Video Article

# Study of Siphon Breaker Experiment and Simulation for a Research Reactor

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## Abstract

Under the design conditions of a research reactor, the siphon phenomenon induced by pipe rupture can cause continuous outward flow of water. To prevent this outflow, a control device is required. A siphon breaker is a type of safety device that can be utilized to control the loss of coolant water effectively.

To analyze the characteristics of siphon breaking, a real-scale experiment was conducted. From the results of the experiment, it was found that there are several design factors that affect the siphon breaking phenomenon. Therefore, there is a need to develop a theoretical model capable of predicting and analyzing the siphon breaking phenomenon under various design conditions. Using the experimental data, it was possible to formulate a theoretical model that accurately predicts the progress and the result of the siphon breaking phenomenon. The established theoretical model is based on fluid mechanics and incorporates the Chisholm model to analyze two-phase flow. From Bernoulli's equation, the velocity, quantity, undershooting height, water level, pressure, friction coefficient, and factors related to the two-phase flow could be obtained or calculated. Moreover, to utilize the model established in this study, a siphon breaker analysis and design program was developed. The simulation program operates on the theoretical model basis and returns the result as a graph. The user can confirm the possibility of the siphon breaking by checking the shape of the graph. Furthermore, saving the entire simulation result is possible and it can be used as a resource for analyzing the real siphon breaking system.

In conclusion, the user can confirm the status of the siphon breaking and design the siphon breaker system using the program developed in this study.

## Video Link

The video component of this article can be found at https://www.jove.com/video/55972/

## Introduction

The number of reactors using plate-type fuel, such as the Jordan Research and Training Reactor (JRTR) and KiJang Research Reactor (KJRR), has increased recently. In order to connect the plate-type fuel easily, the research reactor requires a core downward flow. Since research reactors require net positive suction head of the primary cooling system, some cooling system components could potentially be installed below the reactor. However, if pipe rupture occurs in the primary cooling system below the reactor, the siphon effect causes continuous drainage of coolant that could result in the exposure of the reactor to the air. This means that the residual heat cannot be removed, which could lead to a serious accident. Therefore, in the event of a loss of coolant accident (LOCA), a safety device that can prevent a serious accident is necessary. A siphon breaker is such a safety device. It can effectively prevent water drainage by using an inrush of air. The entire system is called the siphon breaking system.

Several studies for the improvement of research reactor safety have been conducted. McDonald and Marten[1] carried out an experiment in order to confirm the performance of a siphon breaking valve as an actively-operating breaker. Neill and Stephens[2] performed an experiment using a siphon breaker as a passively operated device in a small-sized pipe. Sakurai[3] proposed an analytical model to analyze the siphon breaking where a fully separate air-water flow model was applied.

Siphon breaking is extremely complex because there are many parameters that need to be considered. Furthermore, because the experiments for real-scale research reactors have not been performed, it is difficult to apply previous studies to contemporary research reactors. Therefore, previous studies have not presented a satisfactory theoretical model for siphon breaking. For this reason, a real-scale experiment was conducted to establish a theoretical model.

To investigate the effect of the siphon breaker on a research reactor, real-scale verification experiments were performed by Pohang University of Science and Technology (POSTECH) and Korea Atomic Energy Research Institute (KAERI)[4,5,6]. **Figure 1** is the actual facility for the siphon breaker experiment. **Figure 2** shows a schematic diagram of the facility and it includes the facility mark.

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**Figure 1. Facility for the siphon breaking demonstration experiment.** The main pipe size is 16 in and an acrylic window is installed for observation. The orifice is a device prepared to describe the pressure drop. Therefore, there is an orifice assembly part at the bottom of the upper tank. Please click here to view a larger version of this figure.

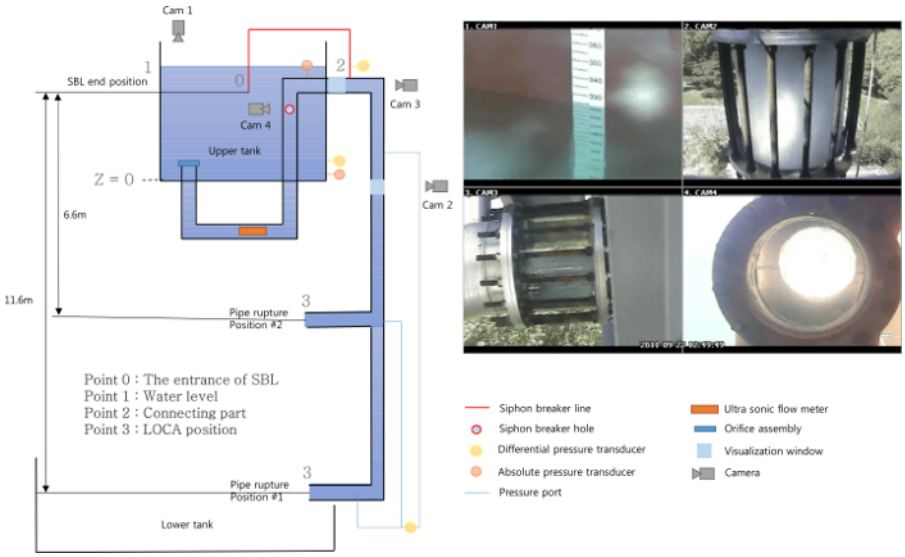


**Figure 2. Schematic diagram of the experimental facility.** The location of measurement points is presented. The numbers indicate these relevant locations; point 0 signifies the entrance of the siphon breaker, point 1 signifies the water level, point 2 signifies the connected part of the siphon breaker and the main pipe, and point 3 signifies the LOCA position. Please click here to view a larger version of this figure.

The siphon breaker experimental facility consists of an upper tank, a lower tank, a piping system, and a return pump. The capacity of the upper tank is 57.6 $m^3$. The bottom area and the depth are 14.4 $m^2$ (4 m x 3.6 m) and 4 m, respectively. The lower tank and LOCA position are located 8.3 m below the upper tank. The capacity of the lower tank is 70 $m^3$. The lower tank is used to store the water during the experiment. The lower tank is connected to the return pump. The water in the lower tank is pumped into the upper tank. The main pipe size of the piping system is 16 in. The end of the Siphon Breaker Line (SBL) is located 11.6 m high above the lower pipe rupture point. In addition, acrylic windows are installed on the pipe for visualization, as shown in **Figure 1**.

Several devices were installed to measure the physical signals. Two absolute pressure transducers (APTs) and three differential pressure transducers (DPTs) were used. To measure the water mass flow rate, an ultrasonic flow meter was used. A data acquisition system was used to get all measurement data at 250 ms time intervals. In addition to the equipment for the measurement, cameras were installed for observation and a ruler was attached on the inner wall of the upper tank to check the water level.

Various LOCA and siphon breaker (SB) sizes, siphon breaker types (Line/Hole), and the presence of orifice regarding reactor fuel and the pipe rupture point were considered in the experiment. In order to verify the effect of LOCA and SBL size, various sizes of LOCA and SBL were used. The LOCA sizes ranged from 6 in to 16 in and the SBL sizes ranged from 2 in to 6 in. In the experiment, line and hole type of siphon breakers were used, but the following content of this study only considers the SBL type used in the JRTR and KJRR. As an example of experimental

results, **Figure 3** is a graph that includes the pressure and water flow rate data. The experiment was conducted on October 4, 2013 and the experimental data sample is LN23 (Line type SB, No orifice, 12 in LOCA, 2.5 in SBL).

From the experiment data, the theoretical model which can predict the siphon breaking phenomenon was established. The theoretical model begins with the Bernoulli equation. The velocity of fluid is obtained from the Bernoulli equation and the volumetric flow rate can be obtained by multiplying the velocity of fluid by the pipe area. In addition, the water level can be obtained using the volumetric flow rate. The basic concept of the theoretical model is as above. However, since the siphon breaking phenomenon is a two-phase flow, there are additional points to be considered. To consider a two-phase flow analysis model, an accuracy verification test was performed. Since the Chisholm model was more accurate than a homogenous model, the Chisholm model is used to analyze the phenomenon. According to the Chisholm model, the two-phase multiplier formula is expressed as **Equation 1**[7]. In this equation, ϕ represents the two-phase multiplier, ρ represents density, and X represents quality.

$$\Phi^2 \equiv 1 + \left(\frac{\rho_{water}}{\rho_{air}} - 1\right)(BX(1-X) + X^2) \quad (1)$$

In the Chisholm model, a coefficient B that varies with mass flow was included. Ultimately, the derivation of a correlation formula between Chisholm coefficient B and reactor design conditions is a significant point of the theoretical model. In other words, another purpose of the experiment was to obtain data to establish the relationship between the design conditions and Chisholm coefficient B. From the test results, a correlation formula between the design conditions and Chisholm coefficient B was established. The resulting theoretical model was developed to predict the siphon breaking phenomenon well.

Furthermore, a simulation program with a Graphic User Interface (GUI) was developed. By the transition of absolute pressure data in **Figure 3**, the phenomenon can be divided into three stages: the Loss of coolant (Single-phase flow), Siphon breaking (Two-phase flow), and Steady state. Therefore, the main calculation process of the algorithm includes a three-step process corresponding to the three stages of the real phenomenon. Including the calculation process, the entire algorithm to describe the simulation process is shown in **Figure 4**[8].

Using the software (see **Supplemental Video 1**) to begin the simulation, the user enters the input parameters corresponding to the design conditions and the input parameters are stored as fixed values. If the user proceeds with the simulation after entering the parameters, the program performs the first step calculation. The first step is the single-phase calculation, which is the calculation for loss of coolant due to the siphon effect after the pipe rupture. The variables are calculated automatically by the theoretical model (as in Bernoulli's equation, mass flow preservation, *etc.*), and the calculation proceeds from the parameters input by the user. The calculation results are sequentially stored in the computer memory according to the time unit designated by the user.

If the water level drops below position 0, it means that the single-phase flow ends, because air starts to rush into the SBL at this moment. Therefore, the first step for single phase flow proceeds until the water level reaches position 0. When the water level is at position 0, this means that the undershooting height is zero. The undershooting height is the height difference between the entrance of the SBL and the upper tank water level after the siphon breaking. In other words, undershooting height indicates how much the water level decreased during the siphon breaking. Therefore, the undershooting height is an important parameter, because it would allow the direct determination of the quantity of coolant loss. Consequently, the program determines the end of the first-step calculation according to the undershooting height.

If the undershooting height is greater than zero, the program performs a second step calculation which can simulate two-phase flow. Because both water and air flow are present in the siphon breaking stage, the physical properties of both fluids must be considered. Therefore, the values of two-phase multiplier, quality, and void fraction are considered in this calculation step. Specially, the void fraction value is used as ending criterion of the second step calculation. The void fraction can be expressed as the ratio of air flow to the sum of air and water flows. The second step calculation proceeds until the void fraction (α) value is over 0.9. When α is over 0.9, the third step calculation proceeds which describes steady state. Theoretically, the ending criterion for siphon breaking is α = 1 since only air exists in the pipe at this time. However, in this program, the end criteria for siphon breaking is α = 0.9 to avoid any error in the calculation process. Therefore, a partial loss of results is inevitable, but this error can be negligible.

Steady state calculation proceeds during the time set by the user. Because there is no further change, the steady state is characterized in that the calculation result values are always constant. If siphon breaking is successful, the final level of the water in the upper tank will remain at a specific value, not zero. However, if the siphon breaking is not performed successfully, the coolant will be almost lost, and the final level of the water approaches zero value. Therefore, if the water level value equals zero in steady state, it indicates that the given design conditions are not adequate to complete siphon breaking.

After the calculation, the user can confirm the results in various ways. The results show the status of siphon breaking, siphon breaking progress, and singularity. The simulation program can predict and analyze the phenomenon realistically and assist in the design of the siphon breaker system. In this paper, the experiment protocol, results of the experiment, and application of the simulation program are presented.

## Protocol

# 1. Experimental Procedure[4,5,6]

1. Preparation step
    1. Check the experimental facility. Based on the test matrix, carefully check the test matrix test conditions, such as LOCA size, SBL size, siphon breaker types, and the presence of orifice, before the experiment. Also, test to confirm that the instrumentations and components of the facility work properly without data noise or malfunctions.
    2. Fill the upper tank with water using the return pump installed inside the lower tank.
    3. Remove the residual air inside SBL. Use a vacuum pump and buffer chamber to remove the residual air from SBL.

4. Check the initial water level of the upper tank. Use the ruler attached to the tank.

2. Test step
    1. Open the valve at the end of piping system.
    2. Using the data acquisition system in the control room, check the measured data, such as water level, flow rate, and pressure changes, during the siphon breaking phenomenon. If there is no outflow of coolant, the first experiment ends. Finally, record the obtained experimental results with the given test conditions.

3. Change the test variables (SBL size, LOCA size, orifice presence, and LOCA position) as follows.
    1. Change the SBL size successively to 2, 2.5, 3, 4, 5, and 6 in; the given SBL is connected to the main pipe by a flange joint at position 2 in **Figure 2**.
    NOTE: The experimental variables, such as SBL size, LOCA size, and the presence of orifice, are changed using the flange joint with bolts and nuts. Therefore, these processes are manually conducted.
    2. Repeat steps 1.1.1 - 1.2.2 until all SBL sizes experiments are done.
    3. With the LOCA in position 1, change the LOCA size successively to 6, 8, 10, 12, 14, and 16 inches; the given reducer is connected to the main pipe by a flange joint at position 3 in **Figure 2**.
    4. Repeat steps 1.1.1 - 1.3.2 until all LOCA sizes experiments are done.
    5. Install the orifice (or remove the orifice) connected to the main pipe by a flange joint at the bottom of the upper tank.
    NOTE: Experiments of the previous step have been carried out with the absence (or presence) of the orifice. Therefore, the orifice should be installed (or removed) for next experiment.
        1. To do this work, ensure that there is no water inside the upper tank.

    6. Repeat steps 1.1.1 - 1.3.4. To confirm the effect of SBL and LOCA size under the presence (or absence) of orifice, repeat the previous step.
    7. Change the LOCA to position 2, as experiments of the previous step have been carried out with LOCA position 1. Change the LOCA position for next experiment.
    NOTE: In the experimental setup, two LOCA positions are constructed. Each LOCA pipe with an isolation butterfly valve is connected to a main piping system.
        1. To change the LOCA position, close the isolation butterfly valve at LOCA position 1 and open the valve at LOCA position 2.

    8. Repeat steps 1.1.1 - 1.3.6.

## 2. Running the Simulation Program

1. Click on the program icon to execute the Siphon Breaker Simulation Program.
NOTE: The procedure is demonstrated in **Supplemental Video 1**. As shown, the initial screen of the simulation program consists of 4 buttons (Show parameter, Run, Manual, and Exit). When the user clicks the 'Show parameters' button, a new command window opens and it includes the list of parameters. The user is able to modify and confirm the numerical values of variables. The 'Run' button performs the calculations by substituting the input parameters into the included formulae. The 'Manual' button is for notifying the usage and program version, and the 'Exit' button closes the program. The results are shown in the 'Show Results' windows.
2. Click the "Show parameter" button.
3. Change the input data considering the given simulation conditions.
4. Click the "Run" button.
5. Check the water level graph shape in the 'Show Results' window. The program organizes the result values with time, and plots the graph automatically.
    1. Through the shape of the graph, visually confirm the possibility of siphon breaking; if the water level or undershooting height has the same value consistently until the end, siphon breaking is possible under the given conditions. See **Figure 3**.

6. Check other outputs in the 'Show Results' window. Note that there are eight options (water level, undershooting height, pressure, water velocity, air velocity, two-phase mixture velocity, quantity, and friction) to check the output. Select the graph type using the check box.
NOTE: It is easy to grasp the siphon breaking phenomenon at a glance because the change of each value with time can be seen through the graph.
7. Confirm the specific value of output depending on the time by clicking the "Calculate in specific time" button. Enter the desired time and check the results according to the set time.
8. Save all simulation result data by clicking the "Save the data" button.
NOTE: Results are saved in the form of text file, and simulated conditions are saved together.

## Representative Results

The entire process of siphon breaking consists of three stages. The first stage is the outflow of coolant due to the siphon effect. The second stage is the process of starting the inflow of air through the SBL to block the loss of coolant, called siphon breaking. The siphon breaking phenomenon can be seen as a sharp increase of absolute pressure in **Figure 3**. After the absolute pressure rapidly increases, it is gradually reduced because of the water level decrease. In the end of siphon breaking, since some residual water flows back to the upper tank, the absolute pressure increases again. If the siphon breaking is completed, there is no further leakage of coolant and this state is called 'steady state'. Because there is no further state change, the absolute pressure is also kept constant. The flow rate, which was maintained at a high value during the first stage, decreases gradually as the siphon breaking starts. When the siphon breaking is successfully completed, the coolant leakage is gradually reduced and stopped as shown in **Video 1**. The differential pressure in **Figure 3** showed a tendency to increase steadily after the start of the siphon breaking.

If the pipe rupture occurs in the absence of the siphon breaker, all the coolant will leak due to siphon effect. The experiment that describes the absence of the siphon breaker is shown in **Video 2** (XN; absence of the siphon breaker). On the other hand, **Video 3** (LN; line type siphon breaker) and **Video 4** (HN; hole type siphon breaker) show that the siphon breaker effectively prevents the loss of coolant. In both cases, it is confirmed that the coolant does not leak below a certain water level. Consequently, the experiments showed that the siphon breaker can be a viable device to prevent loss of coolant.

Moreover, from the experimental results, it was possible to define the relation between the Chisholm coefficient and the design conditions. At first, to reflect the experimental conditions, the process of fine tuning of the pressure loss coefficient was carried out. After adjusting the pressure loss coefficient, Chisholm coefficient B was deduced by a trial and error method. Because the mass flow of air and water should be considered when setting the value of the Chisholm coefficient B, a criterion to evaluate the mass flow quantitatively was necessary. This criterion was derived by using an air flow rate factor and the mass flow of water. The criterion, called the C factor, is used to determine the relation with Chisholm coefficient B. The proposed C factor formula is given by **Equation 2** and the air flow rate factor is given by **Equation 3**[9,10]. In the following formulas, $\rho$ represents density, and $K_{02}$ represents the pressure loss coefficient between position 0 and position 2. Since density and the digit '2' in **Equation 3** are constant, they can be eliminated. Therefore, the simplified type of air flow rate factor is called the F factor in **Equation 2**. The mass flow of water should also be evaluated; it increases as LOCA size increases, but the area also increases at the same time. Therefore, the mass flow with different LOCA size is divided by the area to obtain the mass flow per unit area. Here, the mass flow value is calculated just before air enters into the pipe.

$$\text{C factor} = \frac{Mass\ flux}{\sqrt{F\ factor}} \quad (2)$$

$$\text{Air flow rate factor} = \text{Area}_{\text{SBL}} \sqrt{\frac{2}{\rho K_{02}}} \quad (3)$$

To find the relation between the Chisholm coefficient B and C factor, regression analysis was used. As a result, two type of correlation formulas (Exponential and Quadratic function) could be derived and $R^2$ values were 0.93 (Exponential function) and 0.97 (Quadratic function). Each function is given as **Equation 4** and **Equation 5**[9]. **Equation 4** was able to predict well for a relatively large size of LOCA, such as 12 in and 16 in LOCA sizes. On the other hand, **Equation 5** was able to predict well for relatively small sizes of LOCA, such as the 8 in and 10 in LOCA sizes. Consequently, the exponential function is used to predict for a relatively large size of LOCA greater than 11 in, and the quadratic function is used for that smaller than 11 in.

$$Coefficient\ B = 0.158947e^{0.00001188 \times C\ factor} \quad (4)$$

$$Coefficient\ B = 1.4618 \times 10^{-10} \times C\ factor^2 - 2.7856 \times 10^{-6} \times C\ factor + 1.8316 \quad (5)$$

That is, the establishment of the theoretical model is meaningful in that the prediction of the siphon breaking phenomenon is possible by deriving the Chisholm coefficient B from the design conditions. Therefore, the development of a simulation program which includes the theoretical model would be helpful for analyzing the phenomenon and designing the siphon breaker.

The graph comparing the simulation and experimental results is shown in **Figure 5**. Considering the graph, the simulation program could predict the results obtained from the real-scale experiment. Not only the undershooting height results, but also the flow data obtained from the simulation program show patterns similar to those obtained experimentally. **Figure 6** is the flow rate graph versus the time taken for LOCA sizes of 12 in and 16 in. However, there are some differences at the beginning between the experiment and simulation. In fact, the experimental flow rate evaluation in the beginning phase was based on the visualization video and the flow rate data of the experiment was obtained by calculating the lower water level for 5 s. This method was an alternative way because the ultrasonic flowmeter could not measure the flow rate accurately before the flow fully developed. The difference between the experiment and simulation results appears to be due to this point. Except for the beginning phase, the simulated flow rate was similar to the experimental values and the program predicted the trend according to LOCA size accurately.

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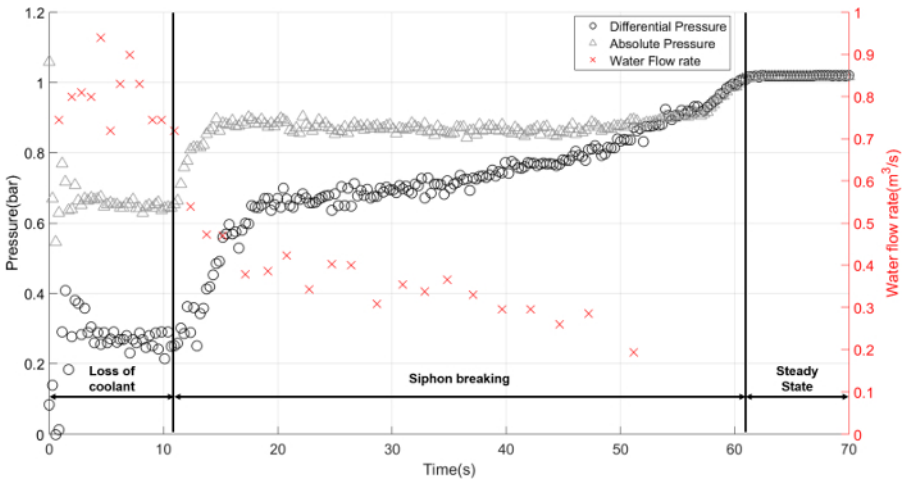



**Figure 3. Experimental result.** The variables measured include water level, undershooting height, pressure, and flow rate. Among the results, pressure and flow rate data are presented.Considering the change of pressure, the phenomenon is largely divided into three sections; Loss of coolant, Siphon breaking, and Steady state. The pressure, which changes slightly changes in the loss of coolant section, increases rapidly in the siphon breaking section. Also, the pressure does not change during steady state. Also, it can be seen that the flow rate gradually decreases due to the siphon breaking. Please click here to view a larger version of this figure.

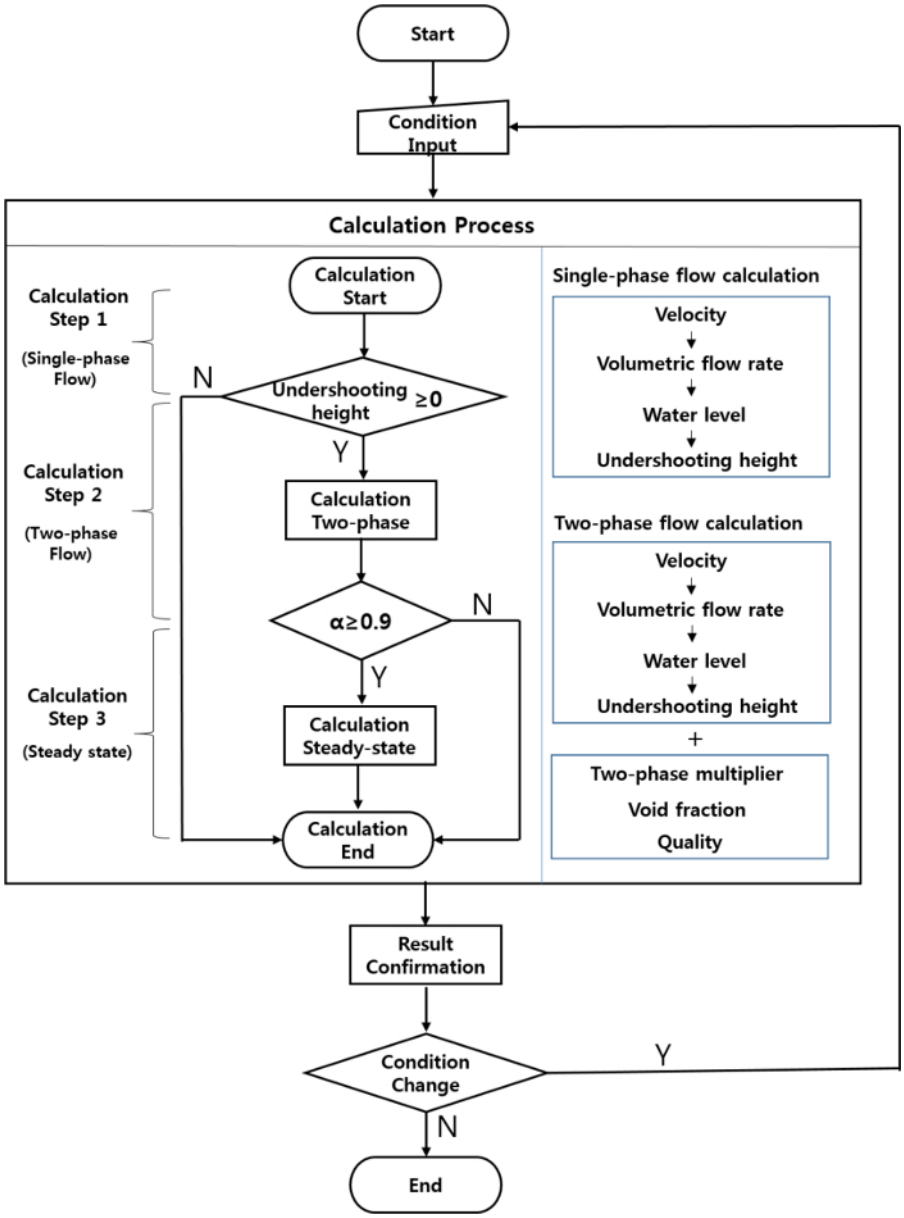



**Figure 4. Algorithm of simulation program.** The algorithm is developed to apply the theoretical model[9]. To reflect the real phenomenon, the main calculation process of the algorithm consisted of three stages. If the input parameters that reflect the design conditions are given, each stage is calculated automatically for the given criteria. Please click here to view a larger version of this figure.

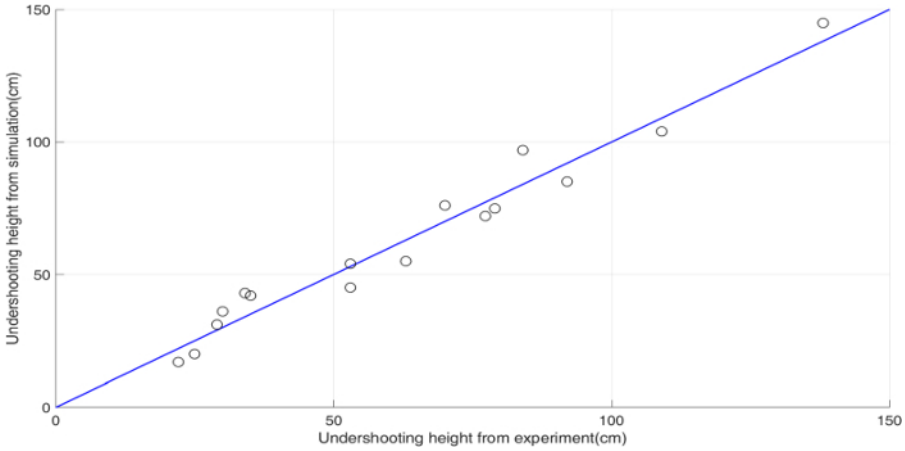



**Figure 5. Estimation of validity.** To evaluate the accuracy of the simulation results, undershooting height is compared with the experiment results. Simulation was found to reasonably match the experiments. In other words, the simulation program has a good performance for analysis of siphon breaking. Please click here to view a larger version of this figure.

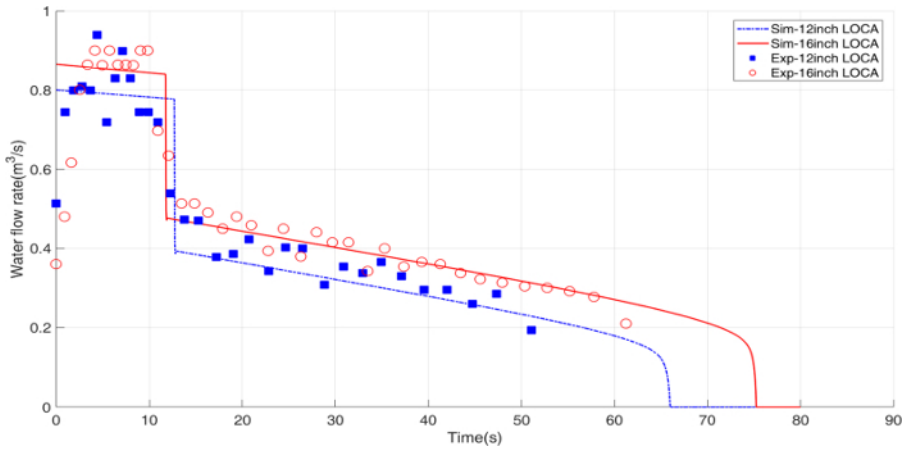
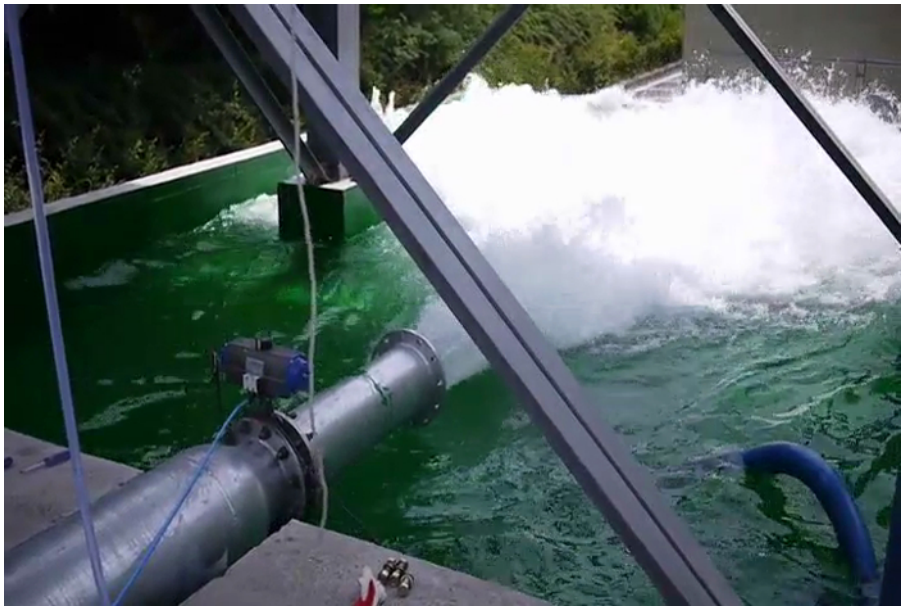


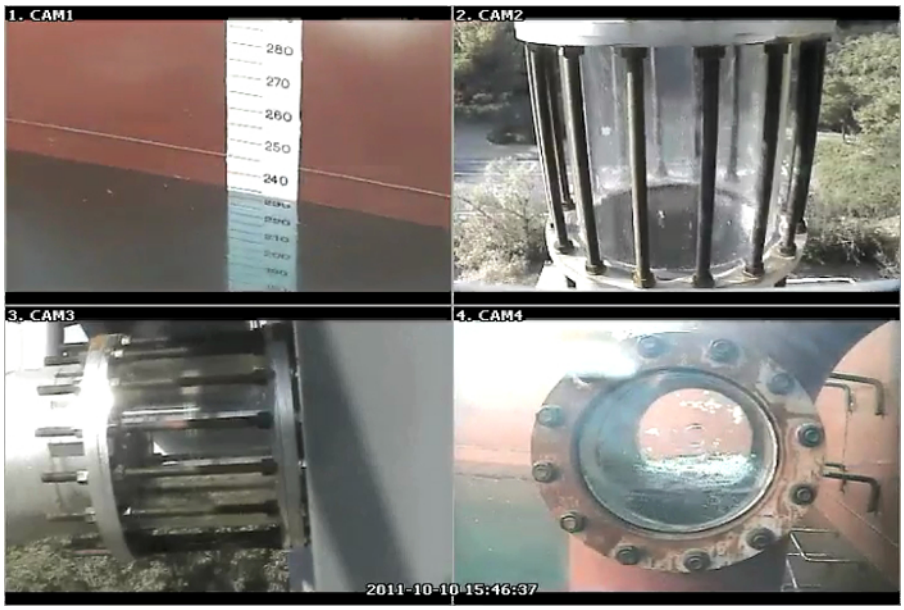

**Figure 6. Flow rate graph.** The simulated (Sim) flow rate was similar to the experimental (Exp) values. Because the simulation could calculate relatively accurately the flow rate quantities, the simulated undershooting height and water level values are similar to the experimental values. Please click here to view a larger version of this figure.



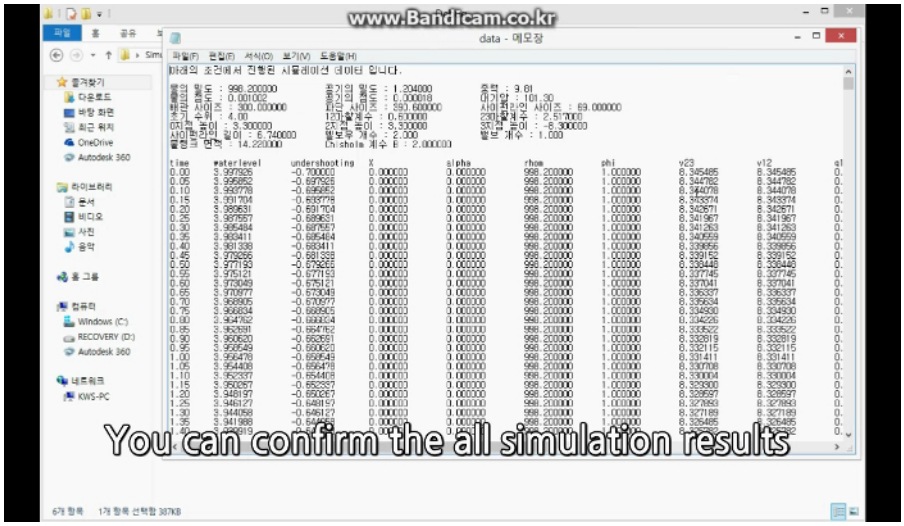
**Video 1. Successful siphon breaking (LOCA).** This video is an experiment with siphon breaker. When the butterfly valve is opened at the LOCA position, the coolant leaks out. However, the coolant leakage is gradually reduced and stopped due to the siphon breaker. In other words, this video shows that siphon breaker can prevent the leakage of coolant. Please click here to view this video. (Right-click to download.)

**Video 2. Absence of the siphon breaker (XN).** In the absence of a siphon breaker, the coolant continues to flow out, and finally the water level of upper tank becomes zero. Please click here to view this video. (Right-click to download.)

**Video 3. Line type siphon breaker (LN).** The siphon breaker effectively prevents the loss of coolant. Please click here to view this video. (Right-click to download.)




**Video 4. Hole type siphon breaker (HN).** The siphon breaker effectively prevents the loss of coolant. Please click here to view this video. (Right-click to download.)




**Supplemental Video 1. Running the simulation program.** The initial screen of the simulation program consists of 4 buttons (Show parameter, Run, Manual, and Exit). When the user clicks the 'Show parameters' button, a new command window opens and it includes the list of parameters. The user is able to modify and confirm the numerical values of variables. The 'Run' button performs the calculations by substituting the input parameters into the included formulae. 'Manual' is the button for notifying the usage and program version, and 'Exit' is a button to close the program. The results are shown in the 'Show Results' windows. Please click here to view this video. (Right-click to download.)

## Discussion

A siphon breaker is a passively-operated safety device used to prevent the loss of coolant when a pipe rupture accident occurs. However, it is difficult to apply to contemporary research reactors because there is no experiment for the real-scale research reactors. For this reason, the real-scale experiment was conducted by POSTECH and KAERI. The purpose of the experiment was to confirm that the siphon breaking is feasible at the real-scale size, and to identify factors that affect siphon breaking. Experimental results show that the LOCA size and SBL size were the main variables influencing undershooting.

The calculation of the siphon breaking is excessively complex because there are many parameters that need to be considered. Previous studies have not presented a satisfactory theoretical model for siphon breaking. For this reason, a theoretical model which could analyze the actual siphon breaking phenomenon was established from the real-scale siphon breaker experiment results. The theoretical model was based on fluid mechanics and the Chisholm model for two-phase flow. From the Bernoulli's equations, the velocity of flow could be derived. Furthermore, other significant variables, such as volumetric flow rate, water level, and undershooting height, could be calculated from the theoretical model considering two-phase flow.

Next, a simulation program was developed based on the theoretical model. When the simulation results were compared with the experimental results, it was shown that the theoretical model could analyze the real siphon breaking phenomenon. The simulation results can be used as a basis for judging the safety of the research reactor against pipe rupture accident, and the program can be used for the design of the siphon breaker.

However, the newly developed theoretical model and simulation program were only developed from the real-scale experiment with a 16 in main pipe size. To verify the applicability of the simulation program on various scales, we are preparing a new experimental facility for small scale siphon breaker tests by miniaturizing the previous real-scale experimental facility. A wide range of the C factor and Chisholm coefficient B, including the range of existing experiment, will be considered.

## Disclosures

The authors have nothing to disclose.

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