http://dx.doi.org/10.5516/NET.03.2014.037

INVESTIGATION ON EFFECTS OF ENLARGED PIPE RUPTURE SIZE AND AIR PENETRATION TIMING IN REAL-SCALE EXPERIMENT OF SIPHON BREAKER

SOON HO KANG[1], KWON-YEONG LEE[2], GI CHEOL LEE[3], SEONG HOON KIM[2], DAE YOUNG CHI[2], KYOUNGWOO SEO[2], JUHYEON YOON[2], MOO HWAN KIM[4], and HYUN SUN PARK[3*]
[1]Department of Mechanical Engineering, POSTECH, Pohang, 790-784, Republic of Korea
[2]KAERI, Yuseong, Daejeon, 305-353, Republic of Korea
[3]Division of Advanced Nuclear Engineering, POSTECH, Pohang, 790-784, Republic of Korea
[4]KINS, Yuseong, Daejeon, 305-338, Republic of Korea
[*]Corresponding author. E-mail : hejsunny@postech.ac.kr

Received March 27, 2014
Accepted for Publication July 31, 2014

To ensure the safety of research reactors, the water level must be maintained above the required height. When a pipe ruptures, the siphon phenomenon causes continuous loss of coolant until the hydraulic head is removed. To protect the reactor core from this kind of accident, a siphon breaker has been suggested as a passive safety device. This study mainly focused on two variables: the size of the pipe rupture and the timing of air entrainment. In this study, the size of the pipe rupture was increased to the guillotine break case. There was a region in which a larger pipe rupture did not need a larger siphon breaker, and the water flow rate was related to the size of the pipe rupture and affected the residual water quantity. The timing of air entrainment was predicted to influence residual water level. However, the residual water level was not affected by the timing of air entrainment. The experimental cases, which showed the characteristic of partical sweep-out mode in the separation of siphon breaking phenomenon [2], showed almost same trend of physical properties.

KEYWORDS : Siphon Breaker, Air Sweep-out, Pipe Rupture Accident, Research Reactor

1. INTRODUCTION

Research reactors are nuclear reactors which were developed for research using neutrons rather than power generation. In open-pool type research reactors, water in the reactor pool acts as the moderator, reflector, and shielding barrier to radioactivity from the nuclear reactor fuel rods. Moreover, the coolant in the reactor pool provides an ultimate heat sink during accidents in which the primary cooling pump stops working. For these reasons, the water level in the reactor pool must be maintained higher than the minimum safe level. However, during the operation of a research reactor, accidents having to do with the fluid system (e.g., rupture of pipe, malfunction of valve, or trouble with pump) can occur. If the pipe ruptures, the siphon phenomenon causes continuous loss of coolant from the reactor pool until the water level in the pool reaches the level of the rupture. In extreme cases, the nuclear fuel rods in a reactor pool would be exposed to ambient air. To keep the reactor core safe when a fluid system accident occurs, fluid system devices must be installed above the safe region. However, because of specific design needs (e.g., required Net Positive Suction Head), the piping or pump could potentially be installed below the reactor pool. To avoid this type of accident, use of a siphon breaker has been suggested as one nuclear safety device for research reactors. The siphon breaker would stop the siphon phenomenon and maintain the coolant level in the reactor pool above the level required for safety.

The siphon breaking phenomenon is transient, turbulent, and two-phase flow. Because of the complexity of the phenomenon, appropriate models or correlations that describe it do not exist. Previous research on siphon breakers was not conducted analytically even though siphon breakers are already used in many industrial applications [1-6]. Researchers have studied siphon breakers for individual purposes, however some technical reports do not develop understanding of the siphon breaking phenomenon with the analysis in two-phase flow. McDonald and Marten [1] used a solenoid valve as an actively-operating siphon breaker to block the reverse flow of sodium in a sodium-graphite reactor. They focused on the pressure drop in the piping system but did not conduct direct comparison with experimental results. Neill and Stephens [2] performed an experimental study of a siphon breaker. They controlled the flow rate of water and air by using various sizes of orifice and measured the flow rates and pressures in diverse positions. They also developed the concept of sweep-out mode (zero, partial, and full sweep-out mode) and used that concept to explain the siphon breaking phenomenon. However, they could not find a relationship between the results of experiments and the results of the nuclear system code RELAP 5. Sakurai [3] conducted experiments on siphon breaking and tried to develop a numerical model with a fully separate air – water flow model. The suggested model could be defined as zero sweep-out mode from Neill and Stephens [2]. It matched the experimental results well, but the authors compared only two cases. Furthermore, the scale of the experimental facility was too small to apply to a full-scale research reactor. Kang et al. [4] studied the siphon breaking phenomenon in a full-scale experimental facility. They attempted to visualize the siphon breaking phenomenon and analyzed it by comparing pressure and water flow rate changes to the visualized image. They also conducted the experiment with various experimental variables: the rupture position and size of pipe rupture, the type and size of siphon breaker, and the existence of core pressure drop. Seo et al. [5] performed numerical simulation using a commercially-available CFD code and compared outputs to experimental results. They found that the CFD results using an inhomogeneous model agreed well with the experimental data, however result of numerical simulation was compared a little cases of experiments. Lee et al. [6] tried to develop an analytical model of a siphon breaker and it matched results well with the variable of pipe rupture position. This model should be verified with other experimental variables.

In the previous study by Kang et al. [4], a 10-inch rupture was considered as the maximum value. However, some need on study the guillotine break of a main pipe was introduced, i.e., a 16-inch pipe rupture, in this study, for the safety design of research reactors. Interest in the trend of the effect of pipe rupture size also causes a need for experiments that consider large pipe ruptures. Previous results [4] have shown that as pipe rupture size increased, the required size of siphon breaker to guarantee a safe range of undershooting height also increased. The curiosity was evaluated that the relationship between pipe rupture size and siphon breaker size was kept on the cases of the large size of pipe rupture. In addition, the time when air began to flow into the main pipe determined the timing of the start of the siphon breaking phenomenon. Therefore, in the present study, the effect of timing of air intake was also evaluated by different end positions of the siphon breaker with the same size of siphon breaker. The experiments were designed and conducted to evaluate the effects of the variables mentioned.

The present study has two detailed objectives. The first one is an investigation of pipe rupture size all the way to a full guillotine break, and the second one is to study the effect of air penetration timing.

2. EXPERIMENT

The experimental facility was established outdoors with an open pool. All tests were conducted at ambient atmospheric pressure and temperature. For simple and convenient presentation, British units are used rather than SI units for the size of pipes (Table 1). The size in SI units means the inner diameter of each pipe.

2.1 Experimental Facility

For the objectives of this study, the previous experimental facility [4] was used and modified to allow a wider range of experimental variables. (Fig. 1) An upper tank mimics the reactor pool. It had a capacity of 60 m^3, with a 4-m depth considering the margin to avoid exposing the fuel rods to air in a real reactor. The main pipe through which most of the water flows was 16 inches in diameter. On the starting point of the 16-inch main pipe, an orifice assembly was attached to mimic the effect of the pressure drop caused by the reactor core. The design condition of the orifice was 110 kPa of pressure difference at 6 m/s of water velocity. A ruler marked in 5 cm increments was installed on the wall of the upper tank and recorded using a camera in each experiment. The pipe rupture position was chosen to mimic the position at which the pipe break would occur in a real situation. A butterfly valve controlled by an air compressor was used to simulate the sudden break of the pipe. At the pipe rupture position, the flange was installed to change the pipe rupture size. The height from pipe rupture to the end of the siphon break line was 11.6 m and that from the pipe rupture to the bottom of the upper tank was 8.3 m. In this study, the pipe rupture size considered was enlarged from 10 inches [4] to 16 inches. From the previous study [4], the enlarged pipe rupture size needed an enlarged siphon breaker, so the size of the connection pipe between the main pipe and

Table 1. Pipe Size in SI Unit

Pipe size(inch)	Inner diameter SI unit size(mm)
2.0	53.2
2.5	69.0
3.0	81.0
4.0	105.3
5.0	130.1
6.0	155.5
12	304.5
14	340.4
16	390.6

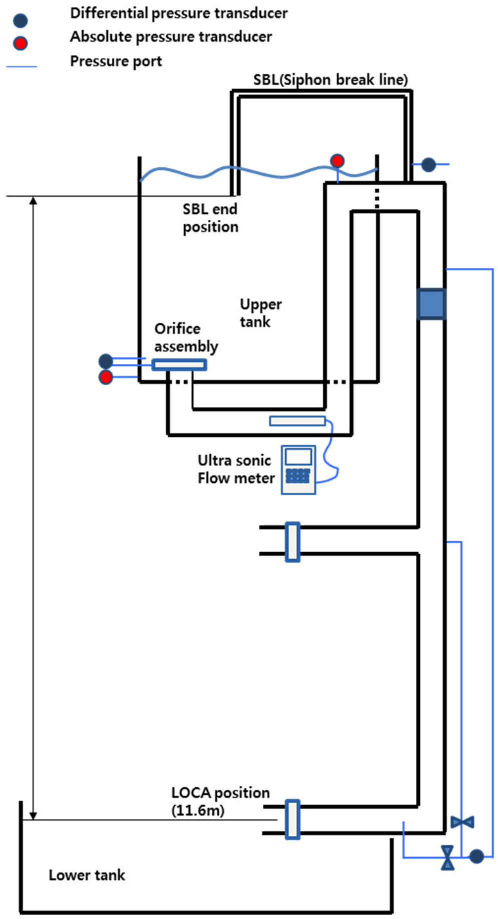

Fig. 1. Schematic Diagram of the Siphon-break Experimental Facility

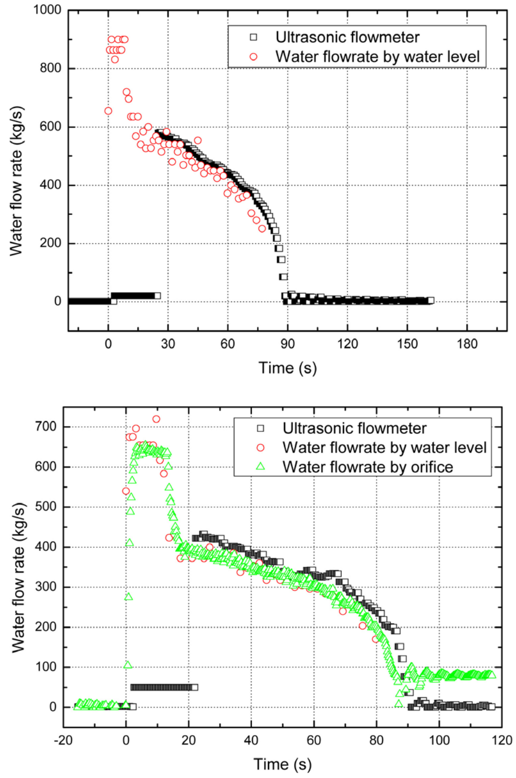

Fig. 2. Comparison of Water Flow Rate Data with Different Methods: (Upper) Case without Orifice and (lower) Case with Orifice

siphon break line was also increased from 3 inches to 6 inches. By increasing the size of this connection pipe, the available size of the siphon break line was also increased to 6 inches.

2.2 Measurements

Several devices were installed to record the physical information. Two absolute pressure transducers (APTs) (CTE9000, Sensor Technics; 0.05% full-scale error) were used. One was installed at the bottom of the upper tank to measure the water level, and was compared with the ruler on the upper tank. The other APT was used to measure the negative pressure at the connection between the main pipe and the siphon break line, because the negative pressure caused by the water flow is the source of the force that causes air inhalation.

Three differential pressure transducers (DPTs) (C230, Setra; 0.25% full-scale error) were used. One was installed to measure the pressure drop through the orifice and one was installed through the main pipe to measure the pressure drop of two-phase water-air flow. Because of the installation characteristics, the measured differential pressure showed the change of the average density compared to water density. The high-pressure port was filled with single-phase water and the low-pressure port developed void as siphon breaking progressed. The third DPT was installed through the siphon break line. The low-pressure port was connected to the siphon break line at the position before the connection of the main pipe and siphon break line. This DPT was used to confirm the value measured by the second APT; the measured values were almost the same within the error ranges.

To measure the water flow rate, an ultrasonic flow meter (UFP-20, Tokyo Keiki; resolution 0.01 m^3/h) was used (Fig. 1). However, at the start of each experiment the water flow rate increased suddenly and the device considered this to be an erroneous measurement. To remedy this lack of information about initial water flow rate, two methods were used. First, the change of the water level was used. A camera with 30 fps (frames per second) was used to record the water level during the experiment and the water flow rate was calculated from elapsed time and the area of the upper tank when the water level was fixed. The second supplementation method was used when the orifice was installed. The design condition of the orifice could be used to calculate the water flow rate. The water flow rates measured by ultrasonic flow meter, change of water level, and pressure drop at the orifice (Fig. 2) show similar trends and values.

In this study, most of the data were used in the raw condition, so additional uncertainty analysis was not conducted.

3. EXPERIMENTAL RESULTS

This study considered pipe rupture size, siphon break line size, the existence of core pressure drop orifice, and the end position of the siphon break line. 'Undershooting height' was used to evaluate the effectiveness of the siphon breaker. The undershooting height was indicated by the difference of water level during siphon breaking, i.e., the height difference from the end position of the siphon break line to the residual water level. The undershooting height was measured using a ruler attached to the upper tank wall, and by an APT. The ruler has uncertainty of 2.5 cm and the APT has uncertainty of 1 cm.

Siphon breaking started when air began to enter the main pipe through the siphon breaker and ended when loss of coolant stopped. Therefore, the water lost before the onset of gas penetration was ignored in consideration of the undershooting height. The measurement point of undershooting height starts from the end position of SBL which is the same level with the center of the horizontal main pipe. There also exists a height difference of 20cm between the end of the SBL position and the bottom of the horizontal main pipe. The 20 cm of undershooting height is the minimum value which should be possible in this definition of undershooting height, because the difference of hydraulic head would cause the continuous flow of water after the end of siphon breaking. As undershooting height increased, the safety factor of the installed or designed siphon breaker decreased.

3.1 Pipe Rupture Size Effect on Undershooting Height

In this study, a larger pipe rupture was investigated than in the previous study [4]. The study considered the guillotine break case (16-inch rupture) and partial (12 and 14-inch) rupture of the pipe. For larger pipe rupture sizes, the range of size of the siphon break line was expanded to 6 inches. Six cases (2, 2.5, 3, 4, 5, and 6 inch) of siphon breaker line sizes were tested. All of the siphon break lines had the same geometry except the diameter, and the end position of the line where air entered also had the same height; i.e., 330 cm from the bottom of the upper tank.

Pipe rupture size affected undershooting height at all sizes of siphon break line (Fig. 3). As the size of the siphon breaker decreased and the size of the pipe rupture increased, the undershooting height increased. The effect of the pipe rupture size was not shown for ruptures greater than 14 inches and this result differs from a previous study [4]. In design aspect, the safe region was set below 50 cm, so the undershooting height with more than 50 cm was considered as a case of failure. From the experimental results, the 4-inch siphon break line is enough to maintain the water level in the safe region. Especially, this study was conducted without the core pressure drop orifice and it meant the case was tested on conservative conditions. Therefore, more safety margin could be obtained by employing a 4-inch siphon break line in this dimension of facility.

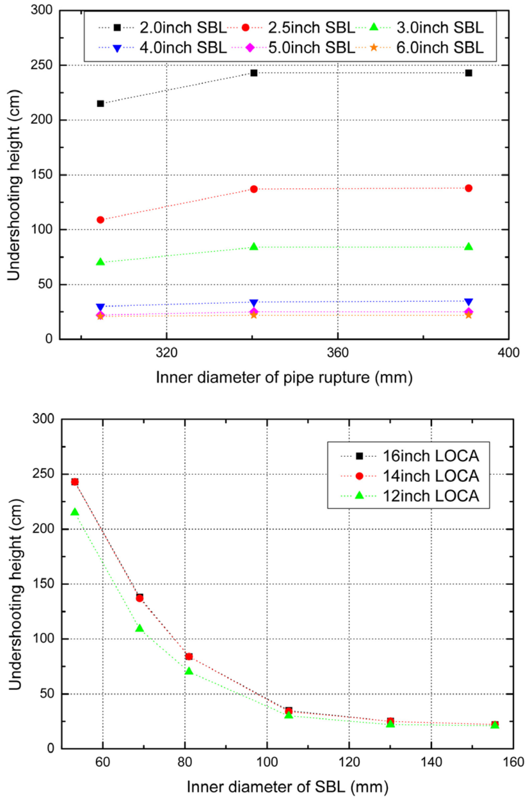

Fig. 3. Undershooting Height Result of Siphon Break Line with Pipe Rupture Size (no Core Pressure Drop Orifice Cases)

The effect of the core pressure drop orifice was also investigated with various pipe rupture sizes and various sizes of siphon break line. As in the cases without the orifice, a larger siphon break line showed decreased undershooting height. However, the effect of the pipe rupture size was not shown in these cases. Undershooting height distribution was decreased by core pressure drop at the orifice (Fig, 4); these results are almost the same as those of the previous experiments [4].

3.2 Water Level Change with Different Position of Siphon Break Line end

In this study, the effect of timing of air penetration was investigated. The size of the siphon break line was chosen as 3 inches and the study focused on a 12-inch pipe rupture because that case had a relatively lower water flow rate and adequate undershooting height to observe the siphon breaking phenomenon. The difference of air penetration timing could be achieved by choosing the height of the end position of the siphon break line to between 310 and 350 cm from the bottom of the upper tank.

Although the time when the air penetrated differed, the siphon breaking finished at the same final water level (Fig. 5). The water level was recorded using a camera and showed good repeatability in replicate trials. However, the undershooting height was dependent on the height of the end of the siphon break line. Therefore the final water level should also be considered.

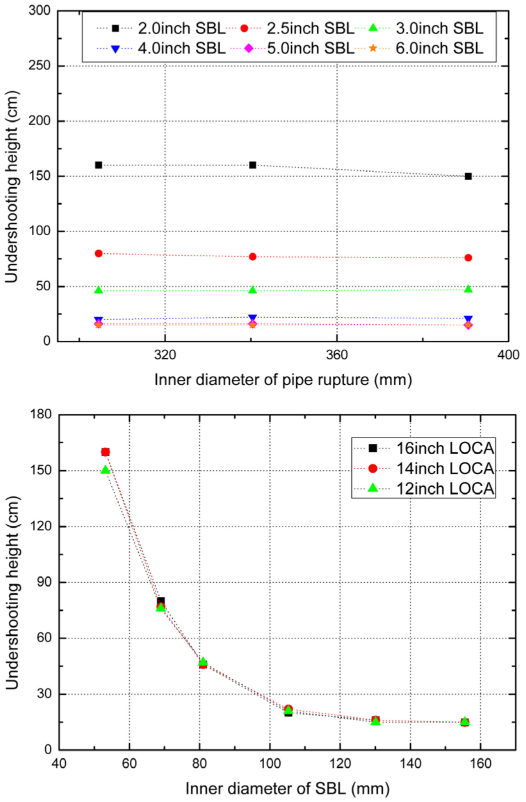

Fig. 4. Undershooting Height Result of Siphon Break Line with Pipe Rupture Size (with Core Pressure Drop Orifice Cases)

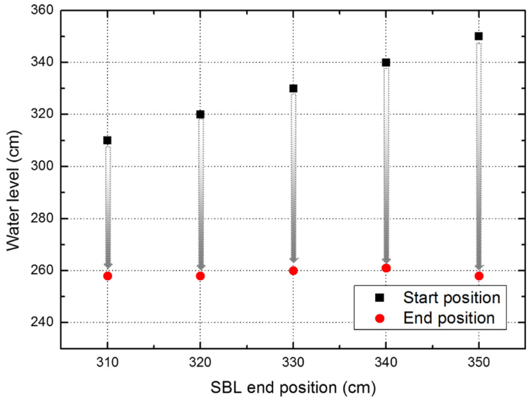

Fig. 5. Water Level Change during Siphon Breaking with Different Start Position of Siphon Break Line

4. DISCUSSION

4.1 Analysis on the Effect of Large Pipe Rupture Size

In previous research [4], the undershooting height increased continuously as the size of the pipe rupture increased. Therefore, the necessary size of the siphon breaker had to be increased to keep the undershooting below the desired height. However, in this study, the undershooting height was the same for 16-inch and 14-inch pipe ruptures (Fig. 3 and 6). In the linearity, there was a gap between the previous cases [4] and present cases. The connection pipe between the main pipe and siphon break line was enlarged in this study and inhaled air met the water flow at the end of the connection pipe. The pressure at the mixing zone is the origin force to entrain the air and that pressure is mainly caused by water flow. Therefore, the velocity of air is mostly determined by water velocity. The enlarged connection pipe influenced to the friction loss of the siphon break line but the little amount was changed by enlargement of the connection pipe. The comparison between the pipe rupture size and water flow rate (Fig. 7) showed a similar trend to the comparison between the pipe rupture size and undershooting height (Fig. 6). It could be demonstrated that the water flow rate

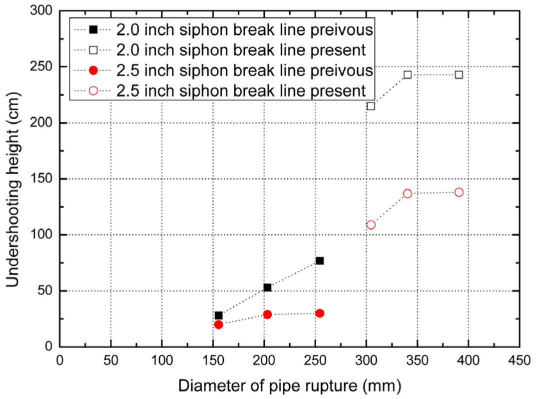

Fig. 6. Undershooting Height with the Inner Diameter of Pipe Rupture

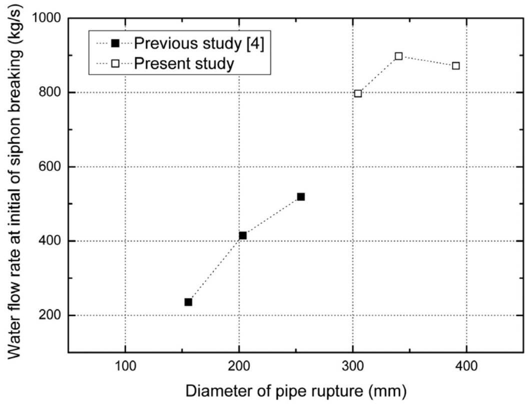

Fig. 7. Pipe Rupture Size Effect to Water Flow Rate at the Start Point of Siphon Breaking

or water velocity at the connection point is the most influential factor to the siphon breaking phenomenon. The mentioned gap would be caused by the water flow rate jump from a 10 inch pipe rupture to the 12 inch rupture. This is the reason for the gap.

The size of pipe rupture affected the water flow rate with the hydraulic height. (Fig. 7). The water flow rate at the onset of siphon breaking was ~800 kg/s for a 12-inch pipe rupture and ~900 kg/s for 14- and 16-inch pipe ruptures. For 14- and 16-inch pipe ruptures, the water flow rates were the same, as was observed for the undershooting height. In the region near a larger pipe rupture, the water flow rate could not increase with increasing pipe rupture size, so the required size of the siphon breaker did not increase. The experiments with the orifice supported this conclusion because the water flow rate was ~650 kg/s in all cases with an orifice. The undershooting height showed a regular relation to the water flow rate with different sizes of siphon break line (Fig. 8). Especially at the undershooting height > 30 cm, the data showed better linearity. In this study, the minimum undershooting height could exist because of the hydraulic head of water with a given end position of the siphon break line. Therefore, this relationship between the water flow rate and undershooting height could be helpful in the development of models of siphon breaking.

4.2 Division of Sweep-out Mode in Siphon Breaker Test

Neill and Stephens [2] developed the concept of sweep-out mode to categorize the siphon breaking phenomenon. As in this study, they measured the pressure drop on two-phase water-air flow and used the slope of the pressure trend to separate sweep-out into three modes: zero sweep-out, partial sweep-out, and full sweep-out (Fig. 9). The zero sweep-out mode and partial sweep-out mode had the same size of water orifice with different sizes of air orifice, while the full sweep-out had larger sizes of water and air orifices. In zero sweep-out mode, the air inhaled through the siphon breaker did not flow out with the water but instead stacked at the head of the pipe, so the differential pressure increased linearly. In partial sweep-out mode, the pressure drop increased with uniform slope as in zero sweep-out mode but the rate of pressure drop decreased after a certain point. As the air developed a path out of the main pipe through the water flow path, it showed the characteristic of zero sweep-out mode, but after formation of the air path, part of the inhaled air flowed out and the rest remained stacked at the head of the main pipe. Therefore, the slope of pressure drop showed a decreased trend compared to zero sweep-out mode. In full sweep-out mode, a region of zero pressure change existed after the short region of zero sweep-out mode because all of the inhaled air flowed out with the water. In all cases which showed full sweep-out mode, siphon breaking failed, i.e., entrainment of air could not block the siphoning of coolant until the water level dropped below the allowed level.

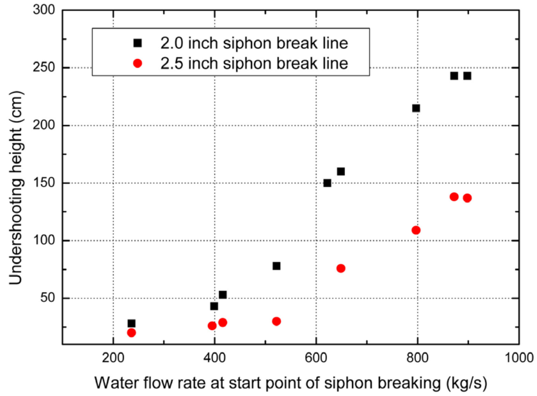

Fig. 8. Undershooting Height with the Water Flow Rate at the Start Point of Siphon Breaking

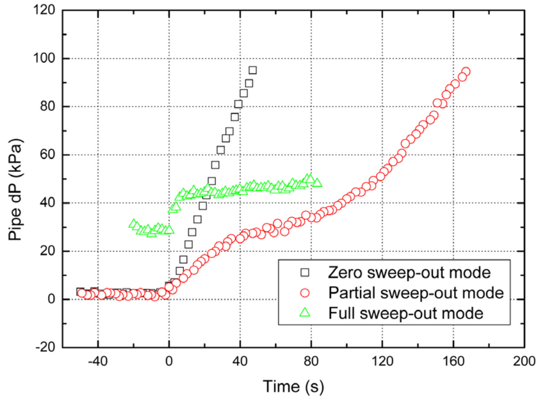

Fig. 9. Different Differential Pressure Trend with Air Sweep-Out Mode [2]

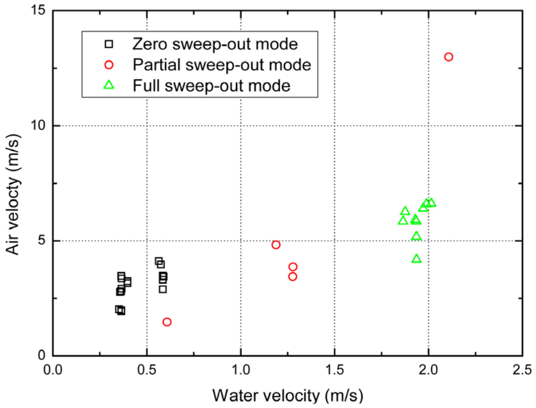

Fig. 10. Air Sweep-out Mode Distribution with Combination of Velocities of Water and Air [2]

It is sure that the momentum of air and water is the most important parameter. The combination of air velocity and water velocity would influence the formation of air sweep-out. Therefore, we plotted Neill and Stephens's experimental results of water velocity to air velocity (Fig. 10). The water velocity continuously decreased during siphon

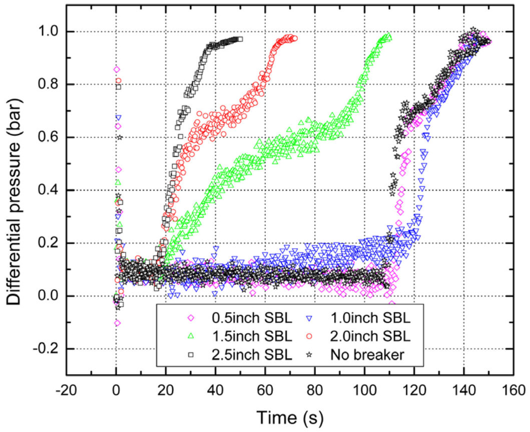

Fig. 11. Differential Pressure Trends at 10 inch Size of Pipe Rupture with Various Size of Siphon Break Line in Previous Research [4]

breaking, so the water velocity at the onset of breaking was used to represent this rate. Moreover, the values of water velocity and air velocity were chosen at the mixing zone, because the inhaled air would act as the resistance to the water flow, so the start position of water-air mixing was considered most important. As shown in Fig 10, air sweep-out mode was developed at increased water velocity. However, less developed air sweep-out mode was shown at the high velocity of air even though the water velocity showed almost the same value. Air velocity was mainly influenced by water velocity but air velocity also affected the formation of air sweep-out mode.

In this study, much larger sizes of the main pipe, siphon breaker, and pipe rupture were considered compared to the facility that Neill and Stephens used. The size of pipe rupture is the most significant factor that determines the water flow rate; therefore, the flow rate of water was absolutely greater in this experimental facility at the pipe rupture sizes considered. In addition, in the 10-inch pipe rupture experiment (Fig.11), the differential pressure data of two-phase water-air flow tended to show the development of air sweep-out, similar to the results of Neill and Stephens [2]. Air sweep-out was developed with the decreasing size of siphon break line. At a 2.5 inch siphon break line, the zero sweep-out mode was observed and the partial sweep-out mode was observed at the 2.0 and 1.5 inch of siphon break lines. Below the 1.0 inch siphon break line, the siphon breaker failed to break the siphon phenomenon before emptying the water in the upper tank and it showed the characteristics of full sweep-out mode.

4.3 Effect of Air Penetration Timing with Sweep-out Mode

The experiment with a 12 inch pipe rupture and a 3 inch siphon break line was selected to investigate the effect of different timing of air penetration. The differential pressure trend of the selected case (Fig. 12) showed the characteristic of partial sweep-out with sudden decrease of the slope of differential pressure during siphon breaking.

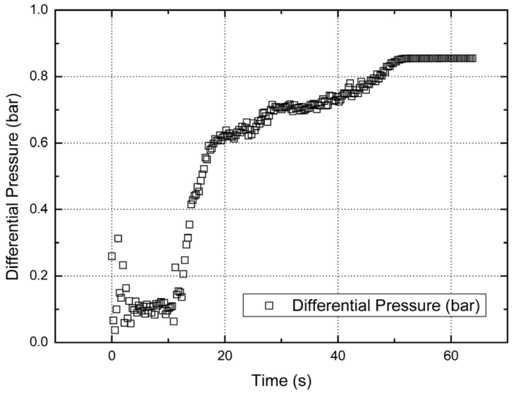

Fig. 12. Differential Pressure Trends at 12 inch Size of Pipe Rupture and 3 inch Size of Siphon Break Line

The gradient of the differential pressure decreased during partial sweep-out mode. Due to the nature of the DPT installation, the gradient of the differential pressure could represent the effect of the decreased average density compared to single-phase water density. The pressure drop by the flow was much less than that by the change of the average density, so the change in measured differential pressure was considered to result from the air volume fraction or the void fraction. From the absolute pressure data, the negative pressure, which causes inhalation of air through the siphon breaker, remained almost the same, so the air flow rate could also be considered constant. With a constant air flow rate, the steady pressure drop meant that all inhaled air flowed out without stacking (i.e., full sweep-out mode). Similarly, the slope of pressure drop between zero sweep-out mode and full sweep-out mode was named partial sweep-out mode.

Water flow rate, pressure drop through the two-phase water-air flow, and pressure drop on siphon break line were plotted for various end positions of the siphon break line (Figs. 13-15). Time ‘0’ was set as the end of siphon breaking. When air flowed into the main pipe, the water flow rate suddenly decreased (Fig. 13). The onset of partial sweep-out mode could be identified by inspecting the trend of pressure drop (Fig. 14). Together, these figures indicate that the water flow rate suddenly decreased before the beginning of partial sweep-out mode and the decreased water flow rate in partial sweep-out mode showed almost the same value in all different cases; i.e., the water flow rate decreased more rapidly when the timing of air entrainment was late than when it was early. Regardless of the timing of air entrainment, the pressure drop at the onset of siphon breaking (Fig. 15), which indicates the air flow rate, was identical in all cases.

If the sweep-out mode showed the characteristic of the zero sweep-out mode, the timing of air entrainment influenced the undershooting height rather than the final water level, because in this mode the air was stacked continuously until the end of siphon breaking. The time tak-

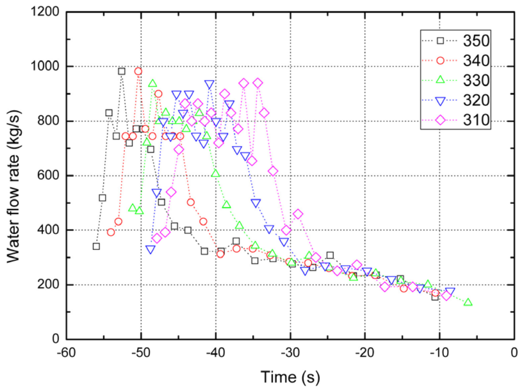

Fig. 13. Water Flow Rate Change with Various Position of Siphon Break Line end

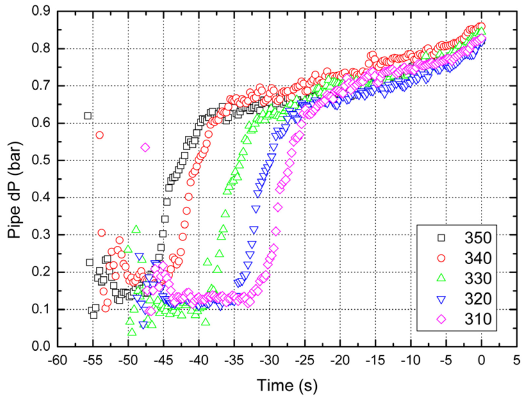

Fig. 14. Pipe Differential Pressure Change with Various Position of Siphon Break Line end

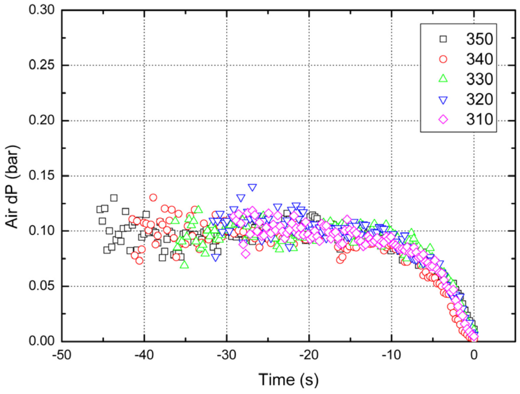

Fig. 15. Differential Pressure on Siphon Breaking Line with Various Position of Siphon Break Line end

en until the onset of siphon breaking may be the significant value. However, during partial sweep-out mode, the final water level was the same, so the time until the onset of siphon breaking cannot be considered a dominant variable. The criterion by which to separate sweep-out modes requires further study. In addition, when a model to predict residual water quantity is established, the characteristics of sweep-out mode should be considered.

5. CONCLUSION

In this study, the characteristics of large-scale siphon breaking were investigated. Large pipe rupture size was considered and analyzed with respect to water flow rate. The effect of air entrainment timing was also studied using the concept of air sweep-out. The findings of this study are:

1. The effect of pipe rupture size was investigated for the guillotine break case. A region existed in which a larger pipe rupture did not need a larger siphon breaker, and the water flow rate was related to the size of the pipe rupture and affected the undershooting height.
2. The siphon breaking phenomenon could be classified according to three modes of air sweep-out: zero sweep-out mode, partial sweep-out mode, and full sweep-out mode. The air sweep-out developed from zero sweep-out mode to full sweep-out mode with increasing water flow rate and decreasing air flow rate.
3. With the same size of pipe rupture and siphon break line, the same residual water level showed with various air entrainment timings and this result was explained with the characteristic of partial sweep-out mode.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. NRF-2012M2C1A1026909).

REFERENCES

[1] J. McDonald and W. Marten, “A Siphon Break as a Blocking Valve”, *Standard Distribution Lists for Unclassified Scientific and Technical Reports* (1958).

[2] D. T. Neill and A. G. Stephens, “Siphon Breaker Design Requirements Final Report”, *USA DOE*, Mar., 1993

[3] F. Sakurai, “Study for Improvement of Performance of the Test and Research Reactors”, *JAERI* (1999)

[4] S. H. Kang, H. S. Ahn, J. M. Kim, H. M. Joo, K. Y. Lee, K. Seo, D. Y. Chi, J. Yoon, G. D. Jeun and M. H. Kim, “Experimental study of siphon breaking phenomenon in the real-scaled research reactor pool”, *Nuclear Engineering and Design*, Vol. 255, pp. 28-37 (2013)

[5] K. Seo, S. H. Kang, J. M. Kim, K. Y. Lee, N. Jeong, D. Y. Chi, J. Yoon and M. H. Kim, “Experimental and numerical study for a siphon breaker design of a research reactor”, *Annals of Nuclear Energy*, vol. 50, pp. 94-102 (2012)

[6] K. Y. Lee, K. Seo, D. Y. Chi, J. Yoon, S. H. Kang and M. H. Kim, “Experimental and analytical studies on the siphon breakers in research reactor”, IGORR 2012 European research reactor conference, Prague, Czech Republic, Mar. 18-22, 2012.