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Original Article

Development of droplet entrainment and deposition models for horizontal flow

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ABSTRACT

Models for the rate of atomization and deposition of droplets for stratified and annular flow in horizontal pipes are presented. The entrained fraction is the result of a balance between the rate of atomization of the liquid layer that is in contact with air and the rate of deposition of droplets. The rate of deposition is strongly affected by gravity in horizontal pipes. The gravitational settling of droplets is influenced by droplet size: heavier droplets deposit more rapidly. Model calculation and simulation results are compared with experimental data from various diameter pipes. Validation for the suggested models was performed by comparing the Safety and Performance Analysis Code for Nuclear Power Plants calculation results with the droplet experimental data obtained in various diameter horizontal pipes.

1. Introduction

Steam binding is an important phenomenon that can affect the peak cladding temperature during a loss of coolant accident. The prediction of the rate of atomization from the liquid layer and the rate of deposition of droplets must be precise and is directly linked with the amount of entrained droplets that reach the steam generator before vaporization. Gas–liquid flow may occur in the PWR (Pressurized Water Reactor) hot leg and is an important component process that is associated with this accident.

The nuclear industries and research institutes in Korea have developed a thermal-hydraulic analysis code for safety analysis of PWRs, named Safety and Performance Analysis Code for Nuclear Power Plants (SPACE). The SPACE code adopts advanced physical modeling of two-phase flows: mainly two-fluid three-field models comprised of a gas, a continuous liquid, and a droplet field. Two-fluid three-field modeling allows the explicit simulation of the steam-binding phenomena. In this study, models for rate of entrainment and deposition are suggested and implemented in the SPACE code. Results of simulation are then compared with experimental data from horizontal pipes of various dimensions. Prediction of the liquid field mass distribution in the liquid layer and dispersed droplets is critical; therefore, this distribution is the figure of merit for this study. This study is a further advancement of the previous study *Droplet Entrainment and Deposition in Horizontal Stratified Two-Phase Flow* [1]. The newly proposed models differ in that the diameter term is more accurately predicted, allowing better predictions for the gravitational settling term. In addition, developing regions are considered with respect to the interfacial area term modeling between liquid layer and gas core. Overall, predictions over a wider range of experimental facilities were improved on previous approximations.

2. Droplet entrainment and deposition experiments

The two-phase flow behaviors of interest in this study include droplet entrainment and deposition in the horizontal annular and stratified flow regime. Measurements of droplet entrainment for air and water flows in horizontal pipe experiments from the studies by Williams (0.095 m) [2], Dallman (0.0231 m) [3], Laurinat et al. (0.0508 m) [4], Mantilla (0.0486 m) [7], and REGARD (0.24 m) [6] are examined. Horizontal annular flow exists under flow conditions in which gas velocities are high and liquid film exists around the perimeter of the pipe. Horizontal stratified flow occurs at lower gas velocities, and liquid film may occupy the lower portion of the pipe. Both flow regimes are studied in this article,

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and the effects of gravity and pipe diameter on droplet behavior are considered.

The entrained ratio is the balance of the rate of atomization of the liquid film, Γ_E, and the rate of deposition of droplets,Γ_D. At the contact point of gas and liquid entering a pipe in two-phase flow, a developing region occurs in which the mass flow of the droplets will increase until the rate of atomization equals that of deposition. The point at which entrainment is equal to deposition is considered a fully developed flow, $\Gamma_E = \Gamma_D$. Five experiments were selected to measure entrainment ratios for horizontal flow conditions. REGARD experiment was performed at CEA Grenoble to study both developing and developed flow for a pipe with diameter of 0.24 m. Williams [2], Dallman [3], and Laurinat et al. [4] performed experiments at the University of Illinois at Urbana–Champaign and observed a fully developed flow for pipe diameter size ranges of 0.0254–0.095 m. In addition, a separate study with droplet measurements for a horizontal flow in a 0.0486-m diameter pipe was performed by Ivan Mantilla at the University of Tulsa.

Williams, Dallman, and Laurinat et al. studied two-phase flow at a range of various scales. The facility has the capability to experiment under pipe diameter sizes of 2.54 cm, 5.08 cm, 7.62 cm, and 9.53 cm and the pipe lengths ranging up to 26.5-m long. The pressure at the test section varied between experiments, such that P=116–212 kpa.

The REGARD facility is another experimental facility developed to study two-phase flows in a hot leg geometrical configuration. The facility differs in that it is specifically designed to study horizontal stratified flows as opposed to Williams' prior investigation of horizontal annular and stratified flows [2]. The experiment used liquid water and air, both at 30°C, at a pressure slightly below 150 kPa. The pipe had a diameter of 0.24 m. Axial measurement capabilities were utilized between L/D ratios 3.8 and 11.6. When compared with other facilities, this facility is the closest in geometrical scale, by far, to actual PWR geometries [6].

Mantilla's experimental facility consisted of a 2-inch flow loop of clear PVC (PolyVinyl Chloride) with an inner diameter of 0.0486 m. For every set of experimental flow condition runs, the pressure was constant at 206.8 kPa. Inlet liquid and gas mass flow rates were maintained constant for each of the experimental runs. Fluid temperatures were also maintained at around 21°C. This experimental facility is a small-scale one that covers droplet entrainment measurements for horizontal flow [7]. Table 1 shows the conditions for the range of experiments used in developing the entrainment and deposition modeling.

3. Previous studies for droplet entrainment and deposition modeling

There are a vast range of existing studies on droplet behavior, including deposition and entrainment modeling. During the first stages of research in this field, vertical pipes were studied because droplet deposition behavior is a less complex phenomenon as opposed to horizontal flow. In vertical flow, droplet concentration profiles are usually uniform. Previous developed models used an approach that predicts the free flight rate at which droplets will be deposited in the liquid film.

Later research expanded toward horizontal pipes covering annular and stratified annular flow regimes. Attempts were made to model the deposition behavior; however, these were limited to one experimental facility for the development of the deposition models. This study includes a deposition model that considers gravitation and can be applied to different scale pipe diameter experiments.

Experimental data were obtained from the aforementioned facilities. Data were further analyzed and validated with the SPACE simulation program. On simulation, existing models for entrainment and deposition did not match well against the experimental data. SPACE used deposition modeling from vertical flows that are not applicable to horizontal flow because gravity was not considered. The deposition model for vertical flows was developed by McCoy and Hanratty [8] from a range of experiments that studied the rate at which injected particles deposit at the wall of a pipe. The droplet diameter has a major influence on the rate of deposition for both gravitational settling and turbulent diffusion. However, the previous deposition experiments did not have enough data for the larger droplet diameters that were observed in the horizontal flow experiments.

In the first stages of development of droplet deposition modeling in horizontal flow, Williams et al. (1996) considered the effect of gravity. The experiments showed that different pipe diameter sizes had significant differences in droplet concentration distributions and liquid film distributions. The author attributed this difference to the influence of gravity. In addition, this effect of gravity was also observed in the REGARD experiment facility. The author defined these distributions with parameters “asymmetry” and “symmetry”. As the pipe sizes increased, liquid film and droplet distributions became nonuniform among the cross sections of a pipe and were considered asymmetric, whereas small diameter pipe experiments saw more uniform symmetric distributions under similar flow conditions.

Before the study by Williams et al. [9], other experiments measuring the deposition rate for droplets in horizontal pipes also observed strong effects of gravity. In the smallest scale experiment, Alexander and Coldren [10] observed symmetric profiles. Larger scale experiments, such as those by Namie and Ueda [11] and McCoy and Hanratty [8], found asymmetric concentration distributions. Visual observations and measurements suggested that almost all the deposition was occurring at the bottom wall of the pipes. More consistent measurements and observations of these trends were shown in the study by Anderson and Russell [12]; they measured the circumferential variation of interchange and found that nearly 90% of the interchange occurred at the bottom half of the pipe. In all these experimental studies, it is clear that gravity has a significant effect on the droplet behavior.

Table 1
Experiments used for entrainment modeling.

	Williams (1990)	Laurinat (1984)	Dallman (1978)	Mantilla (2008)	REGARD (2012)
Fluids	Air–water	Air–water	Air–water	Air–water	Air–water
D (m)	0.0953	0.0508	0.0231	0.0486	0.24
J_g(m/s)	26–88	11–131	15–88	21–84	19–38
W_L (kg/s)	0.12–0.86	0.033–0.97	0.003–0.25	0.006–0.188	0.83–1.66
$\rho_g kg/m^3$	1.3–1.85	2.05	1.26–2.75	2.48	1.75
No. of boundary conditions	29	52	114	22	8
Pressure (kPa)	116	212	212	207	150