Assessment of Subcooled Boiling Model under High Pressure Condition using CUPID

Yun-Je Cho[a*], Seong-Jun Lee, Han-Young Yoon[a]
[a]*Korea Atomic Energy Research Institute, 111 Daedeok-daero, 989 Beon-gil, Yuseong-gu, Daejeon 305-600*
[*]*Corresponding author: yjcho@kaeri.re.kr*

1. Introduction

A subcooled boiling occurs in various heat transfer processes, and it is also very important heat transfer mechanism, in particular, under the accident condition of nuclear power plants (NPPs). So far, various analytical studies on subcooled boiling using computational fluid dynamics codes has been performed to validate the subcooled boiling model. However, it is difficult to validate each sub-model while other relevant parameters are well controlled because the subcooled boiling involves many sub-models and the correlations between sub-models are too complicated. In addition, it is required to validate the model from an atmospheric pressure to the 150 bar because of the operating condition of NPPs. However, the experimental data for the validation under the high pressure condition are limited. In this study, the subcooled boiling model are assessed using the F-SUBO test data.

2. F-SUBO Facility

2.1 Experimental Facility

The experimental facility, named F-SUBO (Freon Subcooled Boiling), was constructed in 2016 for the validation of the various bubble parameters, which is the key of the subcooled boiling model. The facility consists of the test channel, flow loop, measurement instruments, direct power supply, and data acquisition system. A working fluid is Freon R-134a, and the design pressure is 4.5 MPa [1].

The test channel is annulus, and the inner and outer diameters are 27.2 mm, and 9.5 mm, respectively. The total length of the channel is 3900 mm, and the heating length is 1750 mm. The length of non-heating sections of the inlet side and outlet side are 1350 mm and 800 mm, respectively. The test channel has four measurement stations where local bubble parameters are measured as shown in Fig. 1. The distance between two stations is 500 mm.

The measurement stations are equipped with an optical fiber probes, which can measure the void faction, bubble passing frequency, bubble velocity, Sauter mean diameter, and interfacial area concentration. The radial distribution of the parameters are measured by the traverse system of the probe. To visualize the boiling structures, four high speed video cameras are installed in each station.

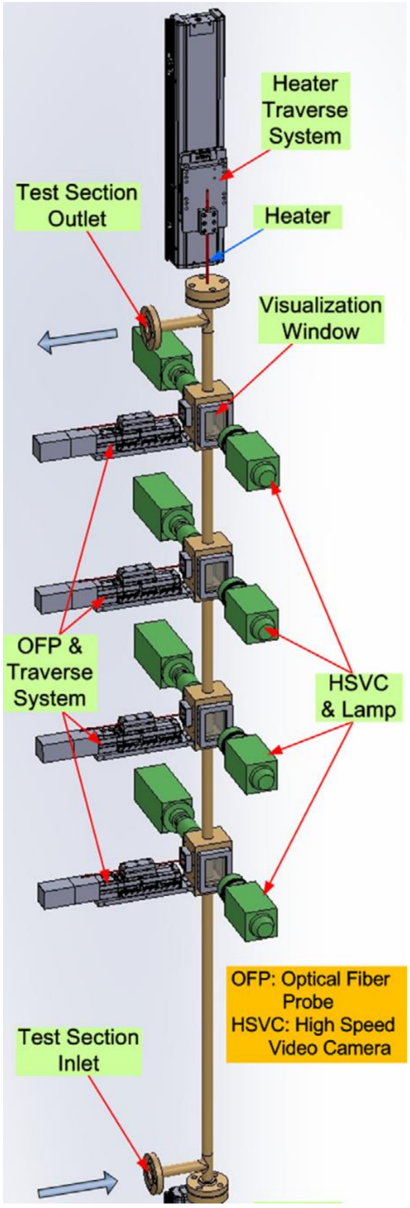

Fig. 1 Schematic of test channel

2.2 Test Cases

The test conditions of three cases are summarized in Table1. The converted pressure, mass and heat fluxes according to the similarity criteria [2] to be equivalent for water are presented together.

In this study, Test-01 and Test-02 were simulated, which have considerably different ranges of the inlet mass flux, inlet subcooling, wall heat flux, and, consequently, void fraction and bubble velocities.

Table I: Test conditions

	Exit pressure [MPa]	**Mass flux [kg/m²s]**	**Heat flux [kW/m²]**	**Inlet subcooling(K)**
Test-01	1.29 (7.95)*	998 (1425)	120.4 (1620)	12.4
Test-02	1.49 (9.10)	149 (213)	60.6 (815)	27.4
Test-03	2.69 (15.60)	999 (1395)	120.7 (1550)	8.0

**The numbers in brackets are converted values by the similarity criteria*

3. Calculation Results

For the validation of subcooled boiling model, we used the CUPID code, which has been developed at KAERI since 2007 [3]. CUPID has capabilities of prediction of subcooled boiling under wide ranges of pressure conditions.

3.1 Computational Grid and Physical Models

Hexa-prism meshes were generated using the in-house grid generation tool named CUPID-POP as shown in Fig. 2.

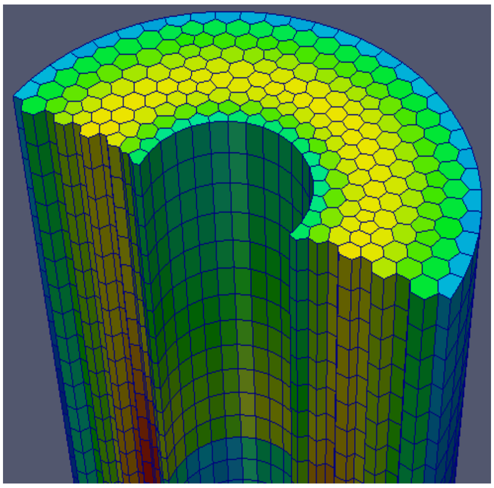

Fig. 2 Mesh generation

The physical models regarding the simulation of subcooled boiling depend on the mesh size, in particular, the size near walls. In particular, the models which have relatively significant effect on the calculation results were developed by using a bulk temperature. Thus, a proper y-plus value at the near-wall cell around 150 to 250 are generally required for these type of models. In addition, the standard k-ε turbulence model requires the y-plus value ranged from 30 to 150. With these two restriction, the mesh was generated to have the y-plus values ranged from 100 to 300.

To simulate the subcooled boiling, the physical models should be used as below.

- Wall heat flux partitioning model and its sub-models: quenching heat transfer, bubble departure diameter, bubble departure frequency, and nucleation site density models.
- Non-drag models: wall lubrication, bubble lift-off, and turbulence dispersion force models
- Bubble size model: bubble diameter, and interfacial area concentration model

3.2 Calculation Results (Test-01)

The radial distribution of the void fraction at seven elevations are compared in Fig. 3. The void fraction was non-dimensionalized by the reference value which corresponds to the measured void fraction in Test-01 at the radial position of 0.7 mm and the elevation of 1730 mm. The calculated void fraction shows good agreement with the experimental data.

The comparison of void fraction was not conducted near walls because the bubble parameters cannot be measured in the close region from walls where the distance is smaller than the bubble size. However, the missing part near walls can be estimated by the calculation results and it seems that the general trends are physically sound.

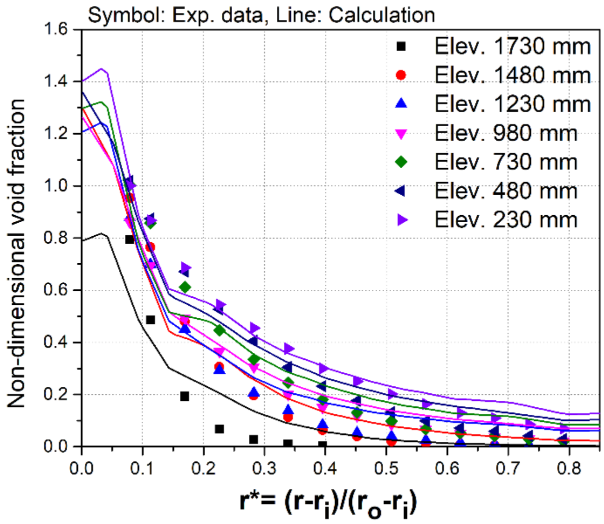

Fig. 3 Radial distribution of void fraction (Test-01)

The non-dimensional interfacial area concentration (IAC) are compared in Fig. 4. The IAC near walls are underestimated because the bubble size are over-predicted. As a result, the bubble velocity near walls are over-predicted as shown in Fig. 5.

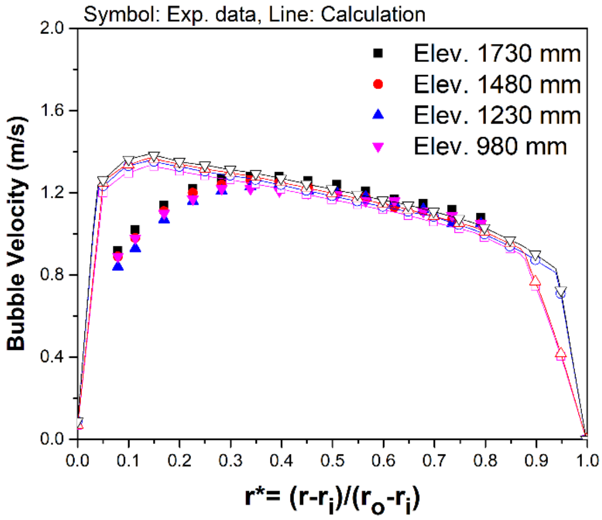

Fig. 4 Radial distribution of IAC (Test-01)

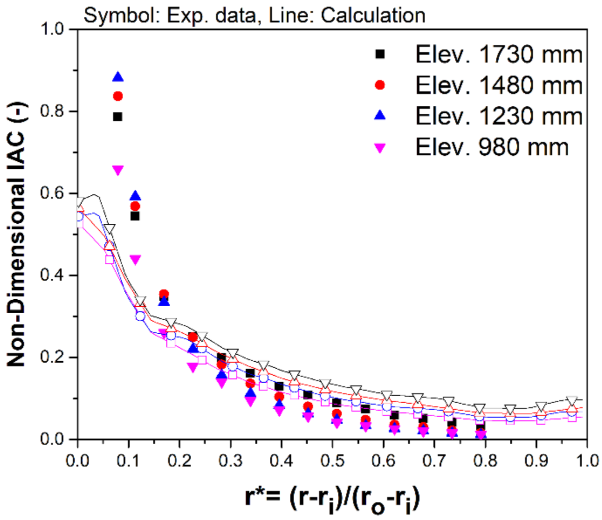

Fig. 5 Radial distribution of bubble velocity (Test-01)

3.3 Calculation Results (Test-02)

The radial distribution of void fraction are compared in Fig. 6. The calculation results show that the void factions are not varied according to the elevation change as the experimental data are significantly decreasing with the elevation. In the experiment, the evaporated vapors are effectively condensed due to the high inlet subcooling and mass flux. The discrepancy between the experimental data and calculation results may be caused by the errors from the physical models or from the heat losses through the outer wall of the measuring stations, which are not simulated in the calculations.

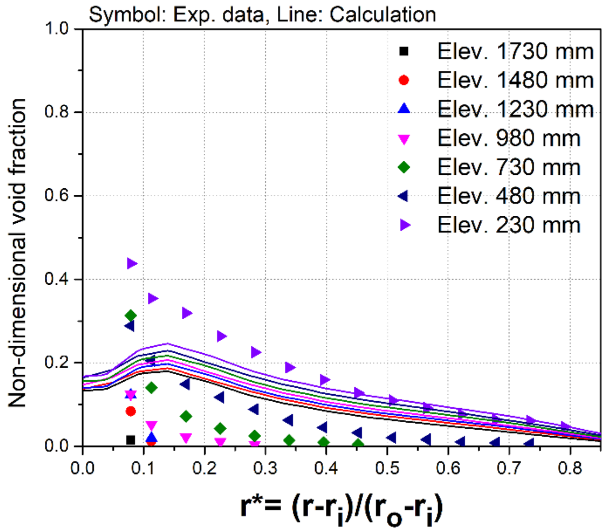

Fig. 6 Radial distribution of void fraction (Test-02)

The radial distribution of void fraction are compared in Fig. 7. On the contrary to the Test-01 case, the bubble velocity near walls are properly estimated. However, as shown in Fig. 6, the prediction of bubble velocity does not guarantee the accurate prediction of void fraction. Thus, it can be concluded that the balance between two model groups is very important. The first group of physical models includes the models that affect the generation of vapor at the wall such as the departure diameter, departure frequency, and nucleation site density models. The second group includes the models, which can vary the radial distribution such as three of non-drag models and bubble size model.

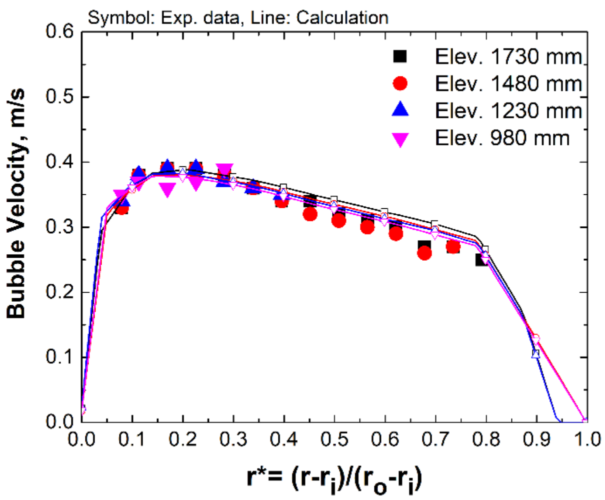

Fig. 7 Radial distribution of IAC (Test-02)

5. Conclusions

The subcooled boiling model was assessed using the F-SUBO experimental data. The experimental data showed that the radial distributions of void fraction, bubble velocity, and IAC are significantly varied according to the boundary conditions such as inlet mass flux and inlet subcooling.

The calculation results showed that the predicted results can be significantly varied according to not only the boundary conditions but also the combination of selected models even though the proper physical models are used by considering its applicable ranges of pressure and temperature.

In the future, additional F-SUBO test data will be simulated and the reasonable guide line for the model selection will be suggested for the simulation of the subcooled boiling under high pressure condition.

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