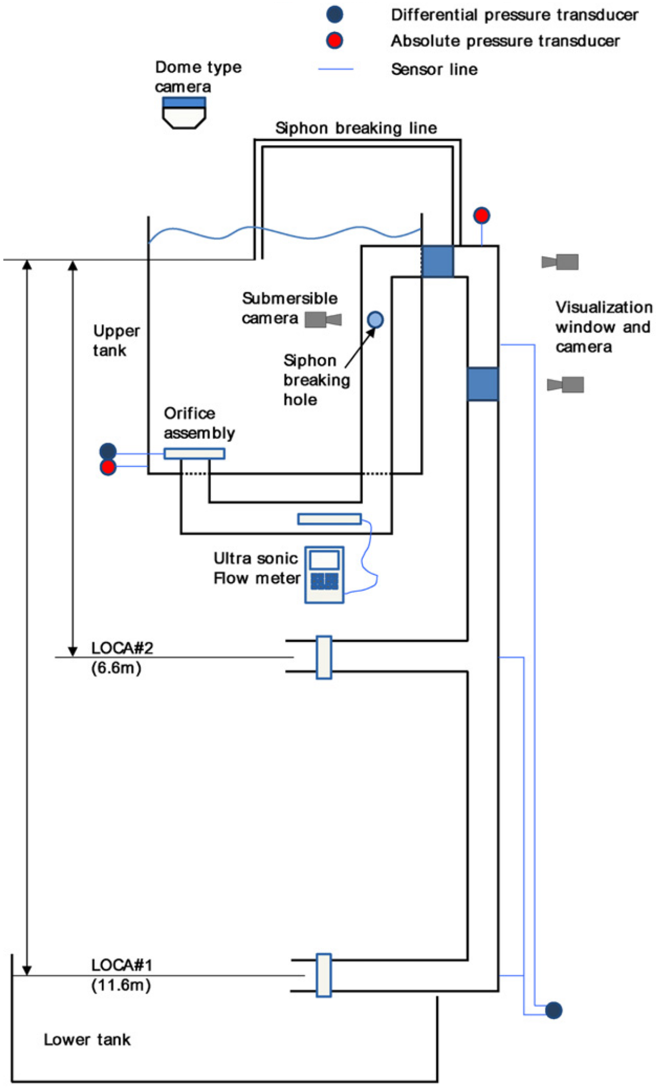

Figure 2: Siphon loop in real scale.

2 Thermohydraulic analysis of the siphon breaker line system

2.1 Reference siphon breaker line

In this section, the reference siphon breaker system is initially introduced. Then the applied configuration and nodalization in the safety analysis RELAP5 code is discussed. Finally, the analysis method in RELAP5 is addressed. According to Fig. 2, the first break is 11.6 m from the entrance of the siphon breaker line, whereas the second break is 6.6 m away. Both line and hole type were considered for siphon breaker in the reference (for the present work, just line type included). The break size in the line type siphon breaker was 16 inches, 10 inches, 8 inches, and 6 inches, and for the hole type siphon breaker, a 10-inches line with siphon breaker hole sizes of 30, 35, 40, 45, 50, and 55 mm was built and analysed. The siphon's main pipe had a diameter of 16 inches, and the pool's capacity was 57.6 m^3 at a height of 4 m. The siphon breaker line was sizes (0.5, 1, 1.5, 2, 2.5, 3, 4, 5, and 6) inches, and the flow rate variations have been measured using an ultrasonic flow meter.

This research simulates the break position of LOCA #1 with diameters of 16 and 8 inches, and models the siphon breaker line with sizes of (2, 2.5, 3 and 4) inches, as shown in Fig. 2. The sizes and dimensions of the siphon system are fully discussed in the final report of reference (Kang et al., 2011) and (Seo et al., 2012).

2.2 Modeling and designing the reference passive safety system

The system schematic in Fig. 3 is obtained by the reference data (Kang et al., 2014), including the system's dimensions, height, volume, diameter, and connections, as well as the break position (Kang et al., 2011; Seo et al., 2012; Lee and Kim, 2016, 2017b). Position 1 refers to the pool's water level, which is initially set to 4 m.

The siphon breaker line's entry within the pool is indicated with position 0 in Fig. 3, at a height of 3.3 m, which is the same height as the bottom of the highest horizontal part of the 16-inch siphon pipe. Position 2 is where the siphon breaker line connects to the siphon pipe. Position 3 is the system's break position, and the test facility's height is approximately 17.67 m.

2.3 Nodalization of the siphon breaker line system in the RELAP5 code

Figure 4 depicts siphon loop nodalization for simulation with RELAP5 code. The ambient air boundary conditions are connected to valve number 222 and branch number 424 via TDVs 111 and 515, respectively. Valve No. 222 remains open from the start of the simulation until the end of the computations. Valve 414 represents the break in the outlet pipe in the lowest location. The boundary conditions of the water entering the pool are connected to the surface of the pool via TDV No. 333 and valve No. 444. Branch 555 indicates the volume of the pool above the siphon breaker line's entry, whereas branch 777 represents the volume of the pool below it. The end of branch 777 is connects to pipe 888, which represents the 16-inch siphon outlet pipe, and the top to pipe 616, which represents the siphon breaker line input. Pipe 909, whose specifications are shown in Table 1, is connected to pipe 313 (the location of the break) via SNJ 212, and the diameter of the break is assumed to be 16 and 8 inches, respectively, in the aforementioned pipe. It should be noted that for a 16-inch broken siphon pipe, the diameters of the siphon breaker line are 4, 3, and 2.5 inches, respectively, and for an 8-inch broken siphon pipe, the diameters of the SBL5 are 2.5 and 2 inches.

Table 1: Specifications of Pipe No. 909.

Parameter	Value
Area (m^2)	0.1297171
Length (m)	11.533
Vertical angle (degrees)	-90.0
Elevation change (m)	-11.533
Wall roughness (m)	0.000046
Pressure (Pa)	1.0×10^5
Temperature (K)	293.15

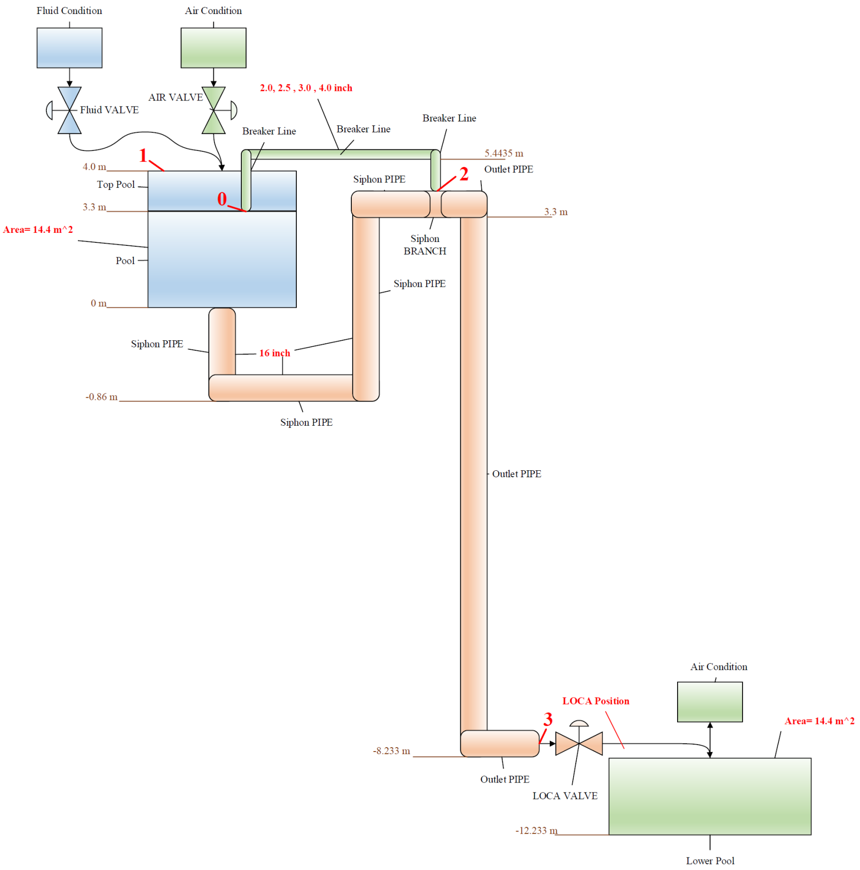

Figure 3: Siphon loop and siphon breaker line.

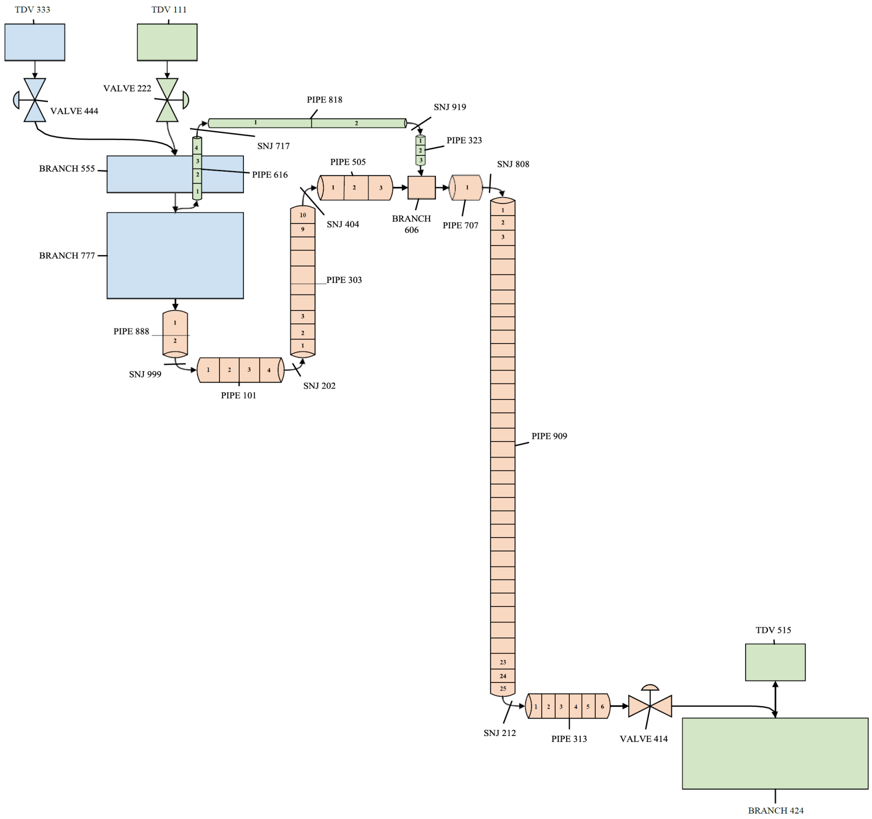

Figure 4: Siphon loop nodalization for simulation in RELAP5.

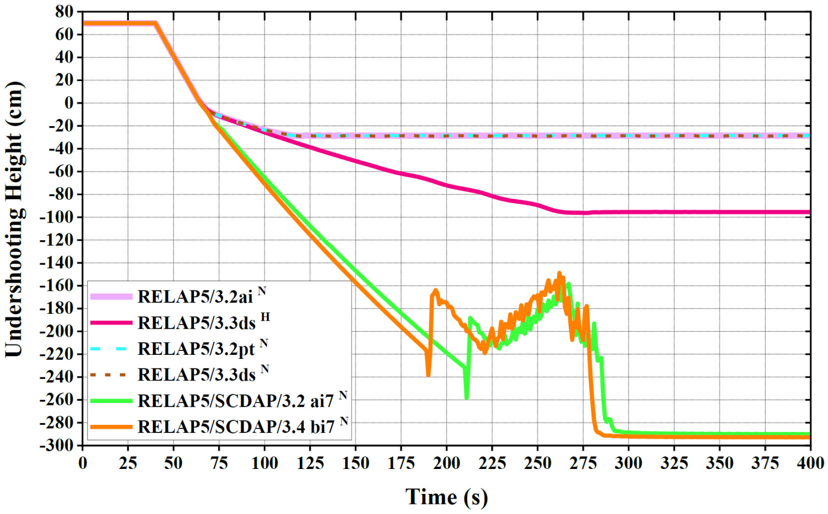

Figure 5: UH in different RELAP5 versions.

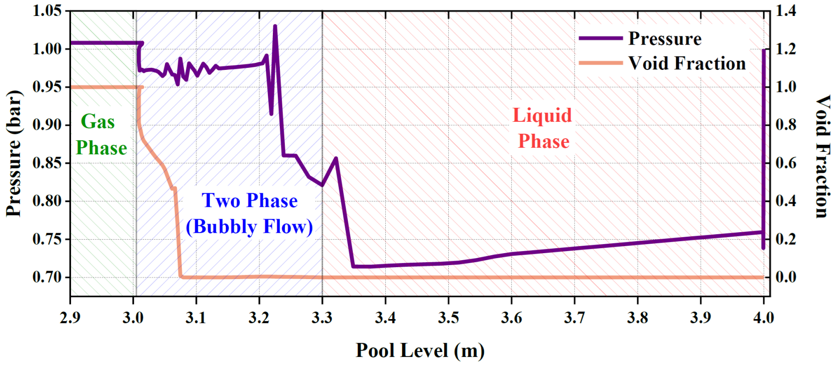

Figure 6: Pressure and void fraction in break size of 8 inches.

2.4 *Analysis method*

The RELAP5 safety analysis code's solution approach was used to analyze momentum equations in a heterogeneous way owing to changes in fluid velocity in two phases. The general form of the inhomogeneous two-phase momentum equation is shown in Eq. (1):

$$\rho_i(\frac{\partial v_i}{\partial t} + v_i.\nabla v_i) = -\nabla P_i + \rho_i F_i + \sum j \\ \neq i\alpha_{ji}(\rho_j - \rho_i)g_i + \zeta_i - M_i \tag{1}$$

where ρ_i is density of phase i, v_i is velocity vector i, F_i is external force affecting phase i, ζ_i is the velocity term or exit term in the governing equation, M_i is surface mass transfer between two phase surfaces, P_i is pressure of phase i, α_{ji} is surface concentration between two phases ji, ρ_j is density of phase j, and g_i is the acceleration vector of gravity.

The control variable card is used to calculate the UH in the RELAP5 code input and represents it graphically in the results. UH is defined as the pool water level difference with respect to the breaker line entrance (the bottom of the highest horizontal siphon pipe), which corresponds to pipe 505, after stabilizing the pool water level.

3 Results and discussion

This section presents the RELAP5 code results in two parts: first for an 8-inch break and subsequently for a 16-inch break: Figure 5 compares five versions of RELAP5 for analyzing a passive siphon breaker system with break size of 8 inches and siphon breaker line size of 2.5 inches. According to the results of this figure, three versions of RELAP5 with the numbers 3.2 ai, 3.2 pt, and 3.3 ds have the solution with minimal error when compared to the experimental result. In Fig. 5, two indices are used: ($^{\mathrm{N}}$) indicates a nonhomogeneous solution approach (two velocity momentum equations), and ($^{\mathrm{H}}$) represents a homogeneous solution approach (single velocity momentum equation). In the homogeneous approach, there is a substantial difference between the experimental data and 3.3 ds ($^{\mathrm{H}}$) version. Furthermore, there is a greater deviation between SCDAP versions and experimental result.

Figure 6 shows the pressure variations for the break diameter of 8 inches and the siphon breaker line size of 2.5 inches. From the beginning of the modeling until 40 seconds (the moment of the accident), the pressure at the top of the siphon pipe drops to 0.72 bar, and then, due to air entering pipe number 909, the pressure rises to atmospheric pressure. The void fraction variations occurs at

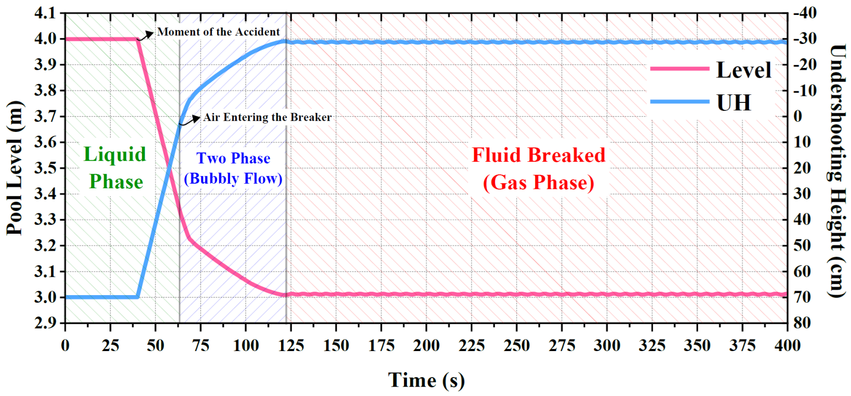

Figure 7: Pool level and UH in break size of 8 inches.

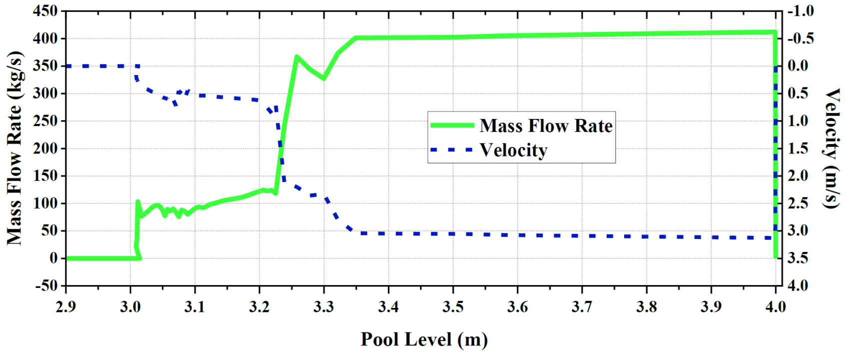

Figure 8: Mass flow rate and velocity in break size of 8 inches.

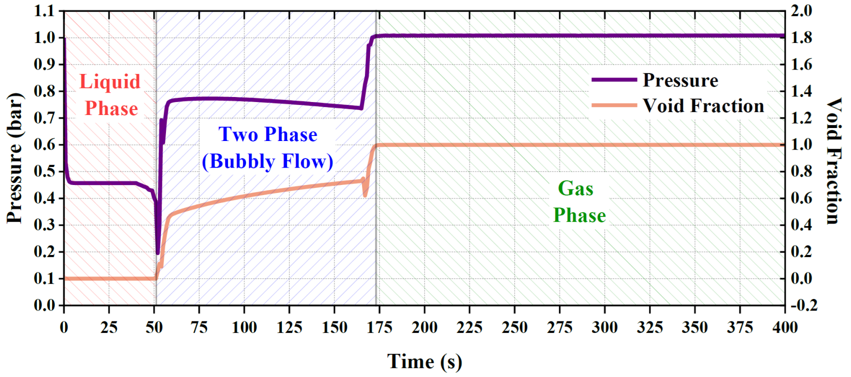

Figure 9: Pressure and void fraction in break size of 16 inches.

the two-phase area from 3.3 to 3 m water pool level until the fluid stabilizes and gas phase dominates.

Figure 7 shows the pool water level for an 8-inch break and a 2.5-inch siphon breaker line, which stabilizes approximately at the pool level of 3 m after the breaker functions, and on the right side, due to air entrance into the siphon pipe and the flow stoppage, the UH value for a 2.5-inch diameter siphon breaker line is -28.9 cm.

According to Fig. 8, on the left side, the outlet flow rate from the siphon pipe for the break size of 8 inches, reduces form approximately 410 kg.s^{-1}, to zero after air entrance and the flow breakage at the level of 3 m. On the right side, the fluid velocity variations are indicated, reaching to zero value after flow breakage.

In Fig. 9, the left side shows pressure fluctuations for a break size of 16 inches and a siphon breaker line size of 2.5 inches. From the start of the modeling to the 50 seconds, the pressure in the top of the siphon pipe is reduced to 0.2 bar, and after 175 seconds, when the pool outlet is stopped due to air entering pipe number 909, the pressure at the top of the siphon pipe equals atmospheric pressure. On the right side, the void fraction variations are displayed which its value changes from zero to one by air entrance into siphon pipe leading to changing liquid phase to two-phase and finally gas phase.

Figure 10 shows that the pool water level for the break size of 16 inches in three cases of the breaker line sizes of 4, 3 and 2.5 inches. The pool's water level reaches 2.933

Table 2: Comparison of experimental results and simulation results.

Size (inch)			UH (cm)		
Siphon Pipe	Break	SBL	Experiment	RELAP5/Mod3.2 ai$^{(N)}$	Difference
16	16	4	-35	-36.7	+1.7
16	16	3	-84	-80.9	-3.1
16	16	2.5	-138	-135.2	-2.8
16	8	2.5	-29	-28.9	-0.1
16	8	2	-53	-51.4	-1.6

m approximately 40 seconds after the pool inlet flow stops in the case of 4-inch diameter siphon breaker line. Pool water level stabilizes in 2.491 m in the case of the 3-inch diameter siphon breaker line and 1.948 m in the case of the 2.5-inch diameter siphon breaker line, approximately 70 and 110 seconds following the initiation of the incident, respectively. With a break diameter of 16 inches and the assumption of a siphon breaker line with sizes of 4 inches, 3 inches, and 2.5 inches, UH has been illustrated in Fig. 11. The water level is 70 cm above the siphon breaker line's entry before the flow into the pool is stopped. After stopping the flow into the pool, it was discovered that the water level of the pool stabilized faster using a larger diameter siphon breaker line. UH is equal to -36.7 in a 4-inch line, -80.9 in a 3-inch line, and -135.2 cm in a 2.5-inch line regarding siphon breaker line diameters.

According to Fig. 12, in the left side, the outlet mass flow rate from the siphon pipe with the break size of 16 inches, is approximately 840 kg.s^{-1}. The fluid flow breaks at 175 seconds, at which point the flow rate is zero. With a breaking size of 16 inches on the right side, the outlet velocity drops to zero when the flow breakage occurs.

Table 2 shows the validation of the simulation results by comparing the simulation results carried out in this work with the experimental results reported in reference (Lee and Kim, 2016). The accuracy of the simulation is demonstrated by the fact that the largest difference in UH between the simulation and reference results is equal to -3.1 cm, while the smallest difference is equal to -0.1 cm.

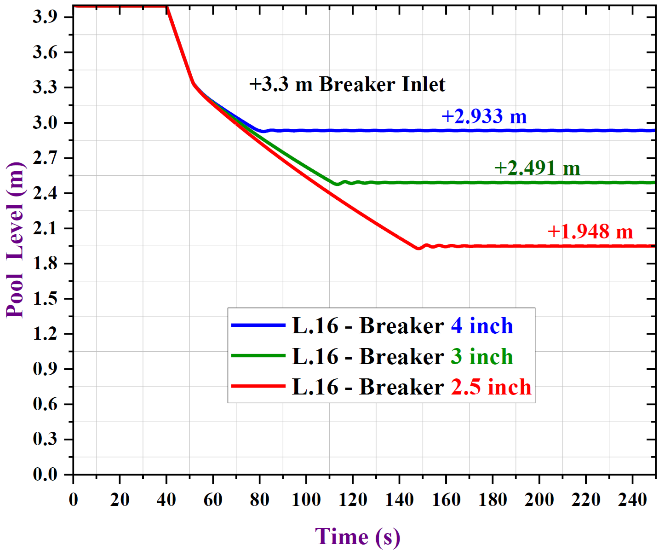

Figure 10: Pool level in 16-inch break size.

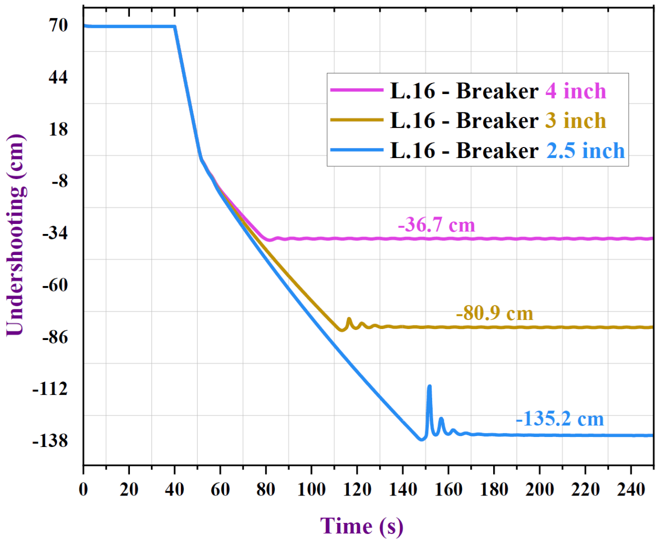

Figure 11: Undershooting height in 16-inch break size.

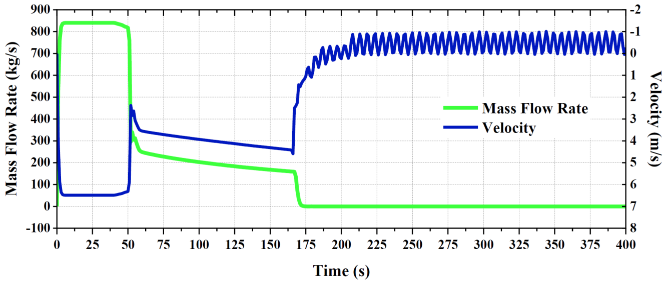

Figure 12: Mass flow rate and velocity in break size of 16 inches.

4 Conclusions

According to this research, the heterogeneous solution approach has fewer errors and is more accurate than the homogeneous solution. By adjusting the parameters of the break size and the size of the siphon breaker line and taking a wide range of numbers into consideration, it is concluded that the amount of UH is increased with the increase of break size or the decrease of the size of the siphon breaker line.

The main result and originality of this study was to demonstrate that the RELAP5/Mod3.2ai thermohydraulic code is capable of modeling this kind of accident on a large scale and to arrive at the findings of previous experiments that have been conducted. Research centers worldwide are presently investigating and developing this problem using two-phase approximations. Special programming has been developed for this test facility, taking into account the complexity of this phenomenon in two-phase state with gravity flow and with increasing mass flux in case of increasing the break size to increase the accuracy of calculations. This study presents a numerical solution of the RELAP5/Mod3.2 code simulating the siphon breaker line type of this system. The UH is equal to -36.7 cm in a break size of 16 inches and a breaker line size of 4 inches, and it is equal to -51.4 cm with an 8-inch break size and a 2-inch breaker line. The largest difference is -3.1 cm, and the smallest difference is -0.1 cm, based on a comparison of the numerical findings with the experimental results (Lee and Kim, 2016). The simulation results showed an acceptable degree of conformance with the experimental data.

Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work.

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