Interaction of Liquid Film Flow of Direct Vessel Injection Under the Cross Directional Gas Flow

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1. Introduction

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 and a hydraulic jump in the film flow and boundaries of the film flow. It was found that CFD analysis results without surface tension model showed some difference with the data in surface tension dominated flow region. For the interaction between a liquid film and gas shear flow, CFD results make a good agreement with the real liquid film dynamics in the case of low film Reynolds number or low Weber number flow.

2. Methods and Results

2.1 1/20 modified scaling of plate DVI apparatus

In order to measure the water film deformation and entrainment phenomena, the 1/20 modified linear scaled plate type DVI apparatus was constructed. Fig. 1 presents the schematic and picture of experimental test rig. The test apparatus consists of an air inlet part with air blower, DVI injection nozzle, and a pump. A rotameter and a pitot tube were used for the measurement of velocity of liquid injection velocity and air injection velocity, respectively. Profile of the film deformation measured by using image processing. The chromatic confocal imaging method was used for the measurement of liquid film thicknesses.

A plate type experimental rig was used instead of a cylindrical geometry because the diameter of downcomer of APR1400 is larger than the diameter of the ECC injection nozzle. The test matrix is shown in the Table II.

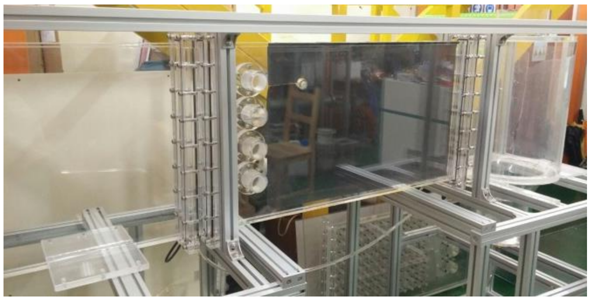

Fig. 1. Picture of 1/20 scaled experimental apparatus

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

TABLE II.
Experiment test matrix

ECC Injection Velocity [m/s]	Air Injection Velocity [m/s]
0.5	0, 5, 10, 20

2.2 CFD of 1/20 scaled plate DVI apparatus with air

We prepared a set of numerical simulation for 1/20 scaled plate tests. It was different type simulation each because of existence of air injection. The simulation work was also conducted for 1/20 scaled plate DVI with the commercial CFD code ANSYS CFX 15.0. (Table VII). Unlike 1/10 simulation, hexahedral mesh was designed as shown in Fig. 2. Mesh has 197502 elements, 214375 nodes, 33 aspect ratios. Air as continuous morphology and water as dispersed fluid with 1mm of mean diameter option were set for steady state analysis.

To simulate interface between water and air, a model of standard free surface was adopted. However, it was adopted no surface tension model and no contacting angle option. For turbulent analysis, SST model was used. Details of numerical parameters are presented in the Table. III and Table IV.

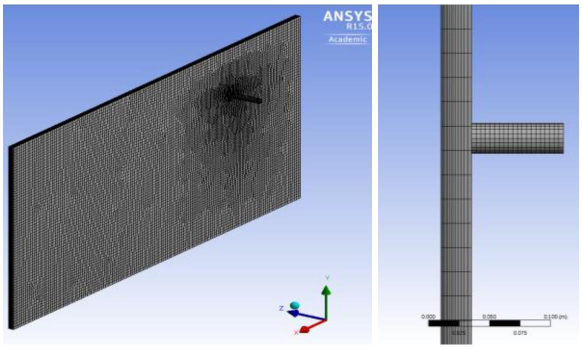

Fig. 2. Numerical mesh of 1/20 scaled plate DVI

TABLE III.
Fixed numerical parameters for CFX calculation (1/20)

Numerical parameter	Value
Air morphology	continuous
Air Dynamic viscosity (kg/m·s)	0.00001831
Air Density (kg/m^3)	1.185
Injection air velocity (m/s)	5, 10, 20
Water morphology	Dispersed fluid
Water mean diameter (m)	0.001
Water Dynamic viscosity (kg/m·s)	0.008899
Water density	998
Injection water velocity (m/s)	0.5, 0.9
Free surface model	standard
Drag coefficient	Ishii and Zuber
Surface tension coefficient	0.072
Buoyancy reference density (kg/m^3)	1.185
Turbulence model	SST, homogeneous
Outlet condition	Opening condition
Wall condition	No slip wall

TABLE IV.
Geometry information of the CFD (1/20)

parameter	Value (1/20 scaled)
Gap (mm)	12.5
Width (mm)	1000
Height (mm)	500

Besides the output current, the MATLAB detector code calculates the detector capacitance. The calculated output current is the input for the rest of the detector channel and the detector capacitance is an important input parameter.

2.3 Results of water film deformation in the 1/20 scaled plate type DVI apparatus

A deformed spreading profile by the interaction between the ECC water injection and a gas shear flow was captured by digital camera. In the case of CFD analysis, deformed liquid film flow boundary was obtained by a distinguishing criteria which is that liquid volume fraction is larger than 0.1. As shown in the Fig. 3, certain hydraulic jump in the boundary was captured and the profile well matched with the experimental result. In the result, little shift of the liquid film and unstable wavy dynamics in the lower left region of the liquid film can be noted. However, the unstable wave dynamics could not be obtained due to the steady state analysis in the CFD results. The unstable region which shows intuitively that region of low volume fraction (0.1~0.3) can be expressed the unstable region in the case of CFD.

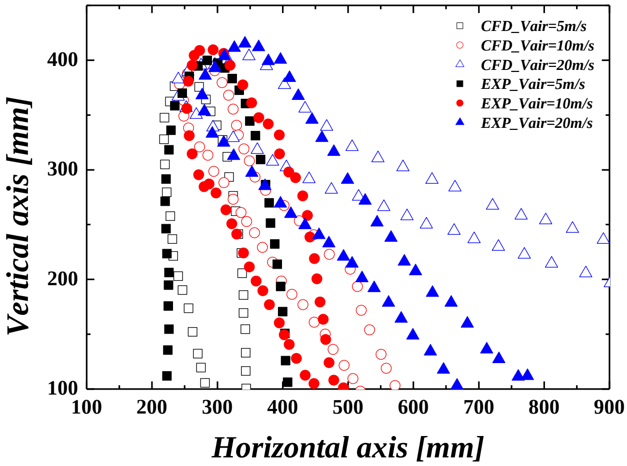

Fig. 3. Deformation of the liquid film spreading profile in the case of 0.5 m/s ECC injection velocity

TABLE V.
Average Reynolds number of the result

		Air injection velocity [m/s]		
		5	10	20
ECC injection velocity [m/s]	0.5	213	504	560
	0.9	179	171	273

3. Conclusions

In the 1/20 scaled plate type experiment and simulation, the deformed spreading profile results seem to accord with each other at the relatively low We and Re regime. However, the result of the high air velocity experiment does not correspond to simulation because interaction between the inertia and surface tension forces of the air-water interface have not considered well for simulation

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