Local Void Fraction Distribution and Flow Visualization in Core Catcher Coolant Channel

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1. Introduction

Core catcher cooling system is designed to cool molten core ejected from reactor vessel and captured in the core catcher following a severe accident. It consists of a large nearly horizontal plate with two symmetrical inclined sections and vertical sections, located below the reactor pressure vessel. Due to thermal induced density differences of working fluids, natural circulation two-phase flow passively removes heat from the captured corium [1].

To have a better knowledge of cooling performance inside of the channel, it is important to know two-phase structure inside of the cooling channel. The prediction of the two-phase flow behavior has a limitation in such a complex geometry with large hydraulic diameter.

Therefore, in this study, testing of two-phase natural circulation using air-water in a full height facility is conducted specifically to visualize and study the two-phase flow structure near the channel surface. By using conductivity probe, time-averaged local void fraction distribution along the channel is obtained. At the same time, mixing and bubble breakup process at the elbow-bend is observed using high speed camera videos. The impact of the two phase flow behavior near the core plate on the cooling performance is analyzed based on the results.

2. Experimental Description

In the design of the scaled testy facility scaling analysis was carried out to identify key scaling parameters, so that model facility could simulates two-phase natural circulation similar to prototype core-catcher cooling system [2]. Based on the analysis a test facility was constructed to carry out tests with air-water system.

2.1 Experimental Setup

A scaled test facility of core catcher cooling system is shown in Fig. 1. The cross sectional area of coolant channel is 30 cm × 10 cm which is 15 cm hydraulic diameter. The length of horizontal, inclined, and vertical channel is 300, 2540, 1450 mm respectively, and inclined to vertical elbow-bend is 300 mm. The test facility was provided with instrumentations for two-phase natural circulation flow measurement. A test channel made of transparent polycarbonate channel has a the followings sections; horizontal section, a section with 10° inclined, a section with 50° elbow-bend and vertical section. High speed camera is used to visualize two-phase flow with 1000 frames per second.

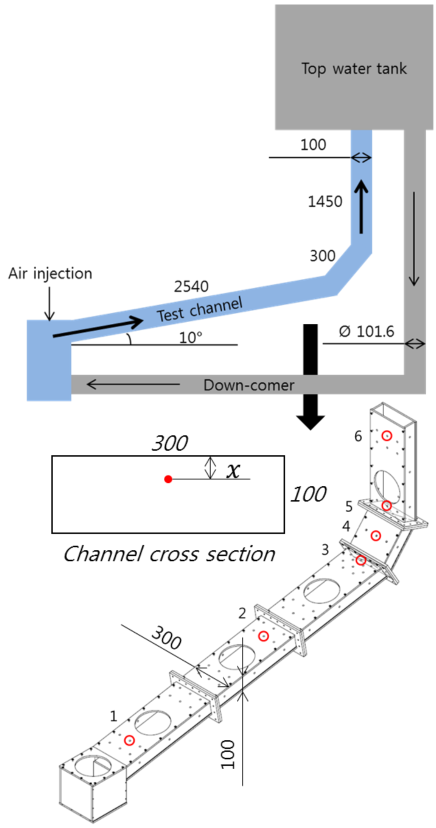

Fig. 1. Experimental facility and test section

From the top side of the horizontal flow channel, air is injected to simulate bubble generation during boiling at core plate. Air flow rates are measured with rotameters with a least count of 10 L/min. Six sets of conductivity probes are mounted on the top wall of the channel at 1 to 6 shown in Fig. 1 to measure the local void fraction. At each position, probes are inserted different depth (x) from the top surface to obtain local void fraction profile. Time-averaged local void fraction defined as a ratio of time for probe tip being surrounded by air to total time is obtained by probe having 0.203 mm diameter tip which is able to sense liquid and vapor phase. Data is acquired in 40 seconds with 20 kHz of sampling rate.

Down-comer pipe where the liquid single phase returns to the flow channel is a 4-inch diameter pipe which provides scaled flow loss in the flow. Natural circulation flow rate is measured by paddle type flow meter which is located at down-comer horizontal line, and transmitter averages flow rate within 50 seconds. Accuracy of the flow meter and transmitter are ±1 and ±0.5 % respectively.

2.2 Natural Circulation Flow Rate

After air is supplied to the inlet, natural circulation two-phase flow starts through an inclined to vertical test section. Air escapes to atmosphere through top water tank, and single phase water is re-circulated to the test loop. Steady state is accomplished when 50 seconds-averaged natural circulation flow rate is not fluctuated over ±4 L/min. Natural circulation flow rate is determined by a balance between the pressure drop and hydrostatic head difference. Table I shows the natural circulation flow rate as a change of supplied air flow rate from 100 L/min to 500 L/min. Each case is measured 16 times and averaged. Maximum difference in one air flow rate case is 5.9%.

Table I: Time-averaged natural circulation flow rate
(Q: Volumetric flow rate, j: superficial velocity; G: Mass flux; subscript g: gas phase, subscript l: liquid phase)

Q_g (L/min)	100	200	300	400	500
j_g (m/s)	0.056	0.111	0.167	0.222	0.278
Q_l (L/min)	315	394	461	509	547
j_l (m/s)	0.175	0.219	0.256	0.283	0.304
G_l (kg/m^{2}sec)	668	835	978	1079	1162

3. Results

3.1 Local void fraction distribution

Fig. 2 shows the distribution of local void fraction measured at 0.5 cm and 1.0 cm away from top surface. Since top wall of the coolant channel is heated and cooled in core catcher prototype, void fraction near the top surface is of major interest in this experiment.

As shown in Fig. 2, local void fraction generally decreases as flowing downstream. Near the inlet, most of the air flow through upside of the channel like wavy flow, while it becomes large slug at downstream of inclined channel. Therefore, local void fraction near the top wall decreases along inclined channel. However, the decreasing trend changes abruptly at elbow-bend where L/D between 17 and 19. Local void fraction near top surface at the elbow-bend is sharply lower than that of other locations. This implies that at the elbow-bend, liquid touches more frequently the top surface of the channel, which has a positive effect on cooling performance. Bubble breakup at the bend makes local void fraction near top surface be lower. Fig. 4 is the high speed camera view which shows breakup of large slug. A slug maintains its shape until slug tail enters elbow-bend. Once its tail enters elbow-bend entrance, the slug is broken into small bubbles. Breakup starts from the tail of slug and complete breakup process takes less than 0.1 second. Sudden change of inclination accelerates and finally breaks up the slug by means of water ingression. Since gas phase is accelerated and breaks soon at the bend, an upper surface is normally wet. Such flow transition can be found in a Fig. 3 graph. Horizontal axis depth is distance from top surface which indicates 0 as a top surface while 10 as a bottom surface. In locations 1, 2, and 3 at inclined channel, the void fraction near the top wall is the highest and decreases away from the top surface towards the bottom of the channel. However it clearly showns that the void fraction profile at location 4 suddenly changes. Since top surface is weted by water ingression, void fraction at top surface is very low and has a peak at 1.5 cm away from the top surface. Air-water two-phase mixing is observed while passing elbow-bend. In vertical channel, already broken small bubbles make shape of void fraction center peak similar to general large diameter vertical pipes [3].

3.2 Safety advantages

Since local void fraction near top wall of the elbow-bend is clearly lower than that of inclined channel, it is desirable to increase the local heat transfer coefficient, which makes the core catcher system cool the decay heat more efficiently. For elbow bend to vertical section the voids are distributed throughout the test section by the mixing phenomena and the air is accelerated by buoyancy effect which provides good nucleate boiling heat transfer. This ensures less probability of forming dry spot which makes local dry out. In the severe accident case, although void fraction increases towards downstream because of bubble generation, better heat transfer performance is expected due to the flow behavior inside of the core catcher coolant channel.

4. Conclusions

Time-averaged local void fraction is measured and analyzed especially near the top surface of channel to predict cooling performance of core catcher system. Bubble breakup due to water ingression and the mixing phenomena are observed by high speed camera view. Sudden change of flow structure is produced passing through the elbow bend because of bubble breakup caused by water ingression. This transition is quantitatively analyzed by using local void fraction distribution and profile. Remarkably low local void fraction at the top surface of the elbow-bend is measured, which is desirable to increase the local heat transfer coefficient.

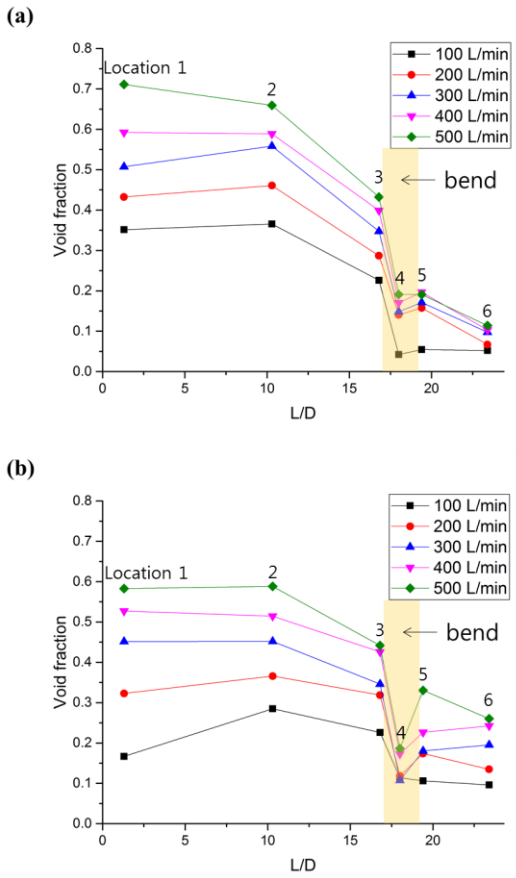

Fig. 2. Time-averaged local void fraction at; (a): 0.5 cm from top surface, (b): 1 cm from top surface

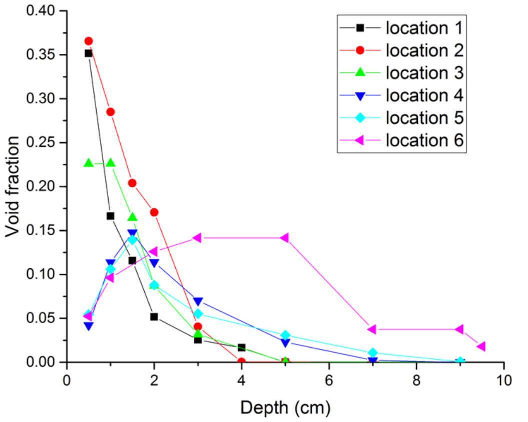

Fig. 3. Time-averaged local void fraction at Q_g = 100 L/m

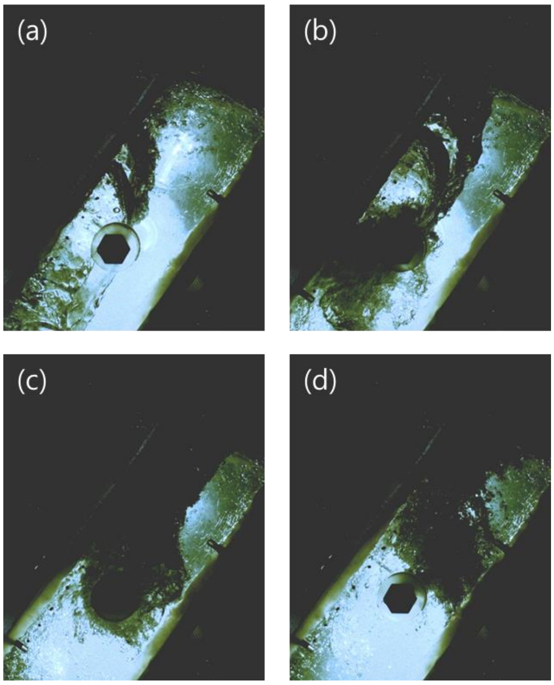

Fig. 4. Time-averaged local void fraction at jg = 0.056 m/s, jl = 0.175 m/s; (a) 0 sec, (b) 0.05 sec (c) 0.1 sec (d) 0.15 sec;

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