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EXPERIMENTAL OBSERVATION OF AIR/WATER MULTI-DIMENSIONAL FLOW IN A TRANSPARENT TEST SECTION WITH SLAB GEOMETRY

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ABSTRACT
Multi-dimensional two-phase phenomena are occurred in many industrial applications, especially nuclear reactor during steady operation or postulated transient conditions which are sometimes considered to significantly affect on a reactor safety. In order to validate a newly developing computational safety analysis code, SPACE, a two-dimensional two-phase flow test is performed with a test section having slab geometry with a dimension of 1.45m X 1.45m X 0.11m. The test section has three inlet nozzles and three outlet nozzles with upward direction and two outlet nozzles having perpendicular direction to the mixture flow in the test section by attaching those on a surface. The latter ones are in order to simulate a multi-dimensional flow in a downcomer near a postulated broken cold leg during LOCA. Various kind of two-dimensional flow is simulated with a selection of inlet and outlet nozzles. In this study, visualization is performed by using a CCD camera and image analysis technique, from which detailed information for the two-dimensional movement of two-phase flow is quantified.

INTRODUCTION
Recently, analysis for a multi-dimensional flow becomes a very challenging topic in many thermal hydraulic applications such as nuclear reactor safety. The conventional analysis for the two-phase flow during a transient period of nuclear reactor has been based on one-dimensional approach since most of concerns related to the safety of the nuclear reactor have been placed on overall system behavior mainly caused from one-dimensional flow. However, multi-dimensional phenomena are occurred in many occasions which are sometimes considered to significantly affect on the reactor safety.[1] Although many unknown phenomena are related to the multi-dimensional flow, many unsolved phenomena still came from one-dimensional behavior at the past several decades. Recently, as most of unknown phenomena have been understood and appropriate models have been developed, the interests are beginning to be moved to quantification and development of model for the multi-dimensional flow. With respect to that, a necessity for the clarification for the uncertainty induced by the applied assumption for the multi-dimensional phenomena is increased.

According to enhanced capacity of CFD(computational fluid dynamics) code, the research activity becomes to be active for the applicability of system analysis code to the multi-dimensional flow field. Along with the modern tend of the safety analysis for the nuclear reactor, a new system analysis code, named SPACE, has been developed based on two-fluid and three field model in KAERI.[2] It has a capability of the multi-dimensional flow application with a component scale. To validate the performance of SPACE, many experimental data should be utilized for various thermal hydraulic models. In the literatures, very limited experiments were found for the large scale of multi-dimensional flow. Bukhari and Lahey Jr. performed a two-dimensional experiment with a slab geometry of a test section having a dimension of 0.91m X 0.91m X 0.0127m.[3] Void fraction data was taken at 27 locations of slab plate. A single-beam gamma ray attenuation technique was used to determine the void fraction distribution within the 2-D test section for various boundary conditions including a recirculation flow condition.

The present study focuses on the quantification of adiabatic two-dimensional flow in large slab geometry. The facility has a test section having slab geometry with a dimension of 1.45m X 1.45m X 0.11m which is made of acrylic plates having 30mm thickness. To remove the wall effect induced by slug bubble, the gap thickness is designed to be 0.11m which is over than the stable maximum bubble size. The operating temperature is 35 °C under a control of a heater and a cooler imbedded in the storage tank. The test section has three inlet nozzles and three outlet nozzles with upward direction and two outlet nozzles in perpendicular direction to the surface which is representing the cold leg connection to a downcomer. Various combinations with a selection of inlet and outlet are set for the test matrix. In this study, visualization is performed by using a CCD camera and image analysis technique, from which detailed information for the two-dimensional movement of two-phase flow is quantified. The data will be directly utilized to validate the SPACE code.

EXPERIMENTAL FACILITY

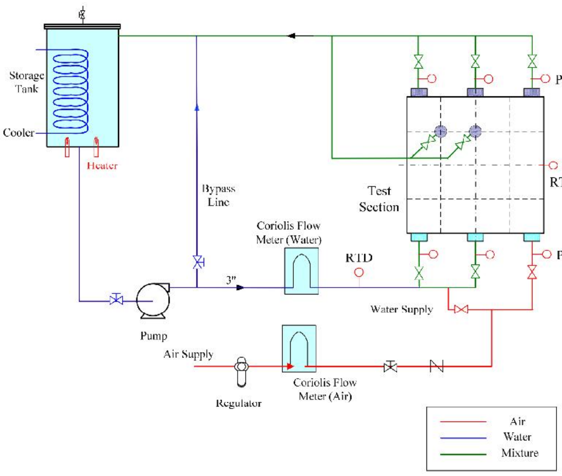


Figure 1 Schematics of test facilities

Figure 1 shows a schematic of the test facility. The test facility consists of a test section, water and air supply systems, storage tank including temperature control devices and a pump. Air is supplied from large size of compressor which is maintained at 6 gage bars which have a maximum capacity of 0.1 kg/sec at atmospheric test condition. At the upstream part, a regulator controls the air injection pressure before air is delivered to the test section. The system water temperature is controlled by cooler and heater imbedded in the storage tank which is installed at the top elevation of the facility. The water flow is supplied with centrifugal pump which has a 92m head and a capacity of 100 m^3/hr of which the impeller speed is controlled by inverter. A bypass line is established for an efficient control of the water flow.

Test section has a dimension of 1.45m X 1.45m X 0.11m based on the internal fluid volume. In order to reduce the wall shear effect induced by large slug, two transparent acrylic plates are installed with a gap dimension of 0.11cm which is corresponding to the maximum stable bubble size at the atmospheric pressure condition. Each acrylic plate has a 30mm thickness. Two support bars are installed on both faces of acrylic plates to prevent inflation induced by hydrostatic head of water. A steel frame is designed to support the weight of the fluid and acrylic structure. The test section has three inlet nozzles and five outlet nozzles. All the nozzles have a size of 3". One of the three inlet nozzles is connected only to air supply line. By using each of the other two inlet nozzle, one can supply single phase water and two phase mixture flow. Three out nozzles are installed at the top face of steel structure, in the meanwhile, two outlet nozzles which are installed on the face of an acrylic plate. The latter ones are established to simulate qualitatively the multi-dimensional flow in the downcomer for a postulated cold leg break LOCA. The nozzle is corresponding to the broken cold leg. With selecting a combination of inlet and outlet nozzles, various kind of multi-dimensional flow behavior can be simulated. In the present study, combinations of one inlet and one outlet nozzles form a test matrix. When a test case selected, engineering plastics are filled up in the outlet nozzles which are not utilized in order to make a smooth wall at inner surface and remove air pocket effect induced by the stagnant volume between test section and outlet valve. Figure 2 shows a photograph of the test section and components at the inlet and outlet of it.

Figure 2 Photograph of test facilities

INSTRUMENTATION AND ANALYSIS TECHNIQUE

Several kinds of commercially available instruments were installed in order to measure the boundary conditions. The location of the instrumentation is shown in Figure 1. A mass flow rate of injected water is measured by 3" Micromotion mass flow meter that is installed at the water supply line. The estimated uncertainty for a measured mass flow is 0.1% of its read value. An 1" Micromotion mass flow meter is used to measure an air flow at the air supply line of which the accuracy is 0.5%. The system pressure is measured at the top and bottom of the test section by two SMART-type PTs (pressure transmitter). The pressure tabs are connected to corresponding PT with common line, which is selected according to used flow path. The estimated uncertainty of each PT reading is 0.065% of full scale. To measure the temperature of fluid, two RTDs are installed at water supply line and side of test section, respectively. A Watrow class A 3-wire standard plug type of 0.25" RTD is used. The uncertainty of RTD is expected to be 0.2 ^{o}C at 35 ^{o}C of operation condition.

In the present work, the PIV technique is used to measure the velocity field of an air/water flow with different air/water flow rate. In recent years, the PIV measurement technique has shown very promising results in fluid flow researches and has been used very extensively for velocity field measurements in particular due to its non-intrusive capability. A typical PIV system consisting of two functions, i.e., image capture and image analysis, was used. In the image capture system, the light source is a day-light. Sony HDCAM (1920×1080 pixels) is operating in a continuous mode. Frame rate of recording device is 30 Hz. Field of view is 1500×1800mm and test area is cropped with 400×480 pixels. Air bubbles can be incidentally used as tracer particles. It is thought that air bubbles are small enough to follow a multi-dimensional flow with a high momentum.

Table 1 Test Matrix

#	Case	Inlet Nozzle	Outlet Nozzle	mf (kg/s)	mg (g/s)	Temp
1	AB01-V	IA	OB	4	2	35ºC
2	AB02-V	IA	OB	4	20	35ºC
3	AB03-V	IA	OB	20	2	35ºC
4	AB04-V	IA	OB	20	20	35ºC
5	AC01-V	IA	OC	4	2	35ºC
6	AC02-V	IA	OC	4	20	35ºC
7	AC03-V	IA	OC	20	2	35ºC
8	AC04-V	IA	OC	20	20	35ºC
9	BB01-V	IB	OB	4	2	35ºC
10	BB02-V	IB	OB	4	20	35ºC
11	BB03-V	IB	OB	20	2	35ºC
12	BB04-V	IB	OB	20	20	35ºC
13	BC01-V	IB	OC	4	2	35ºC
14	BC02-V	IB	OC	4	20	35ºC
15	BC03-V	IB	OC	20	2	35ºC
16	BC04-V	IB	OC	20	20	35ºC
17	AD01-V	IA	OD	4	2	35ºC
18	AD02-V	IA	OD	4	20	35ºC
19	AD03-V	IA	OD	20	2	35ºC
20	AD04-V	IA	OD	20	20	35ºC
21	AE01-V	IA	OE	4	2	35ºC
22	AE02-V	IA	OE	4	20	35ºC
23	AE03-V	IA	OE	20	2	35ºC
24	AE04-V	IA	OE	20	20	35ºC
25	BD01-V	IB	OD	4	2	35ºC
26	BD02-V	IB	OD	4	20	35ºC
27	BD03-V	IB	OD	20	2	35ºC
28	BD04-V	IB	OD	20	20	35ºC
29	BE01-V	IB	OE	4	2	35ºC
30	BE02-V	IB	OE	4	20	35ºC
31	BE03-V	IB	OE	20	2	35ºC
32	BE04-V	IB	OE	20	20	35ºC

In the process of the image analysis, we have used the adoptive cross-correlation (ACC) algorithm, which would be rather useful in the case of measuring the velocity for the free shear layer, where a larger velocity gradient inside an observation area may exist and possibly introduce an erroneous calculation and/or under estimation. For this reason, two steps of an ACC are adopted in this work. The initial interrogation widow is 32×32 pixels and then the refinement process is conducted at 16×16 pixels over the 1 step.

RESULTS

Two inlets which are IA and IB of figure 3 and four outlets which are OB, OC, OD and OE were utilized, which makes 8 combinations of inlet and outlet nozzles. For each pair of inlet and outlet nozzles, four test conditions which are large and small of water and air flow rates were chosen. Table 1 summaries the target values of test matrix for major parameters related to the boundary conditions.

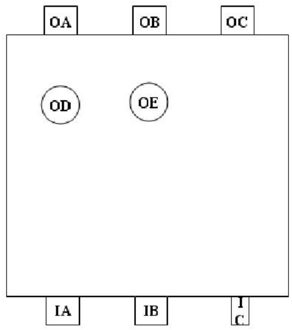


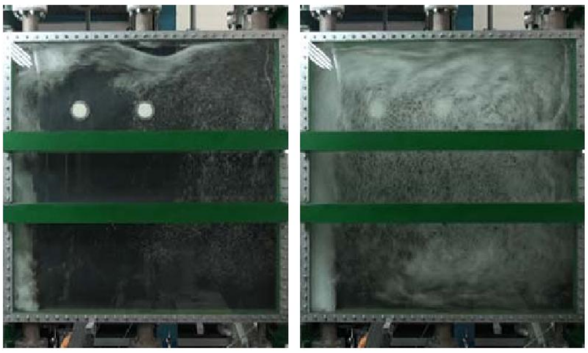
Figure 3 Identification of Inlet and Outlet

In the present study, typical 6 cases were selected among the total test cases which are summarized in table 2.

Table 2 Thermal Hydraulic Conditions for the Typical Cases

Case	Value	M_f (kg/s)	M_g (g/s)	TF (°C)	P_{out} (kPa)
AC01-V	Average	4.02	2.09	35.11	124.40
	STD (%)	2.06	4.71	0.18	0.52
AC04-V	Average	19.99	20.40	35.12	147.77
	STD (%)	0.24	0.90	0.29	1.15
BC01-V	Average	4.06	2.04	34.77	124.29
	STD (%)	2.22	4.90	0.21	0.59
BC04-V	Average	20.14	19.89	35.33	147.35
	STD (%)	0.50	0.86	0.08	2.20
AD01-V	Average	3.91	1.93	35.13	128.66
	STD (%)	5.29	4.48	0.09	1.37
AD04-V	Average	19.95	8.13	35.78	169.36
	STD (%)	0.33	1.86	0.10	0.59

Figure 4 shows visualization results for the AC01-V and AC04-V which are the case of inlet A and outlet D combination, respectively. For lower flow case, most of air flow is going through near the side wall and top wall and delivered to the outlet nozzle. Since the air flow is slow, the separated bubbles are easily collapsed with a sufficient contact time, which induces an air pocket at the top part of the test section as shown in figure 4(a). Generally the low flow case does not have a significant multi-dimensional flow. In the meanwhile, large air and water flow cases induces a strong turbulence in which condition a stable air pocket is hard to be maintained at the top region. Near the left wall, a high velocity of two-phase flow is formed, which induce a nearly one-dimensional upward flow. On the other hand, the region except for the left air column shows a strong multi-dimensional behavior as shown in figure 4(b).



(a) AC01-V (b) AC04-V

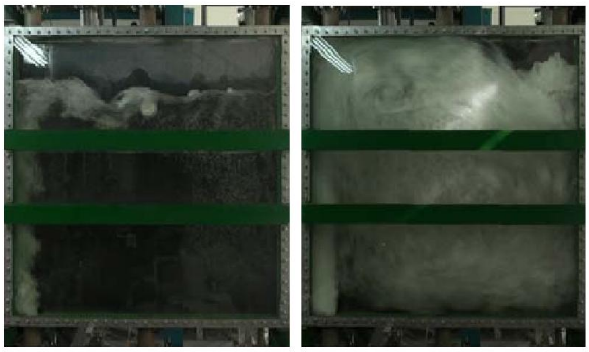
Figure 4 IA-OC Combination of Inlet-Outlet

(a) BC01-V (b) BC04-V

Figure 5 IB-OC Combination of Inlet-Outlet

Figure 5 shows results for the combination of Inlet B and Outlet C. For lower flow case, an air space is formed on the left top part which is the opposite side of the exit nozzle. It is also expected by a collapsing the air bubbles in a stagnant zone. A sufficient moving velocity near the exit nozzle prevents a separation of each phase. For the high flow case for both phases, the large amount of air forms a larger air space at the left upper region of the test section as shown in figure 5(b).

Figure 6 shows results for the combination of Inlet A and Outlet D. For lower flow case, the liquid level is reduced to the level of the exit nozzle. Most air flow forms between injection nozzle and outlet nozzle. Just small amount of air is circulated over the test section. In the meanwhile, high circulated flow is formed with having a center at the outlet nozzle which is place on the surface of the plate as shown in figure 6(b).



(a) AD01-V (b) AD04-V

Figure 6 IA-OD Combination of Inlet-Outlet

With the current images, velocity vectors of air were analysed by using PIV technique. Figure 7 and 8 show the results of the instantaneous and time averaged air velocity vectors, respectively for the AC01-V. Two hundred instantaneous data were utilized for the time averaged data. For the lower flow case, the image analysis shows a good representation of the visualization except for the left upper section where a high void fraction is formulated. Since the image at the high void fraction region shows a nearly constant intensity, the interface can hard to be caught for measuring particle velocity. The problem can be solved by taking images with a higher resolution of time and space, which is scheduled in the further study. Figure 9 shows an image analysis results for the AD01-V. The velocity plot also represents the visualization well.

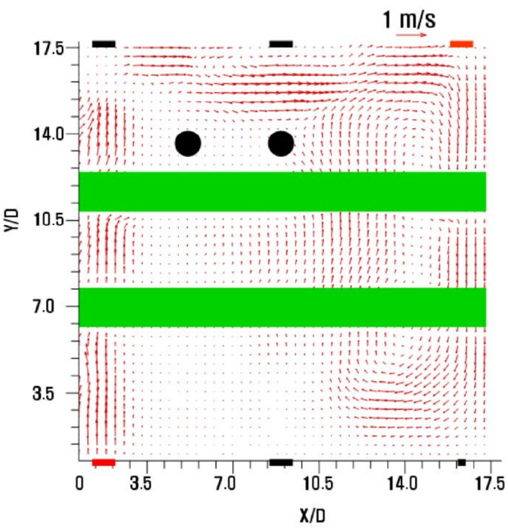


Figure 7 Instantaneous Air Velocity Profile for AC01-V

In general, the PIV technique used in the image analysis is efficient for velocity measurement of the multi-dimensional two-phase flow being shown in this study. However, for large flow condition or the region where large amount of air is gathered, higher time and spatial resolution of images are required to get an improved velocity data.

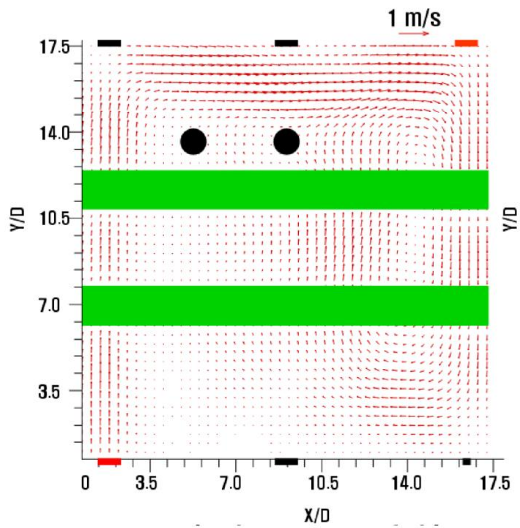


Figure 8 Time Averaged Air Velocity Profile for AC01-V

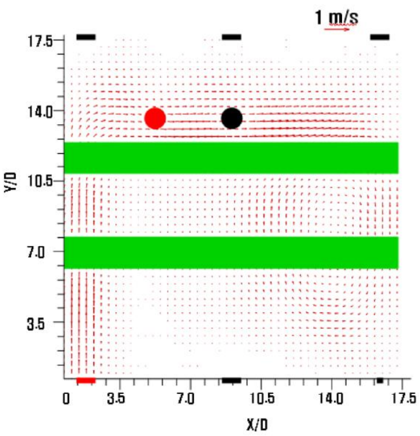


Figure 9 Time Averaged Air Velocity Profile for AD01-V

CONCLUSION

To identify and generate an experimental data for the two-dimensional two-phase flow, an experiment has been performed with a large scale of slab geometry. With a various selection of combination of inlet and outlet of the test section, lots of multi-dimensional two-phase flows were visualized. By using a PIV technique, a movement of the gas phase could be quantified. For lower void fraction cases, the image analysis was successful; in the meanwhile, a definite velocity vector cannot be obtained for a large air flow condition. The problem will be solved in the next study by enhancing the time and spatial resolution of the images. In the future, the test section will be improved to measure void fraction profile by developing an impedance measurement system with attachment of electrodes on inner surface of each acrylic plate. From the studies, a complete set of the void fraction and velocity profile will be obtained for a given geometry of test section and for a various multi-dimensional two-phase flow conditions. The experimental data will be utilized to validate and develop many thermal hydraulic models related to the momentum equation.

ACKNOWLEGEMENT

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