Proceedings of the Korean Nuclear Society Spring Meeting
Gyeong ju, Korea, May 2003

# Liquid Entrainment and Off-take at the Top of the Pressurizer in the case of the actuation of Safety Depressurization System of APR1400

Chang Hyun Kim and Hee Cheon NO
Korea Advanced Institute of Science and Technology
371-1 Kusong-dong, Yusong-gu, Taejon, 305-701, Korea

**Abstract**

In order to determine the bleed capacity of Safety Depressurization System (SDS) of Advanced Power Reactor 1400 (APR1400) in case of Total Loss of Feed Water (TLOFW), we performed an experimental study of liquid entrainment and liquid off-take from the swelled two-phase mixture surface in a vessel. A total of 208 experimental data on the entrainment and off-take are obtained using a test vessel with the height of 2.0m and the inner diameter of 0.3m having a top break with diameter of 0.05m. Two-phase mixture levels are measured by the ultrasonic sensor within ±1.77% with respect to the visual level data. Droplet entrainments are measured and compared with the existing pool entrainment data. The empirical correlation for the onset of off-take is developed in terms of the Froude number ($Fr_g$) at the break and non-dimensional inception height ($h_b/d$). This correlation shows agreement with the present experimental data within ±15%. The present off-take quality data is in agreement with Schrock's off-take quality correlation with the r.m.s. error of 15.8%. In the present experiment, droplet entrainment $E_{fg}$ strongly depends upon $j_g^*/h^*$ and is proportional to the 7$^{th}$ power of $j_g^*/h^*$ in the same way as the off-take data.

## 1. INTRODUCTION

The entrainment is a consequence of dynamic interactions between the liquid and the flowing gas and this phenomenon may occur whenever two phases are brought into contact and when their relative motion is particularly large. The entrainment of liquid by gas flow is often encountered in various areas of engineering applications associated with heat and mass transfer.

There are several different entrainment mechanisms depending on two-phase flow regimes. The first is the entrainment from annular dispersed flow. At this flow regime, an onset of entrainment criterion, a correlation for the amount of entrained droplets, a correlation for droplet size and its distribution, and a correlation for entrainment have been developed based on the shearing-off mechanism of roll-wave crests by a highly turbulent gas flow [1]. The second is the entrainment from a liquid pool by gas flow in boiling or bubbling. As for the pool entrainment in boilers, some experimental works have been carried out and several empirical correlations have been proposed [2-7]. The third mechanism is liquid entrainment or liquid pull-through at the T-junction during Small Break LOCA and Mid-Loop Operation. For the case of an upward oriented break concerned with the present study, the correlations for the onset of off-take and off-take quality have been developed for both air-water and steam-water systems [8, 9].

Recently the Advanced Power Reactor 1400 (APR1400) has adopted an advanced design feature of a safety depressurization system (SDS) to rapidly depressurize the primary system in case of events beyond the design basis accident such as Total Loss of Feed Water (TLOFW). While the pressure of the primary system is rapidly decreased, the two-phase level swelling occurs and a large amount of liquid can be discharged due to the off-take through the SDS valves acting as the top break. Therefore, an important aspect of the SDS design is the determination of the bleed capacity of the SDS connected to the top of the pressurizer. C.H. Kim, et al.[10] have performed the comparison of the RELAP5 results with their experimental data in the case that off-take took place through the break at the top of the vessel during depressurization. The axial void profile and the discharged mass flow rate predicted by RELAP5 did not agree with their experimental data. It is, therefore, a considerable interest to understand the factors that affect the entrainment and to be able to predict the amount of liquid carried away through the break by the gas phase from the swelled two-phase mixture surface.

From the review of the existing works on the liquid entrainment and off-take, the following two deficiencies arise:

1. Almost existing works for the entrainment from the liquid pool have been performed for the case that liquid splashes do not reach the vapor line at the top of the vessel.
2. There are no available works on the liquid off-take from the surface of a liquid pool through the break at the top of the vessel.

In this paper, therefore, a series of experiments are performed to investigate liquid entrainment and off-take through the break at the top of a vessel. Experimental data are obtained for the droplet entrainment, the criterion for the onset of off-take through the top break of the vessel, and off-take quality.

## 2. EXPERIMENTS

A series of experiments were performed and a total of 208 experimental data for the liquid entrainment and off-take are obtained using a test vessel with the height of 2.0m and the inner diameter of 0.3m for bubbly and churn-turbulent flow conditions for various air flow rates and distances from the inlet of the air discharge pipe to the two-phase mixture surface. The test matrix is shown in Table 1.

### 2.1. Experimental Apparatus

A schematic diagram of the experimental apparatus is shown in Fig. 1. The main components of the system were the test vessel, the air supply system, the air-water separator, the water reservoir and their associated piping systems, and the data acquisition system.

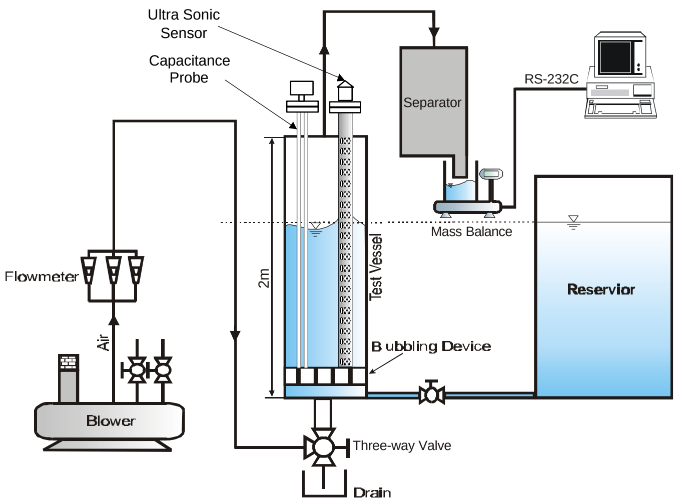


Fig. 1 Schematic diagram of experimental apparatus.

The test vessel is made of a 2 *m* long transparent Pyrex pipe with diameter of 0.3m to enable visual observations of the flow pattern and variation of the two-phase mixture level. Air is supplied to the bottom of the test vessel. The uniform bubble generation is achieved by a bubbling device, which has a number of small holes of 5mm diameter, installed in the lower part of the vessel. The air flow rate is measured at the air supply pipe by rotameters. The air discharge pipe with diameter of 50mm is connected at the top of the vessel. The entrained water passes through the air discharge pipe and then separated from air in the air-water separator.

The weight of entrained water is measured by two online electronic mass balances having the accuracies of ±1.0g and ±0.1g, respectively. A water reservoir is connected to the bottom of the test vessel to make up for loss of water inventory in the vessel as a result of liquid entrainment/off-take. Two-phase mixture level is measured by the ultrasonic sensor installed at the top of the vessel. A waveguide, which has a number of holes with diameter of 20mm with vertical interval of 100mm, is installed in the test vessel to reduce the loss of echo signal by the attenuation effect and the diffused reflection from the fluctuated two-phase mixture surface.

### 2.2 Test Parameters and Test Matrix

The major test parameters in the present work were the air flowrates and the distance from distances from inlet of air discharge pipe to two-phase mixture level. A total of 229 experimental data were obtained for various combinations of test parameters under atmospheric pressure condition, as summarized in Table 1.

The range of air flowrate was 300 – 1500 LPM, which corresponds to 0.07 – 0.35 m/s in terms of the superficial air velocity in the vessel. The range of distance from the two-phase mixture surface to the inlet of the air discharge line was 0.1 – 1.0 m, which corresponds to 50 – 90% of two-phase mixture level with respect to the height of the test vessel.

Table 1 Test matrix of the present experiment

| Type of Experiments | Air Flowrate [LPM] ($j_g$ [m/s]) | Collapsed Liquid Level, $L_c$ [m] | Two-Phase Mixture Level, $L$ [m] | Number of Data |
|---|---|---|---|---|
| Two-Phase Mixture Level | 300 – 1200 (0.07 – 0.28) | 0.8 – 1.2 (40% - 60%) | 1.0 – 1.8 (50% - 90%) | 24 |
| Droplet Entrainment | 400 – 1500 (0.01 – 0.35) | 0.5 – 1.5 (25 – 75%) | 1.0 – 1.9 (50% - 95%) | 126 |
| Onset of Off-take | 400 – 1200 (0.09 – 0.28) | 0.9 – 1.5 (45% - 75%) | 1.6 – 1.9 (80% - 95%) | 33 |
| Off-take Quality | 400 – 1400 (0.09 – 0.33) | 0.9 – 1.5 (45% - 75%) | 1.6 – 1.9 (80% - 95%) | 49 |

## 3. RESULTS AND DISCUSSION

### 3.1. Two-Phase Mixture Level

Two-phase mixture level measurement is very important because the distance between two-phase mixture surface and the inlet of the air discharge line is one of the important parameters in the present liquid entrainment/off-take experiment. Two-phase mixture levels have been measured by visual observation and ultrasonic sensor developed by D.W. Lee and H.C. NO [11]. The visual levels are obtained from the averaged values which are determined from the still images of the motion pictures recorded by the video camera. Figure 2 shows the comparison of ultrasonic sensor data with the visual level data. The ultrasonic sensor measured two-phase mixture level with maximum error of ±1.77% with respect to the visual level data.

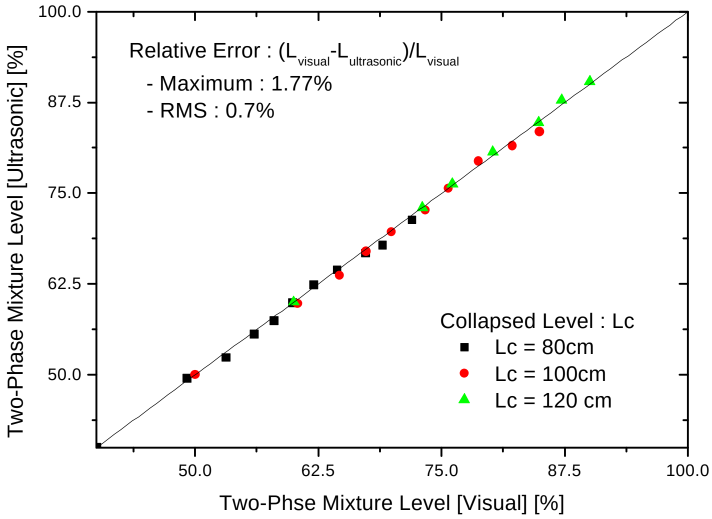


Fig. 2 Comparison of ultrasonic sensor data with visual level data.

### 3.2. Droplet Entrainment

The entrainment, which is the ratio of the droplet upward mass flux $r_f j_{fe}$ to the gas mass flux $r_g j_g$, is measured experimentally by some researchers [3-6]. Here, $j_{fe}$ is the superficial velocity of liquid flowing as droplets, and $j_g$ is the superficial velocity of gas. Thus the entrainment is defined as

$$E_{fg} \equiv \frac{r_f j_{fe}}{r_g j_g}. \tag{1}$$

The experimental data show that the entrainment $E_{fg}$ is a strong function of the gas superficial velocity $j_g$ and the distance from the surface of a pool $h$. When the entrainment is plotted against the superficial gas velocity at a fixed distance $h$, at least, three entrainment regimes can be observed [2]. In a low gas flux regime, the entrainment is small and entrained liquid consists of very fine droplets. In this regime, $E_{fg}$ is approximately proportional to the gas flux. In an intermediate regime, larger drops are ejected from a pool and $E_{fg}$ increases with $j_g{}^{3-4}$. At a higher gas flux, large gas slugs are formed and a pool is highly agitated. Then a considerable amount of liquid can be entrained by splashing. In this high gas flux regime, $E_{fg}$ increases very rapidly with the gas flux, i.e., $E_{fg} \sim j_g{}^{7-10}$.

There are three entrainment mechanism generally accepted by considering the conditions under which droplets are projected: splashing, bursting, and foaming. Although there have been some researches on the liquid entrainment from a liquid pool by gas flow, they have been performed for the application to the evaporators, desalination, and so on [2-6]. Their governing mechanisms of the entrainment are bursting of bubbles and foaming. The experimental data of the entrainment, $E_{fg}$, are proportional to $j_g{}^{3-4}$.

According to Sterman, et al.[4] and Yeh and Zuber [7], if the expansion of the two-phase mixture is such that the liquid splashes may reach the exhaust line, the liquid entrainment will rapidly increase with increasing gas velocities. In this regime, the amount of entrainment is proportional to the $7^{th}$-$20^{th}$ power of the gas flow $j_g$. Therefore, most of the existing experimental data and developed correlations are valid provided that liquid splashes do not reach the vapor line at the top of the vessel.

The liquid entrainment from the liquid pool by air flow with the top break of a vessel has been investigated experimentally. The present experiment, the entrainment $E_{fg}$ has been measured with the various combinations of parameters of distance from the surface and the top of the test vessel $h$ and the superficial air velocity in the vessel $j_g$. Figure 3 shows the present entrainment data in plot of $E_{fg}$ versus $j_g^*/h^*$ where $j_g^*$ is the superficial velocity in the test vessel. The entrainment $E_{fg}$ was fairly proportional to the $7^{th}$ power of $j_g^*/h^*$. It may possible to make a dimensionless correlation based on the present experimental data for this case. However, such a correlation is not very useful because it may give an unreasonably high value of entrainment at large $j_g^*/h^*$ due to its high power dependence on $j_g^*/h^*$. In the present experiment, the coefficient of $(j_g^*/h^*)^7$ has been of the order of $10^{20}$.

Figure 4 shows the comparison of the present entrainment data with the existing entrainment data. The experimental conditions of the existing entrainment experiments are summarized in Table 2. The present entrainment data show large differences compared to the existing entrainment data in view of the dependence of $j_g^*/h^*$ on the $E_{fg}$ and the values of $E_{fg}$.

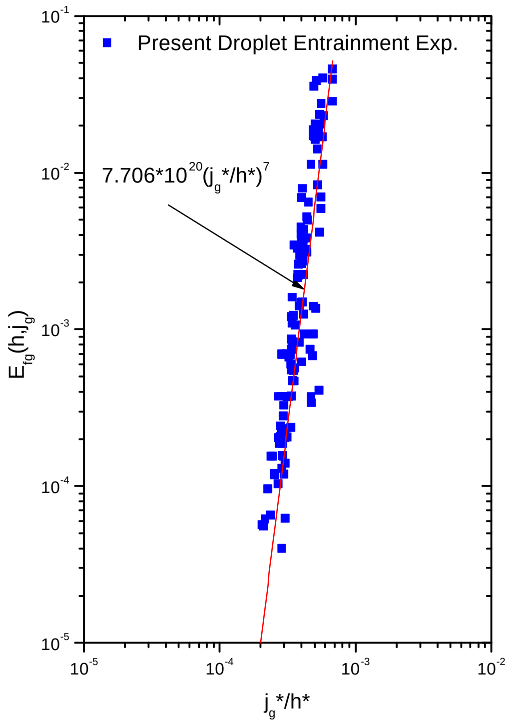


Fig. 3 Present entrainment data in plot of $E_{fg}$ versus $j_g^* / h^*$.

It has been visually observed that large droplets are ejected from the splashed liquid sheets. Some droplets are directly entrained through the break at the vicinity of the inlet of the break; others are fallen back to the surface or deposited at the top of the vessel. With an in crease in air flow, the deposited liquid in the top wall of the vessel is pulled toward the inlet of the break. This liquid being pulled toward the inlet of the break also could contribute to the liquid entrainment. These behaviors of liquid entrainment, which are entraining, depositing, and being pulled consecutively, are observed as an air flowrate increases. A further increase in air flowrate causes to directly pull the splashed liquid sheets through the break as a bulk, therefore, the liquid off-take takes place through the break and the liquid discharge experiences 'lump entrainment'.

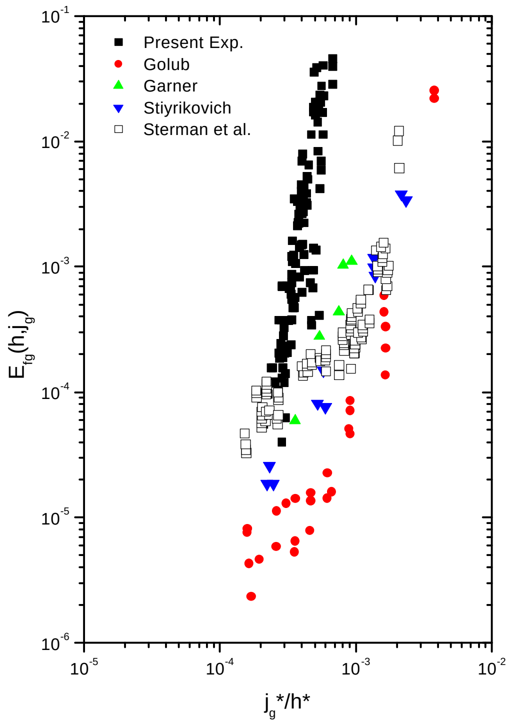


Fig.4 Comparison of the present entrainment data with the existing entrainment data.

Table 2 Summary of various experiments on entrainment amount from liquid pool

| Author | Fluid | Vessel Diameter $D_H$ (m) | Height Above Pool Surface $h$ (m) | Pressure (MPa) | $j_g$ (m/s) |
|---|---|---|---|---|---|
| Present | Air-Water | 0.30 | 0.1 – 1.0 | 0.101 | 0.1 – 0.35 |
| Garner [3] | Steam-Water | 0.30 | 0.5 - 1.0 | 0.101 | 0.3 - 1.3 |
| Sterman et al.[4] | Steam-Water | 0.24 | 0.5 - 0.9 | 1.72-18.7 | 0.01 - 0.3 |
| Styrikovich et al.[5] | Air-Water | 0.10 | 0.26 - 0.72 | 0.11-5.0 | 0.1-1.7 |
| Golub [6] | Air-Water | 0.20 | 0.1 - 2.2 | 0.101 | 0.5-2.0 |

### 3.3. Onset of Off-take

If a break is located at the top of the vessel, there exists the vapor acceleration in the vicinity of the break (Bernoulli effect). As the gas flowrate increases, the liquid-gas interface is agitated so that liquid sheets are splashed in the space above. If the expansion of the two-phase mixture is such that the liquid splashes may reach the vicinity of the break, the liquid off-take takes place and the amount of discharged liquid will rapidly increase with increasing vapor velocities. Figure 5 shows the onset of off-take through of the break in the present experiment. This phenomenon must be distinguished from the droplet entrainment.

Fig. 5 Onset of off-take through the break.

Although there exist the geometrical differences between a liquid pool and horizontal pipe with the top break, it is considered that the same mechanism may govern the off-take for both cases. The liquid off-take takes place in the gas acceleration region in the vicinity of the break by Bernoulli effect.

The inception height, $h_b$, which represents the distance from the surface to the break when the off-take starts to take place, is directly related to the correlations for the off-take quality through the break in the horizontal pipe. The general expression for the onset of off-take in the horizontal pipe can be represented as the following form modeled by Lubin et al.[12]:

$$Fr_g \left( \frac{r_g}{\Delta r} \right)^{0.5} = C_1 \left( \frac{h_b}{d} \right)^{C_2}, \qquad (2)$$

where $Fr_g$ is the Froude number of the flow inducing off-take defined as

$$Fr_g = V_b / \sqrt{gd}, \qquad (3)$$

where $V_b$ is the velocity of the flow inducing off-take, $h_b$ is the inception height, and $d$ is the inner diameter of the break, respectively.

The above equation is used as a general form of the onset of off-take and two coefficients of $C_1$ and $C_2$ are obtained experimentally. In the top break condition, $V_b$ represents the vapor velocity at the inlet of the break.

The present experimental data for the onset of off-take are correlated with the Froude number at the break and non-dimensional inception height. The developed correlation for the onset of off-take is as follows:

$$Fr_g \left( \frac{r_g}{\Delta r} \right)^{0.5} = 0.0764 \left( \frac{h_b}{d} \right). \tag{4}$$

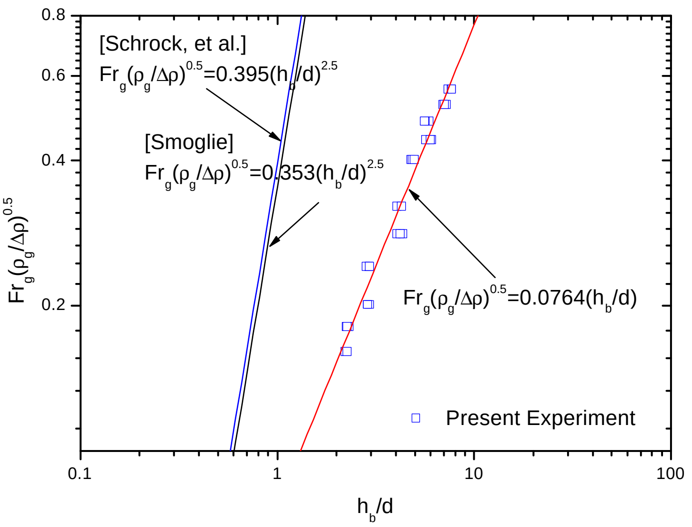


Fig.6 Comparison of the present off-take data with the existing correlations for the horizontal pipe with top break.

Figure 6 shows the comparison of the present off-take data with the correlations of Schrock[8] and Smoglie [9]. This correlation shows agreement with the present experimental data with maximum error of ±15%. In the present experiment, the liquid off-take takes place at the lower air flowrates than those of horizontal pipe flow. In a horizontal pipe flow, the direction of liquid and vapor phases is co-current and liquid-vapor interface remains smooth. To initiate the liquid pull-through in the horizontal stratified liquid surface, a large pressure drop may be required at the vicinity of the break. In a liquid pool, however, there exist violent up and down motions of liquid-vapor interface due to the disintegration of liquid slugs. As the splashed liquid sheets can be reached to the vicinity of the break, the liquid off-take could take place at lower air flowrate compared to that of the horizontal pipe flow with the top break. In the present experiment, The Froude number, which represents the air velocity at the break, is proportional to the inception height.

### 3.4. Off-take Quality

The off-take quality data are obtained with changes of air flowrate and distance from the surface to the break. To obtain the steady-state data, two-phase mixture level is maintained constant by water reservoir connected to the test vessel. The off-take quality is strongly affected by the air flowrate and drastically increased with an increase in the air flowrate.

Schrock, et al.[8] performed the experiments using air-water and steam-water at the maximum pressure of 1 MPa. They developed the off-take quality correlation on the basis of their data together with high quality data of Smoglie[9]. This correlation is implemented into the horizontal stratification entrainment model that simulates the off-take at T-junction geometry in RELAP5/MOD3. Schrock's correlation is expressed as

$$x = \left( \frac{h}{h_b} \right)^{3.25\left(1-\frac{h}{h_b}\right)^2} . \tag{5}$$

Figure 7 shows the comparison of the present off-take quality data with Schrock's ones in plot of x versus $h/h_b$, where $h_b$ means the distance from two-phase mixture surface to the break and is calculated from the present onset of off-take correlation, Eq.(4). Although there are some perturbations in the measured off-take quality data, the present off-take quality data can be correlated with Schrock's off-take correlation developed for the case of the stratified horizontal flow with top break. Schrock's correlation predicts the present off-take data with the root mean square error of ±15.8% in entire range of off-take quality. The fact that Schrock's correlation can be used to the prediction of the off-take quality in the present experimental conditions can be considered as an indirect evidence that the same mechanism governs off-take not only in a horizontal stratified flow with top break, but also in a liquid pool in a vessel with the top break.

Figure.8 shows the present droplet entrainment and off-take data in plot of $E_{fg}$ versus $j_g^*/h^*$. The present droplet entrainment data can be extended on the same line with off-take data. This fact shows the present droplet entrainment has consistency with the present off-take data. Therefore, the reason of strong dependence of $E_{fg}$ on the 7th power of $j_g^*/h^*$ can be considered due to the existence of the gas acceleration region at the vicinity of the break.

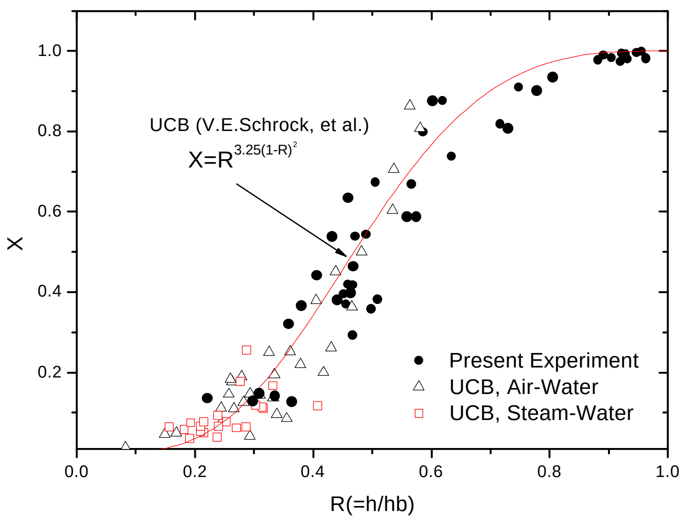


Fig.7 Comparison of the present off-take quality data with Schrock's data.

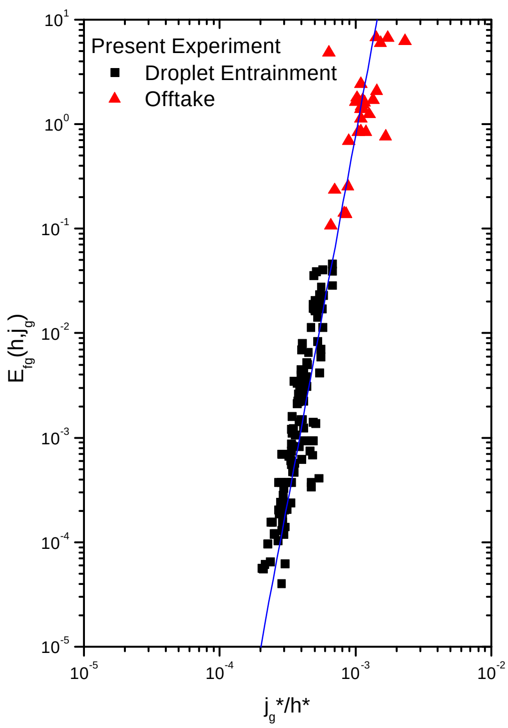


Fig. 8 Present entrainment and off-take data in plot of $E_{fg}$ versus $j_g^* / h^*$.

## 4. COCLUSIONS

We performed an experimental study of liquid entrainment and liquid off-take from the swelled two-phase mixture surface in a vessel in order to investigate the effects of the superficial air velocity in the vessel and the distance between the surface and the break on the liquid entrainment. A total of 208 experimental data on the entrainment and off-take are obtained using a test vessel with the height of 2.0m and the inner diameter of 0.3m having a top break with diameter of 0.05m. Two-phase mixture levels are measured by the ultrasonic sensor with an accuracy of ±1.77% with respect to the visual level data. From the present experimental studies, the following conclusions can be made.

First, the droplet entrainment $E_{fg}$ through the break at the top of a vessel strongly depends upon $j_g^*/h^*$ and is proportional to the 7$^{th}$ power of $j_g^*/h^*$ due to the existence of the gas accelerating regime near the inlet of the break.

Second, a new correlation for the onset of off-take is developed in terms of the Froude number ($Fr_g$) at the break and non-dimensional inception height ($h_b/d$). In the present onset of off-take criterion, the Froude number is proportional to the non-dimensional inception height. Developed correlation shows agreement with the present experimental data with maximum error of ±15%.

Third, the experimental data for off-take quality of the discharged liquid through the break at the top of a vessel have been obtained and have agreement Schrock's off-take quality correlation with r.m.s. error of 15.8%. The present off-take data have consistency with the droplet entrainment data in plot of $E_{fg}$ versus $j_g^*/h^*$.


## ACKNOWLEDGEMENTS

This work was performed under the Korean Next Generation Reactor Development Project and the financial support by Korea Electric Power Corporation is gratefully acknowledged.


## REFERENCES


1. Kataoka, I and K. Mishima, "Mechanism and correlation of droplet entrainment and deposition in annular two-phase flow," ANL-82-44, NUREG/CR-2885, 1982.
2. Kataoka, I and K. Mishima, "Mechanistic modeling of pool entrainment phenomenon," Int. J. Heat Mass Transfer, Vol.27, No.11, pp.1999-2014, 1984.

3. Garner, F.H., S.R.M. Ellis and J.A. Lace, “The size distribution and entrainment of droplets,” Trans. Instn. Chem.. Engrs, Vol.32, p.222, 1954.
4. Sterman, L.S., A.I. Antonov and A.V. Surnov, “An investigation of steam quality at 185atm,” Teploenergetika, Vol.3, No.3, p.17, 1957
5. Styrikovich, M.A., V.I. Petukhov and V.A. Kolokoltsev, “The effect of gas pahses density on the extent of droplet entrainment,” Tploenergetika, Vol.11, No.11, 1964.
6. Golub, S.I., M.BWeisblat, V.V. Ilyuschenko and V.I. Frolov, “Estimation of transported entrainment in flash desalination plants,” Proc. 7th Int. Symp. On Fresh Water from the Sea, Vol.1, pp.137-145, 1980.
7. G.C.K. Yeh and N. Zuber, “On the problem of liquid entrainment,” ANL-6244, 1960.
8. Schrock V.E., Revankar S.T. et al., "Critical Flow through pipe cracks and for small breaks with stratified upstream region," 12th water reactor safety research information meeting, Gaithersburg, MD, USA, Oct 1985 pp.267-273, 1985.
9. Smoglie, C. and J. Reimann, "Two-phase flow through small branches in a horizontal pipe with stratified flow," Int. J. Multiphase Flow, Vol.12, No.4, pp.609-625, 1986.
10. C.H. Kim, H.C. No, and M.H. Chun, “Application of RELAP5/MOD3.2 to the prediction of two-phase mixture level swell and liquid entrainment from the two-phase mixture surface during depressurization in a vessel,” Physor 2002, PHYSOR 2002, Seoul, Korea, Oct 7-10, 2002.
11. Dong Won Lee and Hee Cheon NO, “Development of two-phase level measurement method using ultrasonic”, 2nd Japan-Korea Symposium on Nuclear Thermal Hydraulics and Safety (NTHAS2), Fukuoka, Japan, Oct. 2000.
12. Lubin, B.T., and G.S.Springer, “The formation of a dip on the surface of a liquid draining from a tank,” J. Fluid Mech., Vol.29, p.385, 1967.