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Visualization study of interaction with 2-D film flow on the vertical plate and lateral air velocity for DVI system

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1. Introduction

In the condition of normal, emergency core cooling injected into the downcomer through the DVI nozzle jets the wall and flows down in the form of two dimensional liquid film. As the curvature has almost no effect on the flow of the liquid film because the radius of the internal wall curvature of the downcomer is actually too big, we can see that it is not much different from the case where it is injected onto a plane. When this flow is ideally expressed, it can be said to be a vertically falling liquid film induced by a liquid jet injected horizontally onto a vertical plane. However,

The present study investigates liquid film flow generated in a downcomer of direct vessel injection (DVI) system which is employed as an emergency core cooling (ECC) system during a loss of coolant accident in the Korea nuclear power plant APR1400. During the late reflooding, complicated multi-phase flow phenomena including the wavy film flow, film breakup, entrainment, liquid film shift due to interfacial drag and gas jet impingement occur. In order to obtain a proper scaling law of the flow, local information of the flow was investigated experimentally and also numerically. A series of experiments were conducted in the 1/20 modified linear scaled plate type test rig to analyze a liquid film from ECC water injection through the DVI nozzle to the downcomer wall. A confocal chromatic sensor was used to measure the local instantaneous liquid film thickness. Depth-averaging PIV was used to measure the local liquid film velocity. In this study, 2-D film Reynolds number was calculated and onset of entrainment on the 2-D film flow under the lateral air velocity was predicted.

2. Methods and Results

To precisely simulate the liquid film phenomenon of the flow pattern generated in DVI, a test was conducted unfolding the structure of a downcomer into a flat plate type. As the diameter-height ratio of the downcomer of APR1400 was very big, the extent of the distortion generated by changing it into a flat plate type was regarded to be minor (Kim and suh, 2009). In this test, the superficial velocity was shown using the Wallis parameter of the existing study, and the modified linear scaling technique which had been validated to well simulate two-phase flow by the existing studies (Bang et al., 1991 and Yun et al., 2004) was used to organize the test setup. The modified linear scaling technique is shown in particular to constantly maintain the apparent speed, where the speed is reduced in the form of a square root of the geometric reduction ratio, and it has been shown to well conform to the width and the bypass phenomenon of the downcomer flow and has been continuously used in the existing studies related to downcomer. For this test, a test setup of 1/20 scale using the same downscaling rule was produced.

TABLE I.
Information of the experimental setup (THE LAB)

Parameter	Scale ratio	Present
Length ratio	I_R	1/20
Area ratio	I_R^2	1/400
Time ratio	$I_R^{1/2}$	1/4.472
Velocity ratio	$I_R^{1/2}$	1/4.472
Flow rate ratio	$I_R^{1/2}$	1/447.2
	Real condition	Scaled condition
Water inlet velocity (m/s)	2	0.45
Air velocity (m/s)	15~45	3.4~10

2.1 Experimental setup

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When water is injected from the liquid jet of the nozzle onto the vertical flat plate and lateral air velocity sufficiently high, the flow makes diverse irregular waveforms of liquid film flow and the droplets breakup phenomenon are shown. After diverse two-phase flow phenomena have occurred, air is separated through the open top and water is stored in the tank at the bottom of the isolator and recycled to the pump again. The pump and the air blower are controlled by the inverter. The size of the nozzle was downscaled to 1/20 was 12 mm, the flat plate gap was 12 mm, the flow rate of water was 0.45 m/s, and that of air was 0 to 10 m/s (Table 1. For this the test was carried out total in 5 sections as shown in Table 1. To measure the diverse phenomena of two-phase flow, the thickness of the liquid film flow was measured using a confocal chromatic sensor. Also, the flow rate of the liquid film flow that can be utilized in a situation of two-phase flow of low void fraction was measured using a depth-averaging PIV.

2.2 Liquid film flow thickness measured by CCS

The DVI flow when there is no inflow of air is as shown in the figure 1. The water injected from the nozzle flows along the wall surface in the form of a liquid film. The flows in the radial direction at the top above the nozzle showing a semicircular form and flows down along the edge after the liquid has ascended. And further below a flow showing the form of a gravity flow with the width bigger than the diameter of the elevated semicircle can be observed. As to the liquid film thickness, when we observe the figure 1, on the close top, the peak points of the liquid film thickness occur at both edges and at the third point near the place where there is the nozzle, and, as the flow moves further down, the peak point at the center of the nozzle is alleviated to disappear and a phenomenon occurs where the liquid film flow similar to hydraulic jump grows thicker only at both edges.

TABLE II.
The Specification of the CCS used for this Test

Specification c	value
Sampling frequency	2000 points/sec
Light source	White LED
Measuring range	24000 um
Working range	19.6 mm
Max. object slop	± 8.5 °
Spot size	28 um
Resolution	1500 nm
Measuring thickness	725 um (min) 34000 um (max)

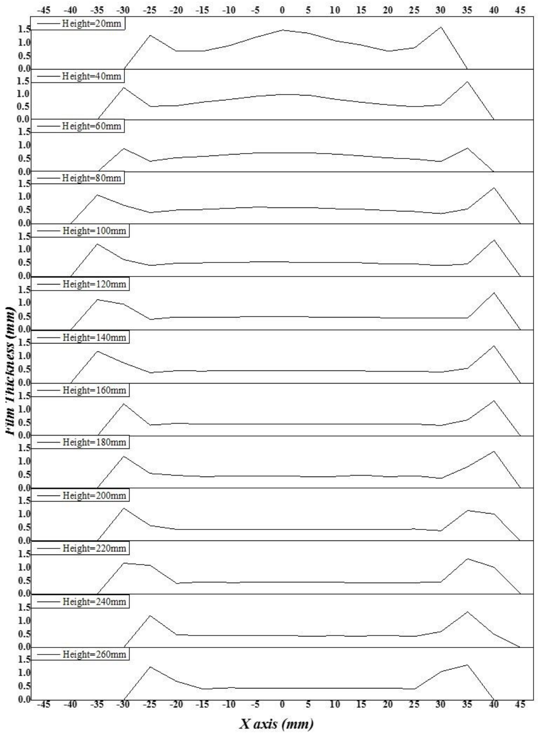
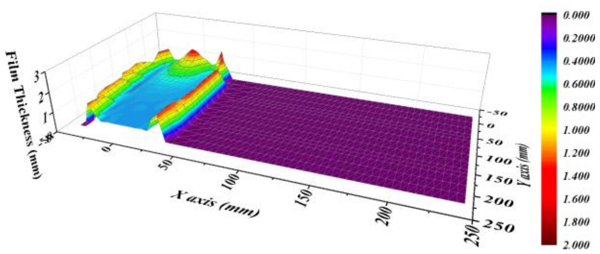


Fig. 1. DVI Liquid Film Flow with No Air(water:0.45m/s)

2.3 Entrainment ratio

The following fig.2-6 shows the thickness data of the average liquid film flow measured using a CCS at intervals of 20 mm vertically and 5 mm horizontally from the nozzle when the flow rate of water is 0.45 m/s and the flow rate of air is 0, 3, 5, 7, and 9m/s. In the case of the flow at the rate of 7 or 9 m/s, droplet breakaway takes place, and the volume of the liquid film flow excluding the liquid removed through the droplet breakaway can be obtained by integrating the thickness data. The entrainment fraction can be obtained, $\frac{volume\ of\ the\ flow\ w/\ entrainment}{volume\ of\ the\ flow\ w/o\ entrainment}$, and the relevant value is as shown in the table 3. In Cases A to C, as no droplet breakaway has taken place, the entrainment fraction has a value within 3 % error from 1, and D has an entrainment ratio value of 0.79 and E has an entrainment ratio value of 0.64.



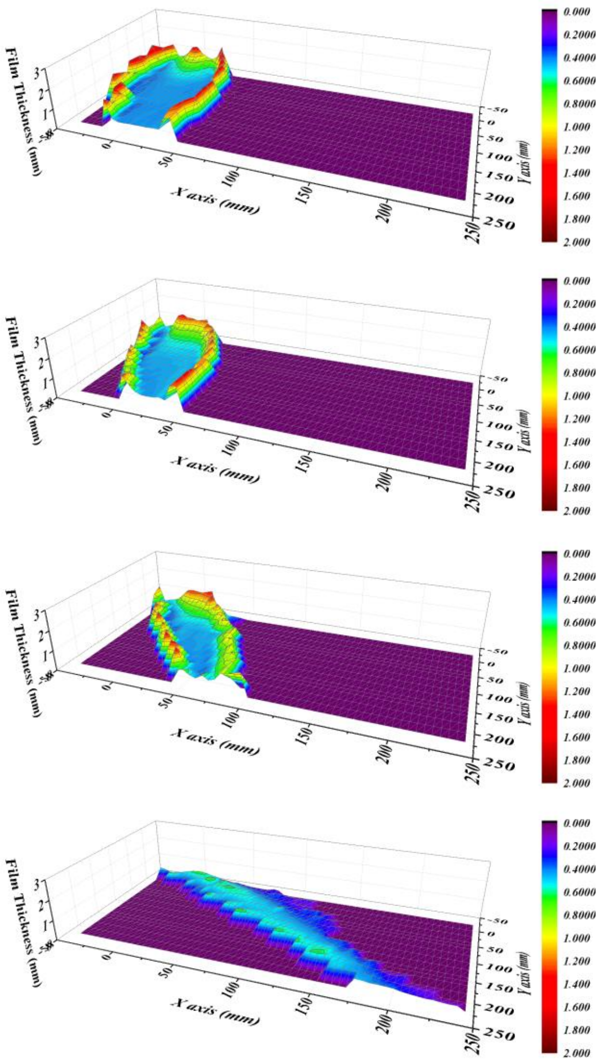


Fig.2-6. Average Liquid Film Thickness obtained by measuring the liquid film flow generated at the water flow rate of 0.45 m/s and the air flow rate of 0, 3, 5, 7, and 9 m/s, respectively.

TABLE III.
The Entrainment ratio

Case	Phenomena	Ratio
Air: 0m/s	Original film flow	1.00
Air: 3 m/s	No entrainment	1.01
Air: 5 m/s	No entrainment	0.97
Air: 7 m/s	Entrainment	0.79
Air: 9 m/s	Entrainment	0.64

2.4 Velocity of the Liquid Film Flow measured by the Depth Averaging PIV Technique

The velocity of the liquid film flow measured using the PIV technique. The velocity of the liquid film flow is faster as the point goes down and slower as the point moves to both edges. Also, the faster the air flow becomes, the faster the speed of the liquid film flow becomes as a whole.

2.5 Film Reynolds number

In the case of DVI, the distribution of the 2-dimensional Reynolds number, not 1-dimensional annular flow analysis, is required to be calculated. Re was obtained using the thickness and the velocity of the liquid film flow, and the 2-dimensional distribution of film Reynolds number of the liquid film flow is as shown in the figure 7. As a result, a droplet break up phenomenon can easily occur in the area of which the Reynolds number is high, through which the area with droplet breakaway and the criterion gas velocity can be predicted.

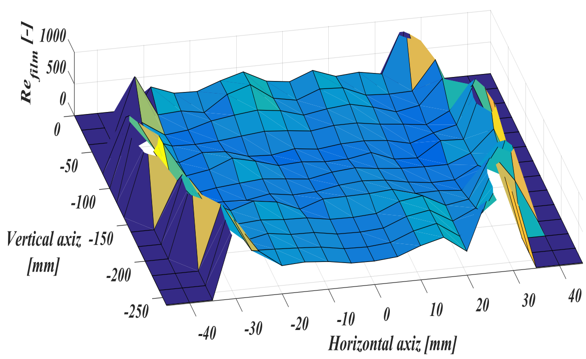


Fig. 7. 2-D film Reynolds number at the water velocity 0.45m/s and the air velocity 0 m/s

3. Conclusions

In this study, the average flow information of the downcomer was analyzed through the information about the thickness, speed, droplet size and speed of highly precise liquid film flow in the structure that occurs in a 2-dimensional liquid film flow, rather than film flow, onset of entrainment, droplet velocity, and size which have been studied in 1-dimension of the existing annular flow. The multi-dimensional flow characteristic information of downcomer can be utilized as the basic data for nuclear safety analysis in the future.

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