An Experimental Study of Droplet Entrainment in the Horizontal Stratified Flow

Byeonggeon Bae, Jaejun Jeong, Byongjo Yun*
Department of Mechanical Engineering, Pusan National University, 63 beon-gil, Busandaehak-ro, Geumjeong-gu, Busan, 46241, Republic of Korea
**Corresponding author: bjyun@pusan.ac.kr*

1. Introduction

Droplet entrainment in a horizontal stratified flow is a major phenomenon that can occur in a hot leg pipe during Loss of Coolant Accident (LOCA) in a PWR nuclear power plant. The droplets entrained in the hot leg move to the steam generator (SG) together with the droplets generated from the reactor. In the SG, the evaporation of droplets causes the pressure increases in the upper head of reactor. This interferes with the injection of the emergency core cooling water into the reactor during the reflood period, which greatly affects the safety of the fuel rods. However, up to now, the experimental study on the droplet entrainment in the horizontal stratified flow has been limited to few researchers at the CEA in France [1] and Tulsa university [2,3].

The objective of this study is to carry out experiments for droplet entrainment of stratified flow condition in a horizontal rectangular channel to extend the database. By using the experimental data, an empirical correlation for droplet entrainment is proposed applicable to horizontal stratified flow.

2. Measurement method for droplet entrainment

In this study, both droplet mass flow rate and entrainment fraction were measured by applying liquid film extraction method as shown in Fig. 1. That is, the droplet mass flow rate can be measured by removing the liquid film from test section.

$$m_d = m_l - m_{lf} \qquad (1)$$

The entrainment fraction is defined as the ratio of the droplet mass flow rate to the total liquid mass flow rate as follows.

$$E = \frac{m_d}{m_l} \qquad (2)$$

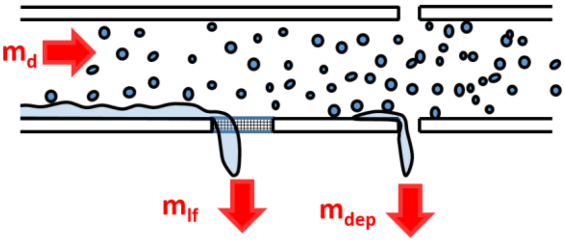

Fig. 1 Schematic diagram of liquid film extraction method

3. Experimental apparatus

The experimental facility consists of the water-air injection lines, horizontal test section, and liquid film extraction system (Fig. 2). Water and air are supplied by a centrifugal pump with a maximum flux of 1890 kg/m^{2}s and a roots type blower with a maximum mass flux of 40 kg/m^{2}s, respectively, in horizontal rectangular channel. Water is recirculated through the water tank and air is discharged to the atmosphere. The test section was made of an acrylic with a width of 40 mm, a height of 50 mm and a length of 4.2 m. As shown in Fig. 2, the liquid film is extracted at liquid film extraction system. The water level in each liquid film extraction box is controlled constantly using the control valve by differential pressure value. Because of the constant water level maintained in the enclosed box, air does not flow out of the test section in the liquid film extraction section.

In this study, the liquid film mass flow rate is measured by a Coriolis mass flow meter. The extracted water is returned to the water tank.

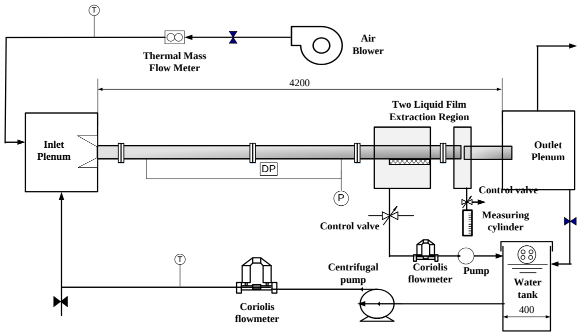

Fig. 2 Schematic diagram of experimental apparatus

4. Experimental results

Droplet entrainment experiments for the horizontal stratified flow conditions were carried out at j_l=0.02 and 0.03 m/s, and j_g=18~26 m/s.

4.1. Droplet mass flow rate and entrainment fraction

The droplet mass flow rate was measured using the difference between the total liquid mass flow rate and liquid film mass flow rate measured by liquid film extraction system. Experimental values were obtained for 5 minutes. Fig. 3 shows the droplet mass flow rate according to the gas and liquid superficial velocities. The droplet mass flow rate does not change significantly with increasing gas superficial velocity at j_l=0.02 m/s, however it increases stiffly with increasing gas superficial velocity at j_l=0.03 m/s. The entrainment fraction increases as gas superficial velocity increases, as shown in Fig. 4.

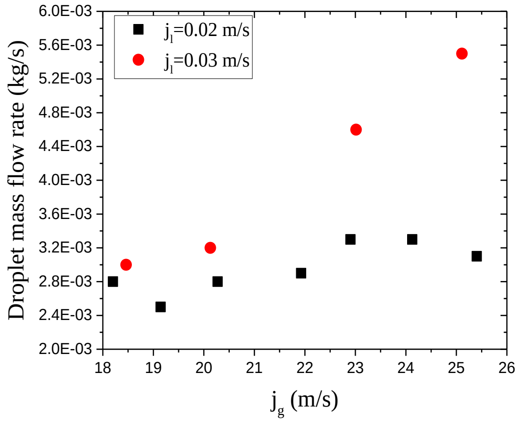

Fig. 3 Droplet mass flow rate according to the gas and liquid superficial velocities

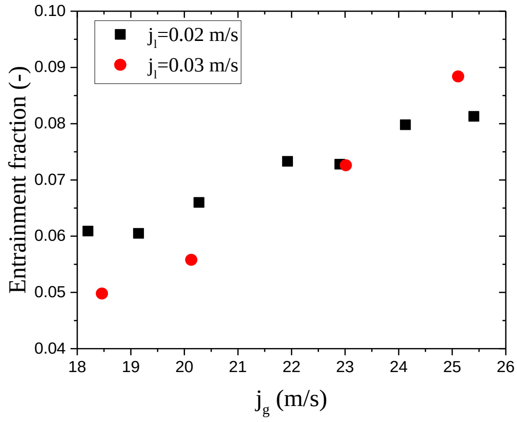

Fig. 4 Entrainment fraction according to the gas and liquid superficial velocities

In addition, it can be seen that the degree of increase of entrainment fraction with respect to the gas superficial velocity change is larger as liquid superficial velocity is larger.

4.2. *Proposed empirical correlation for entrainment fraction*

An empirical correlation is presented based on the data obtained from present experiment and open literature. Henry [1] and Mantilla [3] performed droplet entrainment experiments in horizontal stratified flow condition. Henry [1] measured the entrainment fraction and entrainment rate using an isokinetic sampling probe in a 240 mm large pipe, which is designed as 1/3 scale of a PWR hot leg. Mantilla [3] conducted experiments for droplet entrainment in 152.4 mm pipe diameter. These experiments were carried out at low gas and liquid superficial velocity conditions for simulating stratified flow.

Fig. 5 shows the results of entrainment fraction for the experiments. The entrainment fraction increases with increasing gas superficial velocity and decreasing liquid superficial velocity. Also, as the channel size increases, the entrainment fraction tends to decreases.

The following correlation is proposed to reflect the tendencies of these parameters.

$$E = 0.1 \frac{j_g^{*2.67}}{D^{*0.256}\,\mathrm{Re}_l^{0.565}} \qquad (3)$$

This correlation shows that E depends on the liquid Reynolds number and dimensionless gas superficial velocity and pipe diameter.

$$\mathrm{Re}_l = \rho_l j_l D_H / \mu_l \qquad (4)$$

$$j_g^* = j_g / (\sigma_l g \Delta\rho / \rho_g^2) \qquad (5)$$

$$D^* = D_H \sqrt{g\Delta\rho / \sigma_l} \qquad (6)$$

Fig. 6 shows comparison of various entrainment fraction data with a proposed empirical correlation. The correlations predicted experimental data with mean absolute percentage error of 36.4% and root mean square error of 45.2%.

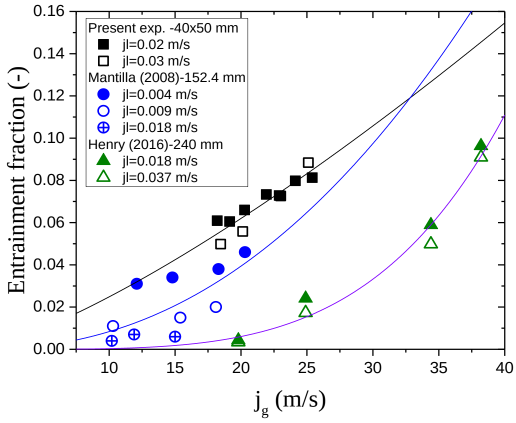

Fig. 5 Entrainment fraction data of various experiments for horizontal stratified flow conditions

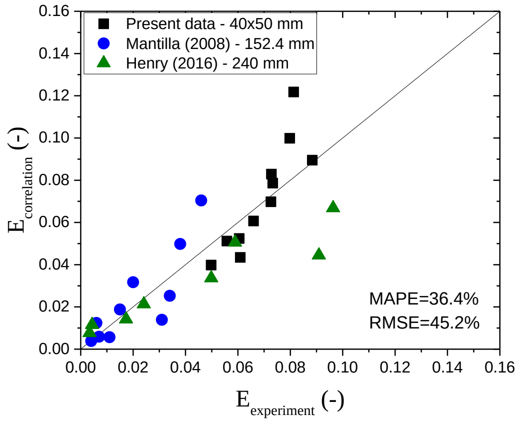

Fig. 6 Comparison of entrainment fraction data with the proposed empirical correlation

5. Conclusions

Droplet entrainment experiments were performed by applying liquid film extraction method in order to extend experimental database for entrainment fraction. We conducted the test in the conditions in which droplet entrainment occurs in a horizontal stratified flow with varying gas superficial velocity for two liquid superficial velocities.

An empirical correlation for entrainment fraction is proposed based on the experimental data obtained from open literatures and present experiment.

Nomenclatures

D	Hydraulic diameter of channel
D^*	Dimensionless hydraulic diameter of channel
E	Entrainment fraction (-)
g	Gravity (kg/m^{2}s)
j	Superficial velocity (m/s)
j_g^*	Dimensionless gas superficial velocity (m/s)
m	Mass flow rate (kg/s)
Re	Reynolds number
v	Actual velocity (m/s)

Greek symbols:

μ	Dynamic viscosity (Ns/m^2)
$\Delta\rho$	Density difference (kg/m^3)

Subscripts:

d	Droplet
g	Gas
l	Liquid
lf	Liquid film

Acknowledgement

This work was supported by the Nuclear Research & Development Program of the NRF (National Research Foundation of Korea) grant funded by the MSIP (Ministry of Science, ICT and Future Planning) and by the Nuclear Safety Research Center Program of the KORSAFe grant funded by the Nuclear Safety and Security Commission (NSSC) of the Korean government (Grant code: NRF-2015M2B2A9029358, 1305011).

References

[1] Henry, Francois. Experimental and modeling investigations on droplet entrainment in a PWR hot leg under stratified flow conditions. Diss. Université catholique de Louvain, 2016.

[2] Meng, Weihong. "Low liquid loading gas-liquid two-phase flow in near-horizontal pipes." (1999).

[3] Mantilla, Ivan. Mechanistic modeling of liquid entrainment in gas in horizontal pipes. Diss. The University of Tulsa, 2008.