Modification of Horizontal Stratification Criteria Using Kelvin-Helmholtz instability in SPACE code

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1. Introduction

It is important to determine the flow regime in the field of nuclear safety analysis, because the models that deal with pressure drop, interfacial friction, and heat and mass transfer are differently used corresponding to each flow regime. Therefore, determinations of correct flow regime for a given flow condition are directly related to prediction capability of safety analysis codes.

A horizontal stratification may frequently occur in hot or cold legs during loss of coolant accidents (LOCAs). Since the interfacial friction and heat transfer models in the stratified flow are remarkably differ from the ones in the other flow regimes, horizontal stratification criteria are important for nuclear safety analysis.

Various studies[1-6] have been conducted for horizontal stratification criteria related to the Kelvin-Helmholtz (K-H) instability. There are two types of K-H instability theory for the one dimensional long-wave approach: (1) the inviscid K-H (IKH) theory in which the interfacial and wall shear stress are neglected, and (2) the viscous K-H (VKH) theory in which the interfacial and wall shear stress are considered. Barnea and Taitel proposed transition boundary models for stratified flow based on VKH and IKH analyses.

The criteria for stratified flow in most one-dimensional thermal-hydraulic codes are expressed as a type of the Froude number ($Fr = u/\sqrt{gl}$). Table I lists the coefficient of horizontal stratification criteria that multiplies with the form of the Froude number used in various thermal-hydraulic codes. K_{HST-T} is the value that determines the boundary between the smoothly horizontal stratified flow (HST) and the transition region (T) like as a wavy-stratified flow, and K_{T-NHST} determines the boundary between the transition region and non-horizontal stratified (NHST) flow. However, most of one-dimensional thermal-hydraulics codes commonly use the value of K_{HST-T} for half of their K_{T-NHST} without any physical basis.

The objective of this study is to consider the horizontal stratification criteria with the transition boundaries by adopting with IKH and VKH instability analysis. The criteria were implemented into the SPACE code and its prediction capability was assessed.

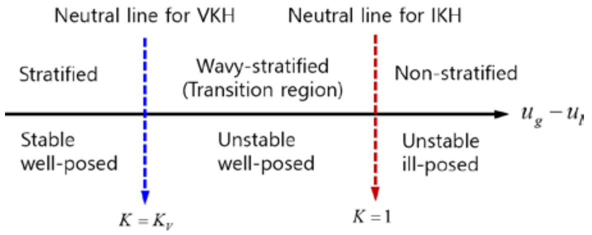
Table I: Values of K for horizontal stratification criteria

	K_{HST-T}	K_{T-NHST}
SPACE[1,7]	0.2435	0.487
RELAP5[8]	0.25	0.5
CATHARE[9]	0.5	1.0
TRACE[10]	$1-h_l/D$	$2(1-h_l/D)$

2. Horizontal stratification criteria and Results

2.1 Horizontal stratification criteria

This section summarizes the proposed criteria based on the K-H instability analysis. Fig. 1 shows the relationship between the flow regime and stability. In the transition region, the flow is unstable but the system equations are well-posed. However, the boundary between the non-stratified flow and stratified flow can be determined by the ill-posedness of the governing equation sets, which equal to the result of IKH analysis. In addition, the criteria for horizontal stratification can be divided with K_V and K_{IV}.



In order to find the criterion for neutral line for IKH, characteristic analysis was conducted. Let us consider an inviscid, incompressible flow in a gravitational field in which the surface tension can be neglected. The mass and momentum equations can be written in the following form:

$$\mathbf{A}\frac{\partial \mathbf{u}}{\partial t} + \mathbf{B}\frac{\partial \mathbf{u}}{\partial x} = \mathbf{C}, \quad (1)$$

where

$$\mathbf{u} = \left(\alpha_l, u_l, u_g, p_i\right)^T, \quad (2)$$

$$\mathbf{A} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ u_l & \alpha_l & 0 & 0 \\ -u_g & 0 & \alpha_g & 0 \end{pmatrix}, \qquad (3)$$

$$\mathbf{B} = \begin{pmatrix} u_l & \alpha_l & 0 & 0 \\ u_g & 0 & -\alpha_g & 0 \\ u_l^2 + \alpha_l g H_{shape} & 2\alpha_l u_l & 0 & \alpha_l / \rho_l \\ -u_g^2 + \alpha_g g H_{shape} & 0 & 2\alpha_g u_g & \alpha_g / \rho_g \end{pmatrix} \qquad (4)$$

$$\mathbf{C} = \begin{pmatrix} 0 \\ 0 \\ \tau_i S_i / A - \tau_l S_l / A \\ -\tau_i S_i / A - \tau_g S_g / A \end{pmatrix} \qquad (5)$$

H_{shape} denotes the coefficient that represents the relationship between the rate of change of the liquid fraction ($\partial\alpha_l / \partial x$) and the rate of change of the liquid level ($\partial h_l / \partial x$) according to the shape of flow channel.

The governing equation set becomes ill-posed when

$$|u_g - u_l| > \sqrt{\frac{\alpha_l \rho_g + \alpha_g \rho_l}{\rho_g \rho_l}(\rho_l - \rho_g) g H_{shape}} \qquad (6)$$

The Eq. (6) can be rewritten in the following form

$$|u_g - u_l| > K \sqrt{\left(\frac{\alpha_g}{\rho_g} + \frac{\alpha_l}{\rho_l}\right)(\rho_l - \rho_g) g H} \qquad (7)$$

According to Barnea [6], K is equal to 1 for the IKH analysis. Barnea and Taitel [4] have conducted a linear stability of VKH instability. In this study, the value of K_V was assumed to be the void fraction value according to Barnea [6].

2.2 Assessment of flow regime prediction

In order to validate the horizontal stratification criteria Mantilla's experiment [11] and REGARD experiment [12] were used.

Mantilla conducted entrainment experiments in a stratified or annular horizontal flow at a low pressure. The inner diameter is 2-inch and, the distance to the measurement location is 11.9 m. It is sufficient to ensure a fully developed flow at the measuring location. The boundary conditions for air-water flow are shown in Table II.

Table II. Test matrix for Mantilla's experiment

Water superficial velocity (m/s)	Air superficial velocity (m/s)					Case
0.0035	20	30	50	70	80	1~5
0.0180	20	30	50	70	80	6~10
0.0340	20	30	50	70	80	11~15
0.1000	20	30	50	70	80	16~20

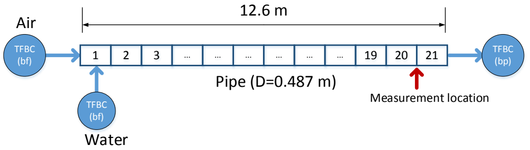


Fig. 1. SPACE nodalization for Mantilla's experiment

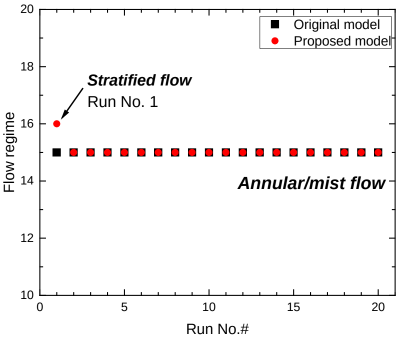


Fig. 2. SPACE results for flow regimes using original model and proposed model

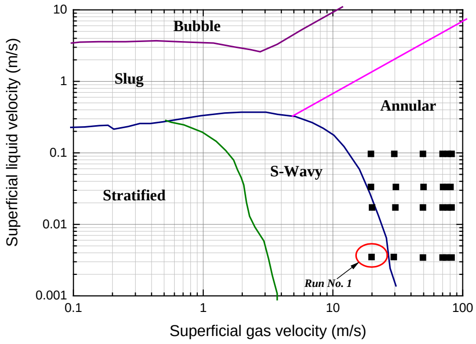


Fig. 3. Flow regime map for Mantilla's experiments [11]

Fig. 1 shows the SPACE modeling for Mantilla's experiment. All plotted data were acquired at the measurement location.

Fig. 2 compare the flow regime of Mishima's model (Original model in the SPACE code) [1] with that of the proposed model to determine the criteria for horizontally stratified flow. The flow regime map was also reviewed for each run as shown in Fig. 3. For the cases using the original SPACE model, the flow regimes is annular flow for all runs. However, Stratified flow is indicated for Run no. 1 when the proposed model is applied.

The REGARD experiment [12] was conducted to understand the flow characteristic in an air-water two-phase flow in a horizontal pipe. The test section consisted of a pipe of 4 m long with an inner diameter of 0.24 m. Table III shows the eight boundary conditions for the REGARD test cases.

Fig. 4. Presents a comparison of the flow regime calculated by the SPACE code between using the

original model and the proposed model for the REGARD experiments. Although the pipe size was relatively large and only a small amount of water was injected, the results calculated using the original model indicated that the flow regimes is annular flow for all cases. In this regards, these results using the original model are not consistent with the experimental observation. In addition, the flow regime is well predicted using the proposed model.

Table III Test matrix for REGARD experiments

case	Water superficial velocity (m/s)	Air superficial velocity (m/s)
1	0.018	19.8
2		24.9
3		34.4
4		38.2
5	0.036	19.8
6		24.9
7		34.4
8		38.2

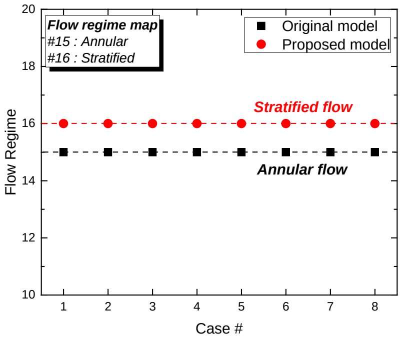


Fig. 4. SPACE results for flow regimes for REGARD experiments

3. Conclusions

The accurate prediction for horizontal stratification is important in the field of nuclear safety analysis. Nevertheless existing thermal-hydraulic codes adopted the horizontal stratification criteria which lack physical background, especially for transition region between stratification and non-stratification. The present study adopted the more correct criteria using both the IKH and VKH analyses. The proposed models were implemented into the SPACE code and two experiments were simulated to confirm the validity of the proposed model for horizontal stratified flow.

According to the validation of Mantilla's experiment, stratified-wavy flow occurred for Run no. 1. Original SPACE model predicted annular flows for all cases. However, the proposed model predicted as stratified flow for Run no. 1.

According to the validation of REGARD experiment, the flow is likely to be stratified due to the large diameter of the pipe. The original model predicted annular flow for all cases. These predictions are not reasonable. However, the proposed model predicted as horizontal stratified flow. These are consisted with the experimental observation. Based on obtained results, the proposed model can improve the predictability of the SPACE code for determining the horizontal stratified flow.

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