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A Simple Free Surface Tracking Model for Multi-dimensional Two-Fluid Approaches

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1. Introduction

Two-fluid approaches have been widely used in two-phase flow analyses. It has been developed in the form of two-phase 1-D pipe flows. The development in two-phase experiments devoted to find unknown phenomenological relationships modified conventional flow pattern maps into a sophisticated one and even extended to the multi-dimensional usage. However, for a system including a large void fraction gradient, such as a pool with the free surface, the flow patterns varies spatially throughout small number of cells and sometimes results in an unstable and unrealistic prediction of flows at the large gradient void fraction cells. Then, the numerical stability problem arising from the free surface is the major interest in the analyses of a passive cooling pool convecting the decay heat naturally, which has become a design issue to increase the safety level of nuclear reactors recently.

In this research, a new and simple free surface tracking method combined with a simplified topology map is presented. The method modified the interfacial drag coefficient only for the cells defined as the free surface. The performance is shown by comparing the natural convection analysis of a small scale pool [1] with respect to single- and two-phase condition.

2. Pool with a Free Surface

Instability on free surface problems is not of importance for forced convection problems in multi-dimensional two-fluid approaches. However, a pool at rest initially, which is being heated, usually shows non-physical and unstable oscillations at the free surface. Some explanations for this non-physical oscillation are as follows.

A pool named as PCCT (Passive Condensate Cooling Tank) is a part of the experiment performed at KAERI to survey the natural convection phenomena [2]. Fig. 1 shows the flow patterns inside the pool, which is predicted using the CUPID code [3, 4] based on the Tentner's topology pattern map [5]. As shown in Fig. 1, the several transition regimes are used to define the free surface. Thus, the pool has an inherent complexity in flow patterns within a few cells representing the free surface. Moreover, the abrupt changes in flow patterns cause severe difference in heat transfer coefficients spatially, that may causes numerical instability and makes a calculation being failed.

Therefore, to stabilize the free surface in a pool, a new free surface tracking model and a continuous and simplified flow regime map are introduced in this research. Since the simplified flow regime map is another topic, we skipped the details of it in this paper.

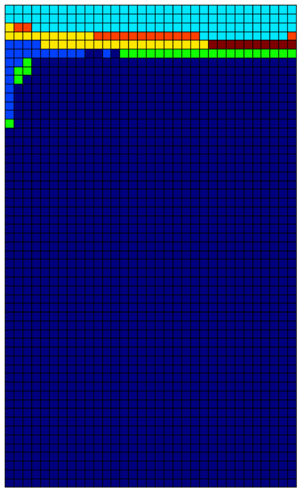
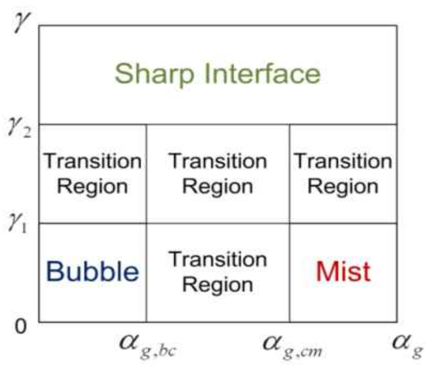
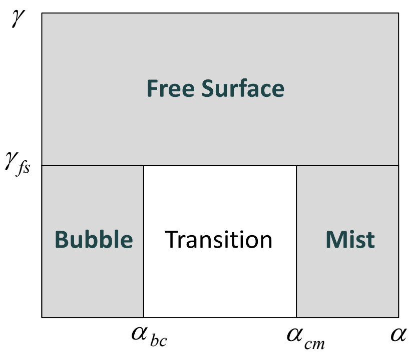


Fig. 1. Various flow regimes of a pool based on a topology map.

3. Simplified Topology Map



(a) Tentner's topology map



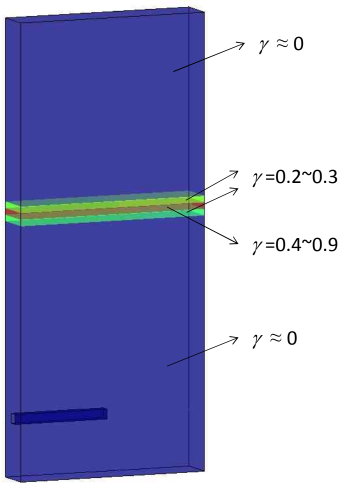
(b) Simplified topology map

Fig. 2. Flow pattern maps.

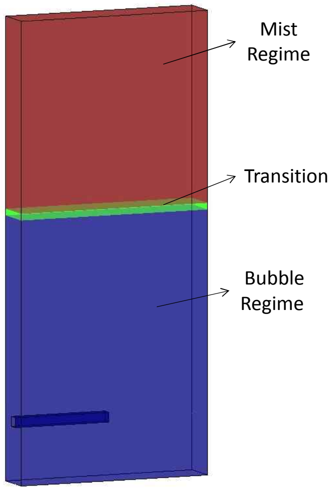
Fig. 2 shows the topology maps. Fig. 2a and 2b are the Tentner's topology map and the simplified topology map, respectively. While the original topology map resolves the two-phase flows into 3 major patterns, such as bubble, mist and sharp interface. Between patterns there are transition regions.

In the simplified one, the sharp interface is deleted, but added over the cells previously occupied by other regimes, e.g. bubble or mist. To find the free surface cells, γ_{fs} is determined within $\gamma_1 \sim \gamma_2$.

Fig. 3 shows the gamma and the flow regimes of a small scale pool [6]. Due to the simplification in topologies, the flow patterns are distributed straightly. In Fig. 3a, the gamma varies vertically, but is similar horizontally. The simple flow patterns are predicted as in Fig. 3b.



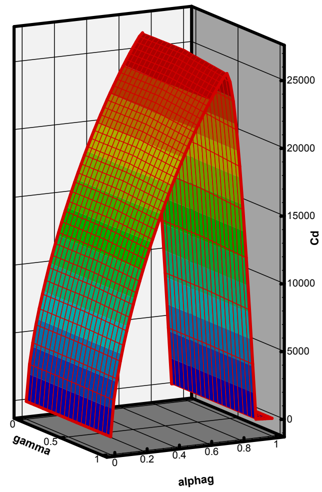
(a) gamma plot



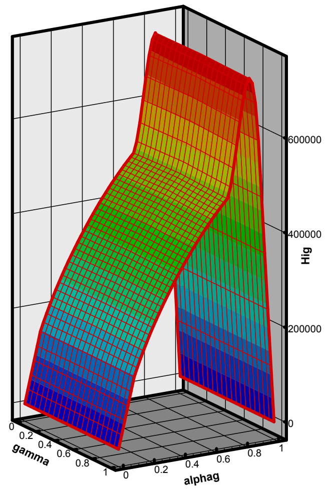
(b) flow pattern plot

Fig. 3. Gamma and flow pattern plot.

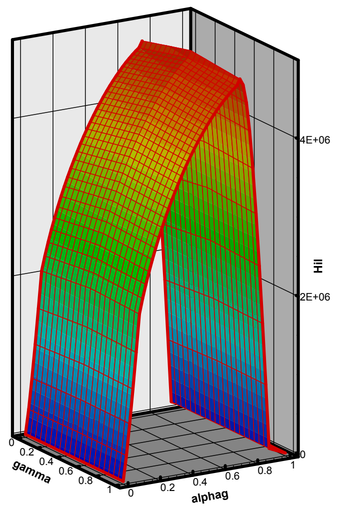
Fig. 4 shows the drag coefficient, the gas heat transfer coefficient, and the liquid heat transfer coefficient, respectively. All coefficients are linearized with respect to the void fraction and gamma. These are used for the coefficients for the simplified topology map.



(a) drag coefficient



(b) heat transfer coefficient: gas



(c) heat transfer coefficient: liquid

Fig. 4. Continuous heat transfer coefficients and drag coefficient w.r.t. the void fraction and gamma.

4. Free Surface Tracking Model

To stabilize the free surface, it can be helpful to increase the interfacial drag coefficient intentionally of the free surface cells, which are defined as the sharp interface regime in the conventional topology map or are chosen by gamma criteria in the simplified one. However, in two-phase evaporation cases, a vapor flow drags the liquid out of the pool. It decreases the pool height unexpectedly in a short time.

$$\frac{\partial}{\partial t}\left(\alpha_g \rho_g \vec{u}_g\right)+\nabla\cdot\left(\alpha_g \rho_g \vec{u}_g \vec{u}_g\right)=-\alpha_g \nabla P+\nabla\cdot\left(\alpha_g \mathbf{T}_g\right)+\alpha_g \rho_g \vec{g} +\mathbf{M}_g^{mass}+\mathbf{M}_g^{drag}+\mathbf{M}_g^{ndrag}+\mathbf{M}_g^{VM}, \quad (1)$$

$$\frac{\partial}{\partial t}\left(\alpha_l \rho_l \vec{u}_l\right)+\nabla\cdot\left(\alpha_l \rho_l \vec{u}_l \vec{u}_l\right)=-\alpha_l \nabla P+\nabla\cdot\left(\alpha_l \mathbf{T}_l\right)+\alpha_l \rho_l \vec{g} +\mathbf{M}_l^{mass}+\mathbf{M}_l^{drag}+\mathbf{M}_l^{ndrag}+\mathbf{M}_l^{VM}, \quad (2)$$

where,

$$\mathbf{M}_g^{drag}=F_{gl}(\vec{u}_l-\vec{u}_g)+F_{gd}(\vec{u}_d-\vec{u}_g) \quad (3)$$

$$\mathbf{M}_l^{drag}=F_{gl}(\vec{u}_g-\vec{u}_l) \quad (4)$$

$$\begin{Bmatrix} F_{gl}\big|_{gas} \\ F_{gl}\big|_{liq} \end{Bmatrix}=\begin{Bmatrix} 50000 \\ 0 \end{Bmatrix} \quad (5)$$

Eqs. (1)~(2) are the momentum conservation equations. They include several interfacial momentum transfer terms written with **M** for both phases. Among the terms, the interfacial drag terms in Eqs. (3)~(4) are modified as presented in Eq. (5) only for the free surface cells. The coefficients means that the free surface cells in liquid phase are not influenced by gas flows, while those in gas phase are influenced by liquid flows. Thus, the liquid drags the gas as the wall-moving boundary condition works.

5. Verification of the Free Surface Tracking Model

The simple free surface tracking model is verified with the small scale pool analysis in single-phase and two-phase natural circulation [6] since it implies all the flow regimes of the typical topology map.

Table 1 Test matrix

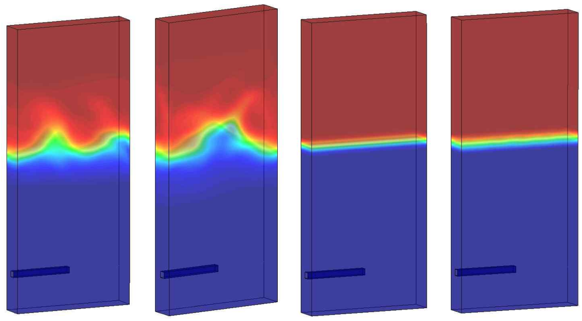
Name	FST*	Topology Map
case 1	none	typical
case 2	none	simplified
case 3	included	typical
case 4	included	simplified

* FST = free surface tracking

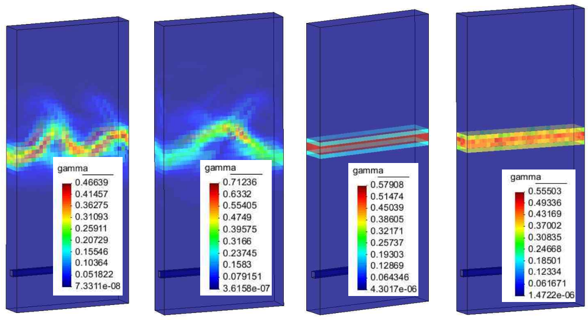
Table 1 shows the test matrix of FST in combination with the topological modification. As the reference of this verification, case 1 is chosen.

Fig. 5 shows the single-phase pool boiling case. From the left figure, they refer to the case1 to 4. For the case 1 and 2, the free surfaces oscillate while they are stabilized in case 3 and 4. Compared to the case 3, case 4 works well and keeps the free surface stable. Moreover, the simplified and linearized heat transfer coefficients soothe the gamma distribution as shown in the figure of case 4.

Fig. 6 shows the two-phase pool boiling case. From the left figure, they refer to the case1 to 4 too. For the case 1 and 2, the free surfaces oscillate and diffuse because of the evaporation at the free surface, while they are stabilized in case 3 and 4. Compared to the case 3, case 4 works well and keeps the free surface stable.

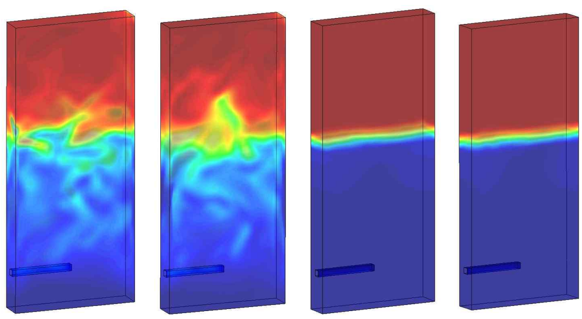


(a) void fraction

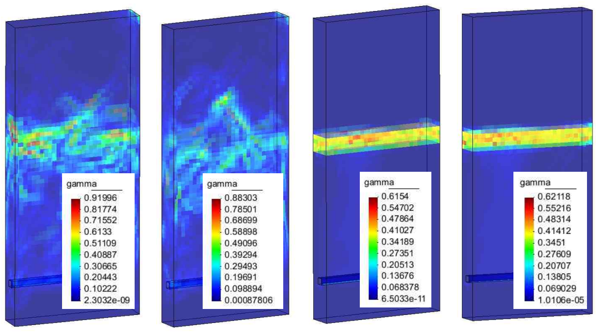


(b) gamma

Fig. 5. Single-phase void fraction contour for a pool having free surface.

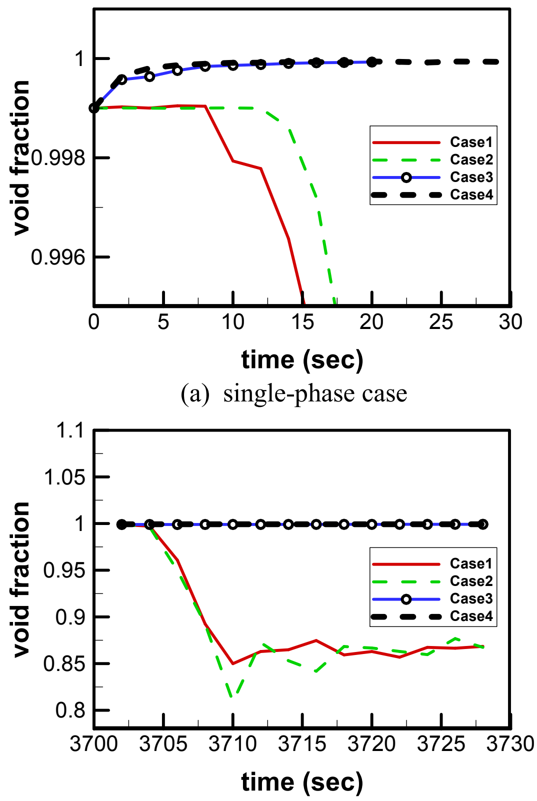


(a) void fraction



(b) gamma

Fig. 6. Two-phase void fraction contour for a pool having free surface.



(b) two-phase case

Fig. 7. Void fraction transient at the outlet of the pool.

Fig. 7 presents the void fraction history at an outlet on top of the pool for single-phase and two-phase condition. In case 3 and 4, the liquid is deviated well from the gas flow for all conditions, while the case 1 and 2 are not. Especially, in two-phase condition the dragging effect is severer in case 1 and 2.

5. Conclusions

A simple free surface tracking model with a simplified topology map is developed. The free surface tracking model modified the interfacial drag coefficients for the free surface cells and combined with a simplified topology map that includes linearized drag and heat transfer coefficients. The model is applied to CUPID and tested successfully with the small scale pool test in single-phase and two-phase condition. In the near future, the linearized drag and heat transfer coefficients will be applied to the typical topology map and the effects will be analyzed with the FST.

ACKNOWLEDGEMENT

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