Validation of RV model in CUPID code against a rod bundle test, SIRIUS-3D, and design of a new rod bundle test

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1. Introduction

LOCA (loss of coolant accident) is one of major concerns related to safety issues of nuclear fuel. Flow characteristics inside nuclear core (rod bundle) under LOCA have been investigated by several researchers. One characteristic is multi-dimensional mixing under accidents because of non-uniform heat flux among fuel assemblies and fuel rods, or asymmetric heat removal through steam generators. The mixing can suppress the peak cladding temperature of fuels in a core. For example, Cathare 3D code showed the effect of cross flow, e.g. chimney effect [1]. There have been a few rod-bundle tests at high pressure and temperature to be used for code validation [2-3].

Regardless of the need for the 3D code validation, especially models related to mixing phenomenon, the validation is not sufficient. Because of that, further validation was conducted using SIRIUS-3D rod bundle tests, and new experiment facility was designed.

2. Validation of RV model in CUPID code against a rod bundle test

2.1 CUPID Code

Because of computing power limit, reactor system is traditionally simulated by 1 dimensional code with hundreds of cells with conservative assumptions. However, multi-D phenomena takes place in the core. CUPID is a three-dimensional thermal hydraulic analysis code developed by KAERI [4]. Specifically, CUPID-RV is developed to simulate each subchannel, or each fuel rod. For example, full-core calculation with subchannel-scale resolution was carried out for a design basis accident [5].

In the code, different models were applied for lateral and flow directions in momentum equations. Pressure drop, or friction factor, in flow direction is calculated by correlations. Pressure drop, or form loss, in the lateral direction is calculated by defining the form loss coefficient by the user. Two models, EVVD(Equal Volume exchange and Void Drift) and EM(Equal Mass exchange), are available for turbulent mixing and void drift. For two-phase flow, EVVD model is appropriate.

2.2. SIRIUS-3D test and calculation set-up

SIRIUS-3D is a 5×5 rod bundle test facility with a heater rod length of 3.71 m, equivalent to the actual fuel length. In one test, subchannel void sensors were installed at different elevations to measure the void fraction, bubble velocity, and bubble size distribution with high spatial resolution at eight elevations [6]. The pressure, inlet temperature, and flow velocity were varied: 1 MPa ~ 7.25 MPa, 172 °C ~ 280 °C, and 0.1 m/s ~ 0.5 m/s, respectively. Heat flux was uniform both radially and axially. In the other test, X-ray CT was used to measure the void fraction distribution at five elevations [7]. The test pressure was 7.2 MPa. The inlet temperature and inlet mass flux were varied: 270.6 °C ~ 284 °C, and 500 kg/m2s ~ 1250 kg/m2s, respectively. The flow velocity was higher than the test with SCVS. In the test with X-ray CT, the radial non-uniform heating was made with 2 or 4 non-heated heaters, leading to enhanced cross flow. The flow regimes of both tests ranged from single-phase flow to churn flow.

To validate the tests data, subchannel-scale nodes were constructed for CUPID calculation as shown in Fig. 1. Each node represents individual subchannel. The axial node number was around 110, with an axial node length of 40 mm. The Chen correlation was used for nucleate boiling, and the EVVD model was used for turbulence mixing and void drift.

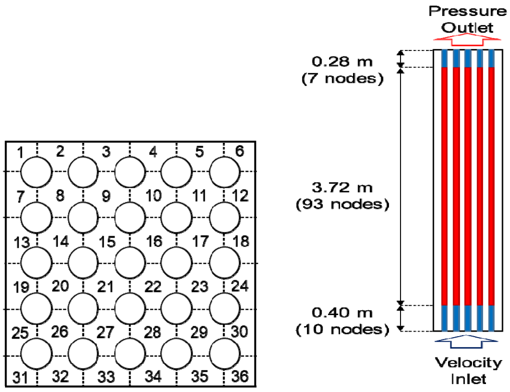

Fig. 1. Computation domain for SIRIUS-3D (left: subchannel arrangement, right: axial direction)

2.3 Validation result

Fig. 2 shows the comparison of the area-averaged void fraction between experiment and CUPID code calculation for the tests with SCVS [6]. The average void fraction was roughly predicted. The prediction error was 0.066 for the 30 test cases.

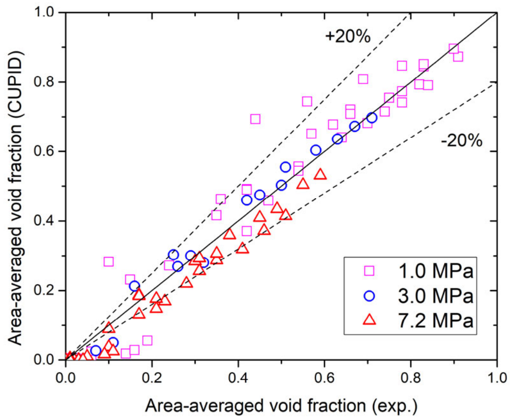

Fig. 2. Area-averaged void fraction prediction for SIRIUS-3D test with SCVS(2022)

Void distribution is given for one case in Fig. 3. The subchannel position number corresponds to numbers in Fig. 1 (left). Red one represents void fraction at low elevation of 1.22 m. No bubble is generated. Because of vapor generation at the heater, more bubbles are measured at higher elevation of 2.44 m and 3.78 m. Void fraction has an inverted U shape: velocity is low at the wall and high at the center. The calculation underpredicted the void fraction for this case. Bottom figure shows the gas velocity. Same with the void fraction, the gas velocity was underpredicted. The EVVD model had little impact for the calculation.

The test with X-ray CT explored the void drift phenomenon using non-uniform heater arrangement [7]. Fig. 4 shows comparison of the area-averaged void fraction between experiment and calculation. Compared to the previous test, the velocity was higher (0.1 – 0.5 m/s for 2022 tests vs 0.66 – 1.66 m/s for 2023 tests). The average void fraction was precisely predicted. The prediction error was 0.024. The better prediction is anticipated to be related to higher flow velocity or more accurate measurement by the X-ray CT.

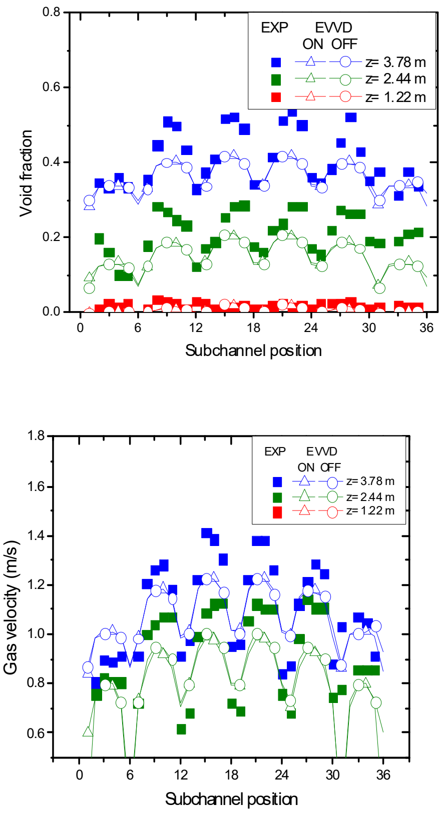

Fig. 3. Void fraction (top) and gas velocity (bottom) prediction for SIRIUS-3D test with SCVS(2022)

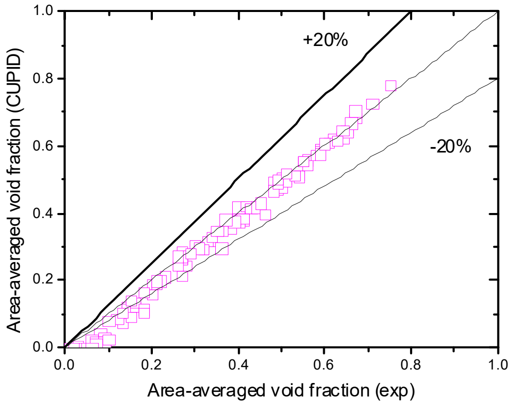

Fig. 4. Area-averaged void fraction prediction for SIRIUS-3D test with X-ray CT(2023)

On the other hand, the code predicted reasonably well the void fraction distribution, or the mixing of the two-phase flow as shown in Fig. 5. There was void fraction drop at the subchannel position 15, which was adjacent to the non-heated rods. One interesting finding was that the calculation without the EVVD model gave better prediction, which was against common understanding. The effects of EVVD model need further study.

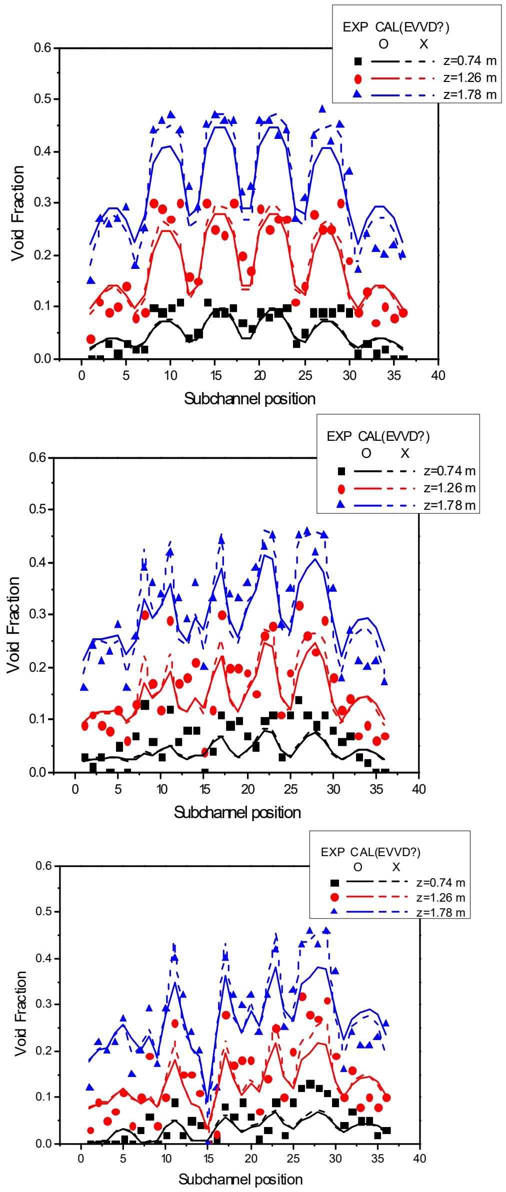

Fig. 5. Void fraction prediction for SIRIUS-3D test with X-ray CT(2023) (top: uniform heat flux, middle: 2 non-heated rods, bottom: 4 non-heated rods)

3. Design of a new rod bundle test

3.1. Test facility

Fig. 6 shows the schematics of the test section and test facility. The test section has a rectangular geometry with a dimension of 81.1 mm × 55.4 mm × 2.0 m. The rod bundle is 4 x 6 array of rods with a diameter of 9.5 mm and a pitch of 12.85 mm. This configuration is similar to the commercial PLUS-7 fuel assembly.

Because the purpose of the test is the exploration of cross flow characteristics under the intermediate break loss of coolant accidents (IB-LOCA), the inlet section at the bottom vessel was divided into two regions separated by the flow screen in the middle. The two inlets are expected to have different temperature or flow rate. The full development of flow at the two inlet regions was confirmed by preliminary calculation. At the main test section, the flow is intended to be mixed. The main test section corresponds to the active heating region with bubble generation. The heaters are divided into two groups, i.e. left 12 rods and right 12 rods, with different heat fluxes. The two heater groups enhances cross flow. In order to minimize the heat loss, the rectangular test section is installed inside a cylinder pressure vessel. The region between the rectangular test section and outer cylinder pressure vessel is expected to be filled with ceramic.

Table 1 shows the summary of the test facility. The operating pressure and the heater power were determined based on the ATLAS experimental results, especially on the moment when peak cladding temperature takes place under an IB-LOCA.

The test scope covers both steady-state and transient tests. In steady-state tests, the cross flow of bubbles will be mainly explored. In the transient tests, the swelled water level will be gradually reduced leading to rise of heater temperature. Through the tests, cross flow of bubbles below the swelled water level as well as the cross flow of steam and droplets above the swelled water level will be explored.

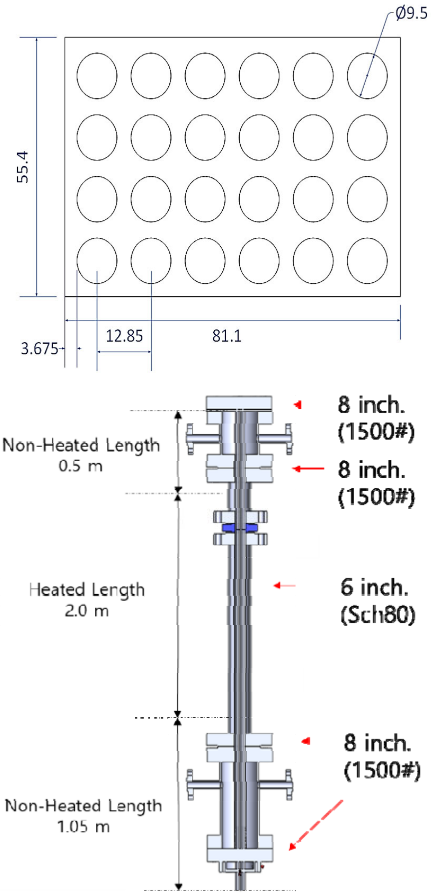

Fig. 6. Schematic diagram of the test section (top) and test facility (bottom)

Table 1. Summary of the test facility

Heater arrangement	4 × 6
Active heater length	2.0 m
Heater power	10 kW/rod
Operating Pressure	Up to 5 MPa
Instrumentation	WMS
WMS Number	1
Asymmetric Parameter	Heater Power Inlet flowrate Inlet temperature

3.2. Wire mesh sensor

To evaluate cross flow prediction performance of subchannel analysis codes, high level of precision is required in the acquisition of void fraction, bubble size and bubble velocity distribution. For the instrumentation of the new facility, a wire mesh sensor (WMS) technique was deployed to be installed at the downstream of the main test section as shown in Fig. 6. Because ordinary wire mesh sensors have low spatial resolution under the rod arrangement, a special wire mesh sensor developed by CRIEPI is adopted. The sensor uses heater rods as electrodes to enhance the spatial resolution by five times. However, to use heater rods as electrodes, the rods should be electrically insulated. For the insulation, O-rings are deployed with the cooling device at the heater flange. Furthermore, new spacer grids, made of stainless steel and alumina, have been developed as well.

The wire mesh sensors will be purchased from HZDR. There have been discussions for determining the specifications. There are issues being discussed such as replacement of wires.

Electronics and algorithms are being developed by Seoul National University(SNU) as collaboration work. Previously, SNU developed an algorithm to measure the bubble characteristics using a single layer wire sensor [8]. Similar algorithm is expected to be applied for the special WMS. Currently, several tests are being made, such as optimization of the algorithm under different environments.

3. Conclusions

The three-dimensional mixing phenomenon has gained interests because it can enhance the coolability of the core under LOCA. With the progress in computing power and high fidelity experiments results, subchannel-scale codes, such as CUPID, are being validated and applied.

In this paper, validation results using open data with SIRIUS-3D are presented. Area-averaged and local void fraction were predicted with good accuracy. Especially, the prediction was better at high velocity cases. EVVD model had little or worse effects on calculation results. Because available data are limited, further validation tests are needed.

In KAERI, a rod bundle test facility is being designed. The new experiment will focus on two-phase mixing under different conditions, such as pressure, velocity, subcooling, heat flux, and scenario. The main instrumentation includes a special wire mesh sensor (similar to SCVS), which needs optimization and validation.

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