Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 29-30, 2015

PIV Visualization of Bubble Induced Flow Circulation in 2-D Rectangular Pool for Ex-Vessel Debris Bed Coolability

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1. Introduction

At Korea PWR, wet cavity strategy by flooding the cavity by the water coolant is adopted as the severe accident management measure [1]. If IVR-ERVC (in vessel retention of molten core through external reactor vessel cooling) is unsuccessful, molten core material will be discharged into the water pool in the reactor cavity following the vessel failure. By the interaction with the water in the cavity, the molten core is fragmented, solidified and settled on the cavity floor as a debris bed. The previous research works demonstrated the debris bed formation on the flooded cavity floor in experiments [2, 3].

Even in the cases the core melt is once solidified, the debris bed can be re-melted due to the decay heat. If the debris bed is not cooled enough by the coolant, the re-melted debris bed will react with the concrete base mat. This situation is called the molten core-concrete interaction (MCCI) which threatens the integrity of the containment by generated gases which pressurize the containment. Therefore securing the long term coolability of the debris bed in the cavity is crucial.

According to the previous research works, the natural convection driven by the rising bubbles affects the coolability and the formation of the debris bed [4, 5]. Therefore, clarification of the natural convection characteristics in and around the debris bed is important for evaluation of the coolability of the debris bed. In this study, two-phase flow around the debris bed in a 2D slice geometry is visualized by PIV method to obtain the velocity map of the flow.

2. Experiment

2.1 Experimental Facility

DAVINCI-PIV was developed to simulate the natural convection induced by the rising bubbles in the cavity and to visualize the flow by PIV. The system mainly consists of two parts for an experimental pool part and a visualization part. The experimental part consists of a transparent acrylic pool to visualize the natural circulation flow in the 2D cross section of the cavity pool, and an air injection equipment simulating boiling situation developed by the decay heat of the debris bed. And the visualization part consists of a laser system to conduct PIV by illuminating seeding particles in the experimental pool, and a high speed camera to record the flow around the particle bed which simulates the debris bed in the flooded cavity.

2.1.1. Experimental Pool Part

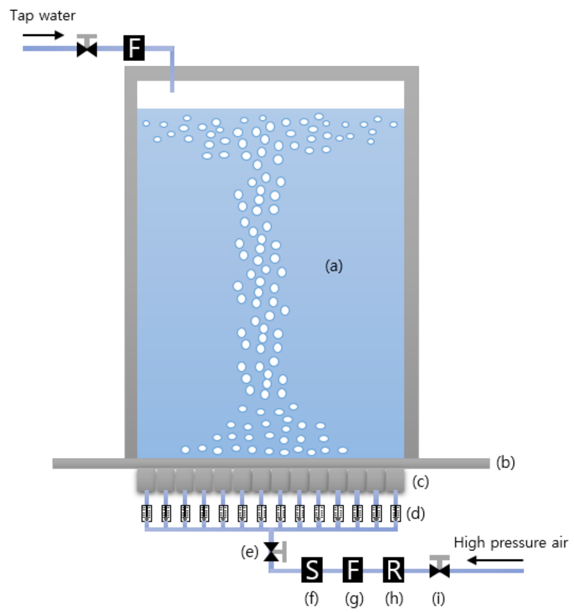

Fig. 1. Schematic diagram of the experimental pool: (a) Acrylic pool, (b) aluminum frame, (c) air chambers, (d) panel type air-flowmeters, (e) air valve, (f) digital air flow-meter, (g) air filter, (h) regulator

The experimental pool part was developed to simulate the two-phase flow induced by the decay heat. The experimental pool part consists of three parts for the acrylic pool, air chambers, and flow control system.

Figure 1 is a schematic diagram of the experimental pool part. The acrylic pool which has a dimension of 1.0 m height, 600 mm width, and 50 mm depth simulates 2D cross section of the cavity pool. Front, back, and both side of the pool were made with the transparent acrylic plate which has a dimension of 20 mm thickness. Therefore it is possible to illuminate the pool through the both side of the pool and to observe the flow through the front of the pool. The acrylic plates were fixed each other by M8 bolts, and installed on a metallic plate. And all junctions between the acrylic plates and the metallic plate were sealed with silicon to prevent the experimental pool from a leakage. In order to install a particle bed to simulate the debris bed on the cavity, it is necessary that the front plate of the experimental pool should be opened and closed freely. But if the bolts are used frequently to open and close the experimental pool, the acrylic plates can get damaged. Therefore a metallic frame was installed behind the front acrylic plate to prevent the acrylic plates from the damage. And the O-ring (NBR) which has a dimension of 5 mm diameter was installed in the metallic flame to prevent the experimental pool from leakage. There are 14 air-chambers installed below the metallic base plate to simulate the distribution of the bubbles generated from the decay heat. An air-line was connected to each air-chamber to supply air independently. Supplied air passing through air-holes on the metallic base plate makes bubbles to simulate nucleate boiling on the debris bed. There are totally 340 air-holes (20 holes for an air-chamber) which has a dimension of 1.5 mm diameter. These holes play a role as a bubble generator. A panel type flowmeter with control valve was connected to each air-line connected to an air-chamber. Therefore air flow rate can be controlled independently for the each air-chamber to simulate the distribution of the generated bubbles according to the shape of the debris bed. Dwyer's RMA-series were used for the panel type air-flowmeter. And the 14 panel type air-flowmeters were connected to a digital air-flowmeter in parallel to confirm total air flow rate supplied to the experimental pool. The digital air-flowmeter was PFM525-C8-1-A-WS (SMC) which has a range of flow rate from 0.5 to 25 liter/min, and operating pressure up to 1 MPa. In order to avoid to over the maximum operating pressure, a regulator was installed between the digital air-flowmeter and an air inlet. The regulator was AC30B-03G-A (SMC) which has a pressure gage and a pressure control valve to check and control the pressure of the supplied air.

2.1.2. Visualization Part

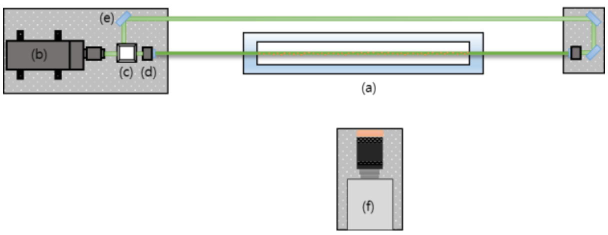

Fig. 2. Top view of the visualization system:
(a) experimental pool, (b) laser generator, (c) beam splitter, (d) cylindrical lens, (e) laser mirror, (f) high speed camera

In this experiment, the visualization of the flow in the experimental pool was conducted by PIV method. In order to visualize the flow, laser beam was used to illuminate seeding particles floated in the experimental pool. A 532 nm green DPSS laser (SLOC) which has maximum power of 5 W was used as a laser generator. The laser beam emitted from the laser generator was expanded to laser sheet which was perpendicular to the ground by a cylindrical lens. By the laser sheet, the seeding particles floated in the experimental pool were illuminated for 2D PIV. The cylindrical lens used in this experiment was 30° full fan angle laser line generator Lens (Edmond optics).

The laser is reflected and refracted in the interface of the bubble due to the difference of refractive index between water and air. In this experiment, most bubbles were generated in the center region of the experimental pool, so a bubble column was made in the center region of the experimental pool. In order to solve the problem that the laser was blocked by the bubble column, the laser was illuminated through the both side of the experimental pool. A beam-splitter (Edmond optics, 10 mm 532 nm, laser line polarizing cube beam splitter) was installed in front of the laser generator to divide the laser line into two laser lines. One laser line passed the beam-splitter and illuminated the experimental pool through the one side. And the other laser was reflected from the beam-splitter and shifted to the other side of the experimental pool by three laser mirrors. As a result, the other laser illuminated the other side of the pool. 532 nm 45°, Nd:YAG laser line mirrors which have a dimension of 12.5 mm diameter (Edmond optics) were used for the experiment.

When the laser reflected from the beam splitter went to the other side of the pool, the diameter of the laser was expanded. In this experiment, the diameter of the laser is expended from 3 mm to 10 mm. In order to avoid distortion of the laser beam, a convex lens (Edmond optics, 20.0 mm diameter x 100.0 mm FL, 532 nm V-Coat, PCX lens) and a concave lens (Edmond optics, 25mm diameter x -25 FL, VIS 0° coated, plano-concave lens) were used to decrease the diameter of the laser. The diameter of the laser passing through the convex lens decreased linearly. After passing through the concave lens which was in 75mm distance from the convex lens, the laser became parallel. Through this process, the diameter of the expended laser which was 10mm decreased back to 3 mm.

The two laser beams generated by the above process illuminated the same plane in the experimental pool. Therefore, the motion of the seeding particles floated in the plane were recorded by the high speed camera (Phantom, MIRO 310S). The flow velocity was calculated by cross correlation function between the two images recorded by the high speed camera.

2.2 Measurement (PIV)

In this experiment, measurement of the flow velocity was conducted by the PIV method. Fluorescent particles painted by rhodamine b were used as a seeding material. This fluorescent particle is small enough (20~50 μm) and has similar density (1.19 g/cm^3) with water, therefore it can follow the water flow.

To obtain the high quality image, maximum power (5 W) was used for this experiment. The fluorescent particles are excited by 540 nm light, and emits 580 nm light. This characteristic of the fluorescent particles prevents CCD sensor of the high speed camera from over exposure. Laser light reflected by the bubbles or the structure of the experimental pool is too strong, so the CCD sensor can be damaged. But the fluorescent particles emits light which has longer wavelength than the laser light. Therefore it is possible to block the laser light going to the high speed camera by a long pass filter. In this experiment, the long pass filter which has cut-off wavelength of 550 nm was used to block the laser light. As a result, only the light emitted by the fluorescent particles were recorded to the high speed camera. The other benefit of this method is that it is possible to observe the bubble interface clearly. Because the intensive light in the bubble interface is removed by this method [6].

In order to record the interesting region which has a dimension of 380 mm height and 600 mm width, a wide-angle lens (Nikon nikkor 28 mm 1:2.8D) was mounted on the high speed camera. The laser sheet illuminating the seeding particles in the experimental pool was in the focal plane of the camera. Every experiments were recorded by the high speed camera installed in front of the experimental pool. The image resolution was 1920×1200 pixels and 400 images were recorded in each second during 2.14 s.

The flow velocity was calculated from the consecutive images recorded by the high speed camera. Firstly a highest correlation between the two images were found by cross correlation function for an interrogation area to get a displacement of the particles. In this experiment, the interrogation area was 25×25 pixels. Next, the real displacement which has a dimension of millimeter (mm) was calculated by the calibration process. In order to conduct the calibration, the distance (mm) per pixels should be known. In this experiment, a reference object was placed in the focal plane inside the experimental pool, and a calibration image was recorded in the same recording condition with the experiment. After getting the information about Δx and Δy, the flow velocity (u, v) can be calculated by $\Delta x/\Delta t$, $\Delta y/\Delta t$. This process was conducted by the PIVlab which is the shared PIV software. The flow was quasi-steady state. Therefore the results calculated from the all images were averaged for 2.14 s.

2.3 Test Cases & Conditions

The experiments were conducted with the different geometry and the decay heat rate to investigate the effects of the debris bed characteristics on the natural convection in the ex-vessel cooling situation. In order to simulate the debris bed on the flooded cavity floor, a porous bed which was an isosceles triangle filled with 5 mm spheres was installed in the experimental pool. The volume and the porosity of the triangle structures were same for the all cases. But the base angle was different for the case 1, 2 and 3. In this paper the base angle is called the repose angle.

To investigate the effects of the geometry of the debris bed on the natural convection, the comparative experiments were conducted with the different repose angle. The air injection rate was 18 LPM for the cases. In the lowest repose angle cases, the air was injected through the 45 cm width of the pool bottom. In the highest repose angle cases, the air was injected though the 24 cm of the pool bottom. To investigate the effects of the decay heat rate of the debris bed on the natural convection, the geometry of the triangle structure was constant and the air injection rate was different for the cases. The repose angle was 45°, and the air injection rates were 10, 14, 18 LPM respectively. All the cases for the experiments are listed on the table 1.

Table I: Specifications of the test cases

	Repose angle (Degree)	Air injection rate (Liter/min)
Uni. #01	15	18
Uni. #02	30	18
Uni. #03	45	18
Uni. #04	45	14
Uni. #05	45	10

3. Results

The experiments were conducted with the different repose angle and the air injection rate to investigate the effects of the debris bed characteristics on the natural convection. Figure 3 to 7 show the velocity field of the each experiment. The color map represents the velocity magnitude, and the white line means the streamline. From the images, it is recognized that the natural circulation flow is generated by the rising bubbles. The released bubble from the particle bed structure made a bubble column in the center of the pool. This bubble column dragged ambient coolant, so up-flow was generated in the center of the pool. After reaching to the surface of the water pool, the up-flow returned down through the side of the pool. By this process the circulation flows were generated in the both side of the bubble column. From the figures, it is noticed that stagnant area was in the bottom corner of the pool. The velocity magnitude was comparatively low in the stagnant region.

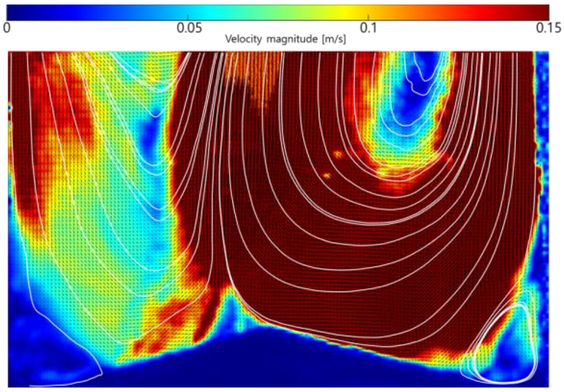

Fig. 3. Velocity field of Uni. #1
color map: velocity magnitude, white line: stream line

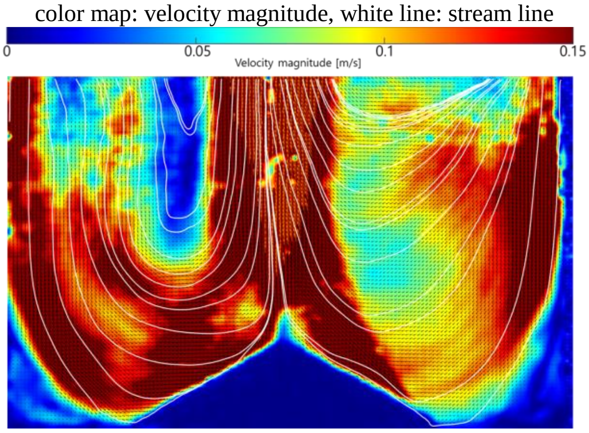

Fig. 4. Velocity field of Uni. #2

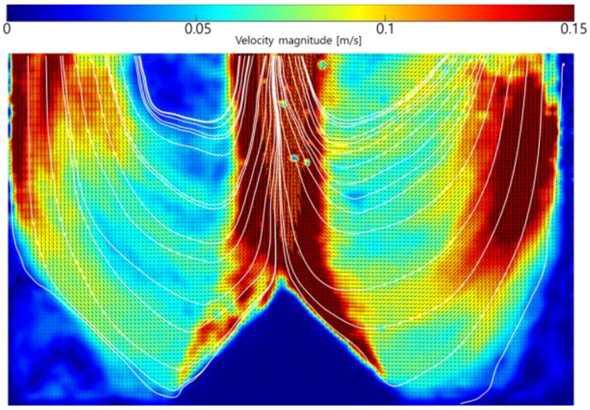

Fig. 5. Velocity field of Uni. #3

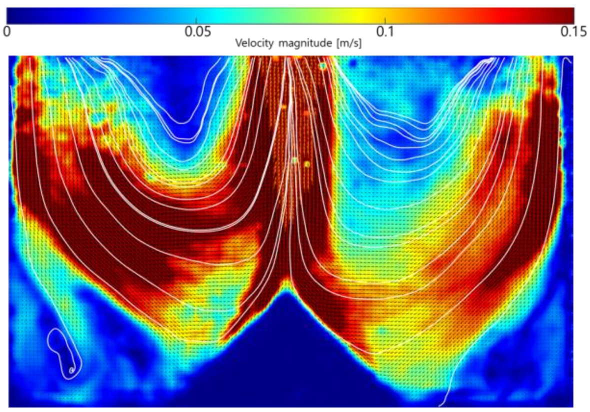

Fig. 6. Velocity field of Uni. #4

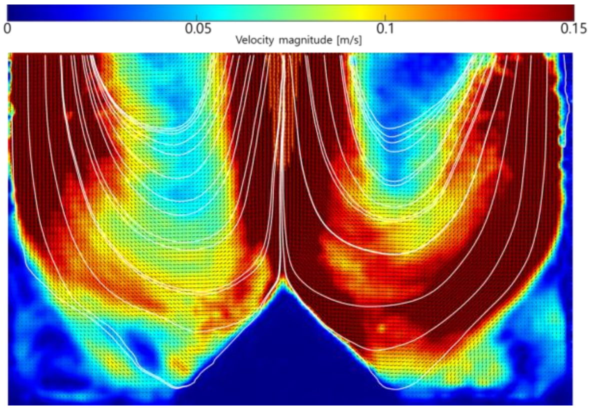

Fig. 7. Velocity field of Uni. #5

3. Conclusions

The DAVINCI-PIV was developed to investigate the flow around the debris bed. In order to simulate the boiling phenomena induced by the decay heat of the debris bed, the air was injected separately by the air chamber system which consists of the 14 air-flowmeters. The circulation flow developed by the rising bubbles was visualized by PIV method. As a result, the velocity field in the experimental pool was obtained.

The experiments were conducted to investigate the effects of the characteristics of the debris bed on the natural convection. The velocity map shows the flow pattern and the velocity magnitude of the natural convection. The results can be used for validation of simulation codes.

Acknowledgments

This work was also co-sponsored by the Nuclear Safety Research Program of the Korea Radiation Safety Foundation grants funded by Korean government (NSSC) (Grant Code: 1305008-0113-HD140)

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