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Onset of liquid droplet entrainment on a direct vessel injection system for APR1400

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1. Introduction

In this research, a series of visualization works was conducted to understand droplet entrainment of the flow pattern generated in direct vessel injection system(DVI) of Korea nuclear power plant, APR 1400. In the emergency situation of a nuclear power plant, reliability of DVI cooling can be an important issue. It is known that, the amount and the rate of entrainment during the DVI cooling process can significantly affect the total heat removal. To visualize the film Reynolds number closely related with onset of droplet entrainment induced by falling film flow and lateral air flow in a small gap, confocal chromatic sensing method for measuring accurately film thickness and depth averaging particle image velocimetry for film velocity were used. The results have been post processed 4G Insight software. By measuring two dimensional film Reynolds number, we can predict the onset of droplet entrainment and obtain visible breakup region intuitively. To visualize the droplet entrainment induced by falling film flow and lateral air flow in a small gap, shadowgraph method with CCD camera (2200fps, 1280 pixel X 800 pixel,) on coated plate with super water-repellent agent was used. The results have been post processed using 4G Insight software. By adopting both super hydrophobic coating method and shadowgraph method, entrainment in a narrow gap was successfully visualized that has rarely performed before and meaningful results for DVI system research fields have been made.

2. Experimental setup

In this research, an experimental apparatus with narrow gap between two flat plates, water inlet nozzle and air inlet duct was set to study onset of droplet entrainment in DVI system. The size of test section was decided as 500 mm X 1000 mm by downscaling downcomer of APR1400 to 1/20 size. Also the size of nozzle was downscaled to 12 mm of diameter and the gap between flat plates was determined as 12 mm. 0.45 m/s of flow rate was set for water inlet and 0,7,and 9 m/s of velocity for air inlet. Figs. 1 and 2 show a schematic and photograph of the experimental test rig, respectively. The test apparatus consists of an air inlet part equipped with an air blower, a DVI injection nozzle, and a pump. A rotameter and pitot tube were used for measuring the liquid injection velocity and air injection velocity, respectively.

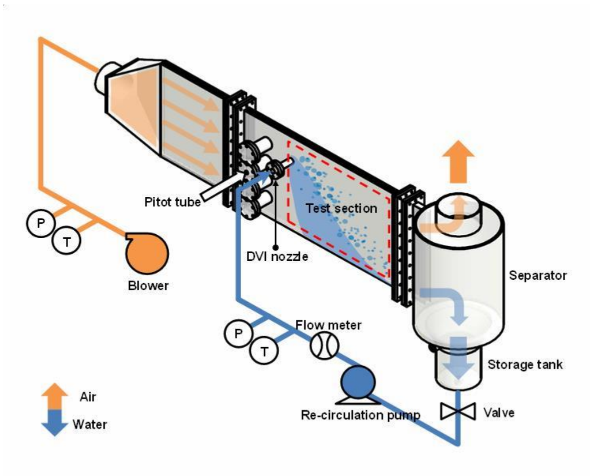


Fig.1 Schematics of experimental setup

Fig.2 Picture of experimental setup

Test section is shown Fig.3 and Fig.4. A plate-type experimental rig was used instead of a cylindrical one because the diameter of the downcomer of the APR-1400 is much more larger than the diameter of the ECC injection nozzle. The test matrix details are listed in Table 1.

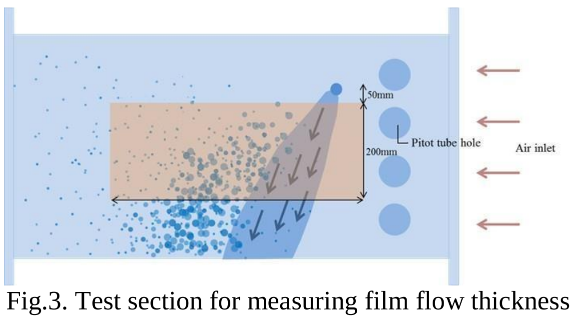


Fig.3. Test section for measuring film flow thickness and film velocity for calculating film Reynolds number

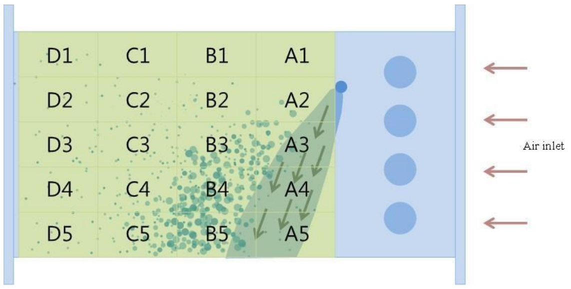


Fig.4. Test section for measuring droplets

Table1. Test matrix

1/20 modified scaled	A	B	C	D	E	F	G
Water inlet velocity	0.45 m/s (3.03lpm)						
Air velocity	0 m/s	3.5 m/s	4.9 m/s	6.4 m/s	7.8 m/s	9.2 m/s	10.6 m/s

3. Measurement

3.1. Film thickness

The method to measure film thickness is shadowgraph, electrical sensor and optic. Because the film thickness is very thin, almost below 2mm, The method should be high sampling frequency and highly accurate.

The chromatic confocal imaging method was used for the measurement of the liquid film thickness. The principle of the chromatic confocal imaging method is shown in Fig. 5. The confocal chromatic sensing method uses the confocal imaging principle and the effect of the chromatic aberration of a lens. As shown in Fig. 5, light from a polychromatic LED point source passes through a fiber-optic cable with a half-transparent mirror. The white light from the polychromatic point source is split through the lens into a continuum of monochromatic images with focal points at different distances because of chromatic aberration (Lel et al., 2005). The light is reflected from the surface of the plate. The pinhole in front of the spectrometer only passes the focused part of the spectrum in point-type light way through the fiber-optic cable. Then, the spectrometer measures the intensity of the light spectrum. The spectrometer converts the analog intensity signal to a digital one. This wavelength is converted into a position within the view field of the optical sensor by means of a calibration curve provided by STIL Corporation. Table 2 lists the specifications of the chromatic confocal sensor unit, CCS Prima (STIL Corporation). In this study, experiments were performed at a frequency of 1 kHz.

3.2. Film flow velocity

Depth-averaging PIV method was used for measuring film flow velocity. Two 5W laser were used. And our sampling frequency is 2kHz, 500 pairs of the PIV picture were analyzed. Rhodamin B dye was used with 560nm long pass filter.

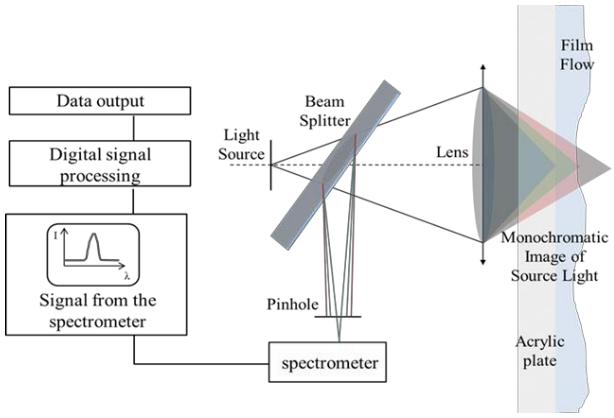


Fig. 5 Schematic of confocal chromatic sensor

Table.2. schematics of the sensor

Specification	Value	
Sampling frequency	2000 points/sec	
Light source	White LED	
Measuring range	24000 um	4000 um
Working range	19.6 mm	16.4 mm
Max. Object slop	± 8.5 °	± 21 °
Spot size	28 um	14
Resolution	1500 nm	300 nm
Measuring thickness	725 um (min) 34000 um (max)	120 um (min) 5700 um (max)

3.3. droplet characteristics

To visualize the droplet entrainment induced by falling film flow and lateral air flow in a small gap, shadowgraph method with CCD camera (2200fps, 1280 pixel X 800 pixel,) on coated plate with super water-repellent agent was used. The results have been post processed. By adopting both super hydrophobic coating method and shadowgraph method, entrainment in a narrow gap was successfully visualized that has rarely performed before and meaningful results for DVI system research fields have been made. Contact angle of water droplet is 140 degree. This is magnified 100 times picture. Image processing was used. 2kw halogen lamp was used as light source. 5000 pairs of pictures were taken with 2200 Frame per second. Diameter was obtained by the pixel information of droplet.

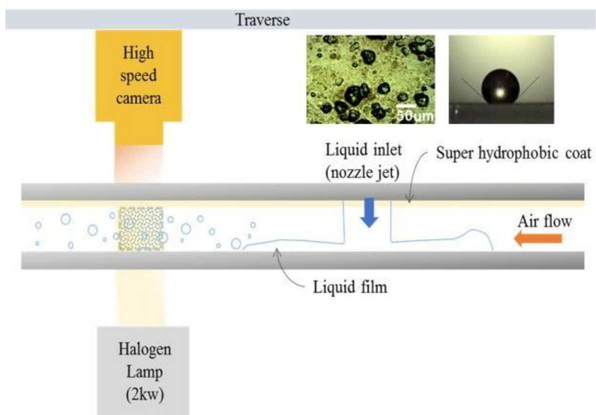


Fig. 6. Schematic of measuring droplet characteristics

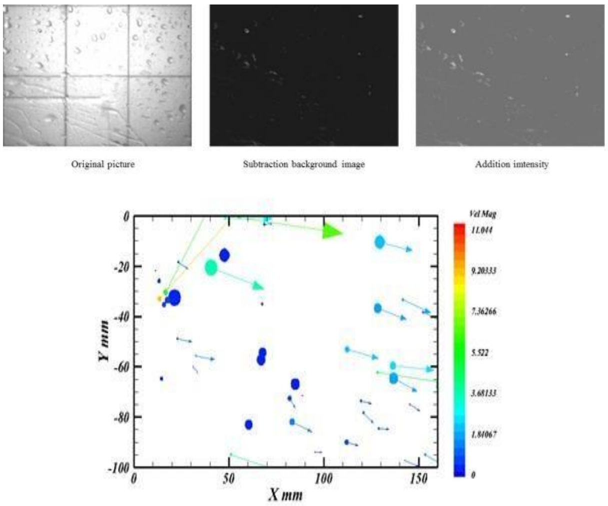
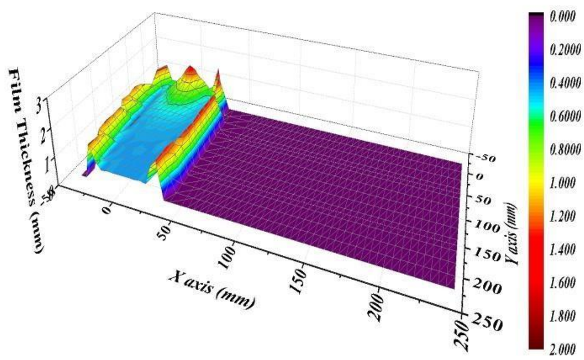


Fig. 7 Image processing method

4. Results and Discussion

4.1. Wave characteristics

Fig.8 and Fgi.9. represents the experimental results of liquid film thickness measurement without inlet air. The average film thickness at the rim appears to be larger than those at the other positions. The film thickness progressively decreases as the film spreading width increases. Film thickness of the center and upper part is also larger. This is because the nozzle concentrates the injected water at the centerline. In the rim, unstable liquid film behavior such as a hydraulic jump is observed. Generally, the average film wave has the value near the base film flow. However, the roll wave in the film flow has 2-3 times thickness than the average film flow thickness. There fig. 9 represents distribution to film thickness at certain horizontal positions. The rim shows that the rim has an unstable wave.



4.2. Onset of entrainment

Onset of entrainment criterion is in the fig.10. that the film Reynolds is over 1700 and dimensionless superficial gas velocity is over the 0.6.

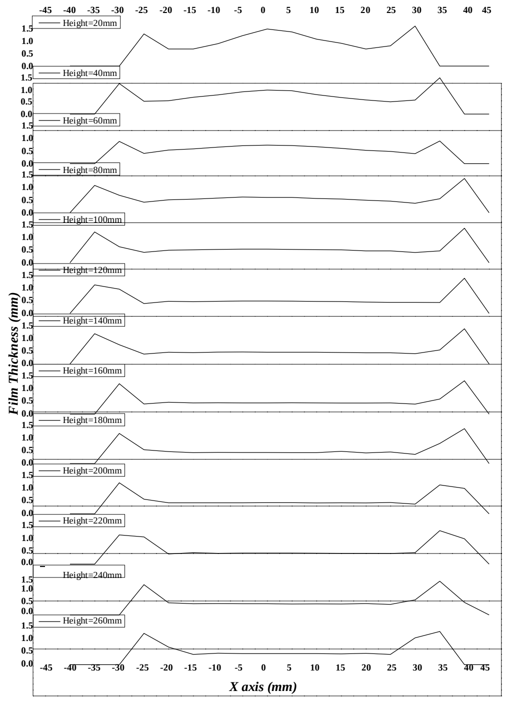


Fig. 8. Film flow w/o air

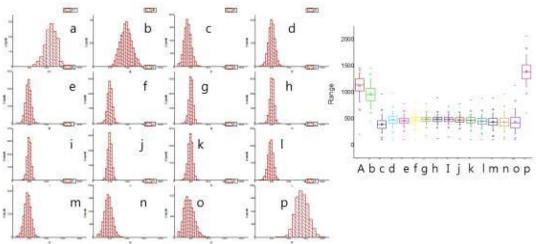


Fig. 9 Distribution of film flow on the horizontal line

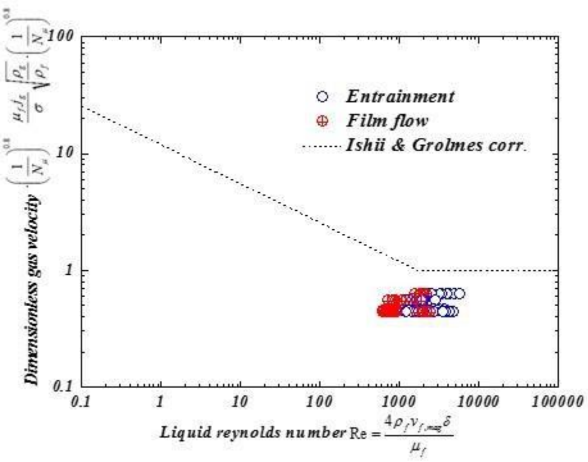


Fig. 10. Onset of droplet entrainment of vertical film flow on the wall and lateral air flow w/ Ishii's corr.

4.3. Droplet characteristics

Fig.11 provide detail information of droplet size and amount. In the Fig. 12, first graph is the sauter mean diameter by a height. And second graphy is the mean diameter by a height. Conclusion, we show that largest amount of the droplets are located in the region 5. and they are characterized with bigger sauter diameters than that in other region. In the other regions are reversely proportional to height except region 2 because of location of near nozzle.

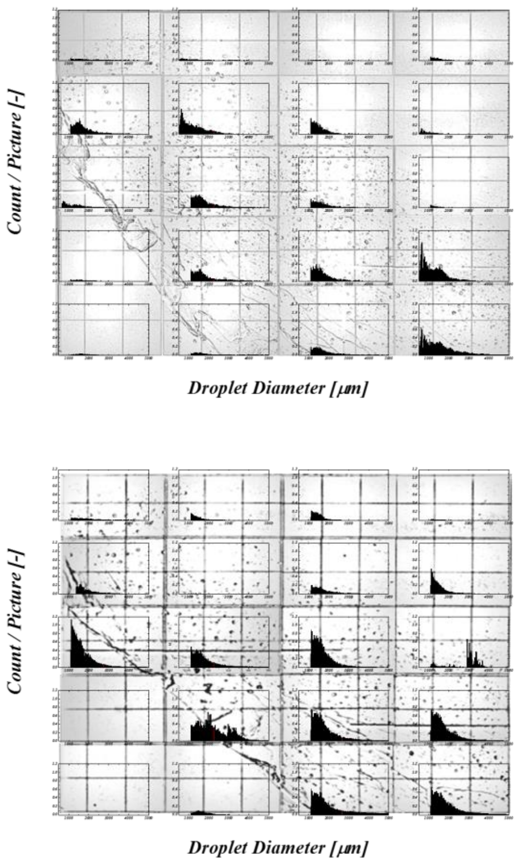


Fig.11. Total droplet size and amount (case F, G)

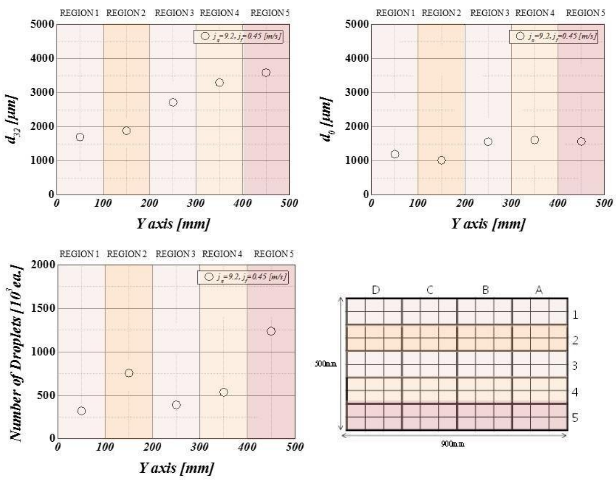


Fig. 12. Sauter mean diameter, mean diameter and amount by height

5. Conclusion

By measuring two dimensional film Reynolds number, we can predict the onset of droplet entrainment and obtain visible breakup region intuitively. By adopting both super hydrophobic coating method and shadowgraph method, entrainment in a narrow gap was successfully visualized that has rarely performed before and meaningful results for DVI system research fields have been made.

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