Two-phase Flow Regime Maps in Horizontal and Vertical Tubes

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1. Introduction

A safety analysis code to design a pressurized water reactor and to obtain the licenses including entire proprietary rights is under development in domestic R&D project. The tasks of KAERI is to develop the constitutive relations including models for defining flow regimes and flow regime related models for inter-phase friction, wall frictions, wall heat transfer, and inter-phase heat and mass transfer in the two-phase three-field equations. In this paper, the process will be presented for choosing the best flow regime maps which occur in gas-liquid two-phase flow in horizontal and vertical tubes.

2. Method

2.1. Investigation of exiting best-estimate codes

In order to choose the flow regime criteria, we have investigated various existing best-estimate codes. They are the RELAP5-3D[1], TRAC-M[2], MARS(COBRA-TF)[3], CATHARE[4] codes. Around 500 references used in these codes have been collected and reviewed. The collected references are research papers, textbooks and research documents in the form of PDF files or hard copies. Flow regime maps of these codes are determined based on a combination of void fraction and mass flux because flow regimes depend directly on geometrical parameters. Ishii et al. [5] also suggested that traditional flow-regime criteria based on the gas and liquid superficial velocities may not be suitable to the analyses of rapid transients or entrance flows by the two-fluid model. Under these considerations, the void fraction has been chosen as one of the flow regime criteria.

In RELAP5-3D, both the volume and junction flow regime maps are defined differently as a result of the finite difference scheme and staggered mesh used in the numerical scheme. The flow regime map for horizontal flow in RELAP5 is based on the woks of Taitel et al. [6] for the transition from bubbly to slug flow, Barnea [7] for the transition from slug to annular-mist flow, Taitel et al. [8] for the transition to horizontal stratification. The vertical flow regime map is similar to the horizontal flow regime map except stratified flow. The vertical flow map is based on the work of Taitel et al. [6] for the transition from bubbly to slug flow, Mishima et al. [9] for the transition from slug to annular-mist flow, the criteria in TRAC-B code for the transition to vertical stratification. In TRAC-M, it adopts a very simple flow regime map that generally is assumed to apply to both horizontal and vertical flow geometries [2].

2.2. Investigation of state-of-the art flow regime maps

A very large research effort on two-phase gas-liquid flow regime criteria has been carried out at universities, national laboratories, and at industrial research organizations in many countries in the past decades. Unfortunately, most researchers have been largely proposed on results which are based on a gas and liquid superficial velocity coordinate system. We have investigated ten papers in detail which uses void fraction and mass flux as coordinate system. Rouhani et al. [10] give a literature review covering various aspects of two-phase flow patterns on 1983. Dukler et al. [11] provide a comprehensive review. Especially, Mishima et al. [9] presented new flow regime criteria for an upward gas-liquid flow in vertical tubes by considering the mechanisms of flow regime transitions. They suggested that more reliable parameters should be used in flow regime criteria than the traditional parameters.

2.3. Choice of flow regime maps

We have decided the flow regimes from a workshop which was attended not only by KAERI(16 persons) but also KEPRI(3 persons), KHNP(2 persons), KOPEC(2 persons), KNFC(2 persons), and one consultant. Table 1 shows a summary regarding the selected flow regimes to consider.

Table 1. The summary of selected flow regimes to consider.

	Contents
Coordinate system	Void fraction vs. Mass flux
Flow regimes in horizontal tube	Single phase liquid, bubbly flow, slug flow, annular-mist flow, single phase vapor, stratified flow
Flow regimes in vertical tube	Single phase liquid, bubbly flow, cap-slug flow, churn flow, annular flow, single phase vapor, stratified flow
Transition region	Interpolate between the transition region as the RELAP5-3D and TRAC-M

Based on the selected flow regimes, the flow regime maps for a gas-liquid flow in horizontal and vertical tubes have decided including the mechanisms of flow regime transitions regions.

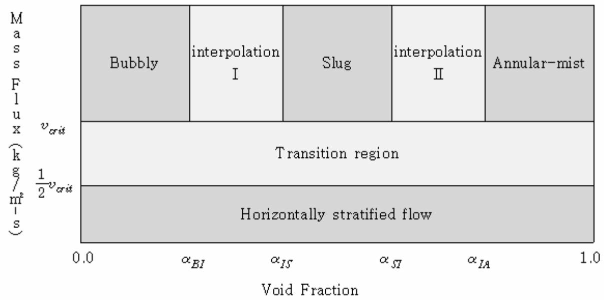

Figure 1. Flow regime map in horizontal tube.

Figure 1 shows the flow regime map in a horizontal flow. For the horizontal stratified flow, we adopt Eq. (1)

based on the study of Mishima et al. [9]. The critical relative velocity in this equation is developed based on the Kelvin-Helmholtz instability. This criterion is used in both RELAP5-3D and TRAC-M.

$$V_{crit} = \frac{1}{2}\left[\frac{(\rho_f - \rho_g) g \alpha_g A}{\rho_g D \sin\theta}\right]^{1/2} (1 - \cos\theta) \quad (1)$$

For the transition from bubbly to slug flow, we have chosen the values as follows. The limit such as the mass flux is obtained from the work of Choe et al.[12].

$$\begin{array}{ll} \alpha_{BS} = 0.3 & G_m \le 2{,}000 kg/m^2 s \\ \alpha_{BS} = 0.3 + 0.0003(G_m - 2{,}000) & 2{,}000 < G_m < 2{,}700 \\ \alpha_{BS} = 0.5 & G_m \ge 2{,}700 \end{array} \quad (2)$$

For the transition from slug to annular-mist flow, the transition takes place between void fractions of 0.75 and 0.80. The criterion is referred by the study of Barnea [7].

$$\alpha_{SA} = 0.75 \sim 0.8 \quad (3)$$

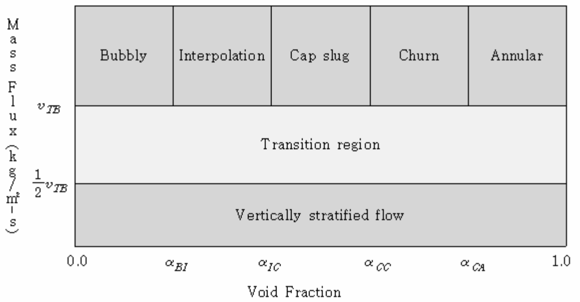

Figure 2. Flow regime map in vertical tube.

Figure 2 shows the flow regime map in a vertical flow. A vertical stratified flow occurs if the mixture velocity is less than the Taylor bubble rise velocity such as:

$$\frac{\alpha_g \rho_g |V_g| + \alpha_f \rho_f |V_f|}{\rho_m} < 0.35\left[\frac{gD(\rho_f - \rho_g)}{\rho_f}\right]^{1/2}. \quad (4)$$

The transition from bubbly to cap slug flow is identical to Eq.2.

The transition from cap slug to churn flow is assumed to occur between void fractions of 0.6~0.9. This criterion is also obtained from the study of Mishima et al. [9]. The term $(\Delta\rho g D^3/\rho_f v_f^2)^{1/18}$ can be replaced by a constant value of 3 for water.

$$\alpha_{CC} \ge 1 - 0.813 \times \left\{\frac{(C_o - 1)j + 0.35\sqrt{(\Delta\rho g D/\rho_f)}}{j + 0.75\sqrt{(\Delta\rho g D/\rho_f)}\left(\Delta\rho g D^3/\rho_f v_f^2\right)^{1/18}}\right\}^{0.75} \quad (5)$$

The transition from churn to annular flow can occur due to flooding phenomena. Two conditions are used according to the tube diameter. The first criterion agrees well for small tubes (below 5cm) and the second criterion can be applied to large tubes (above 5cm). It is based on the study of Mishima et al. [9].

$$j_g = \frac{\alpha_g v_g}{\left[\frac{gD(\rho_f - \rho_g)}{\rho_g}\right]^{1/2}} \ge j^*_{g,crit}, \quad j^*_{g,crit} = 1 \quad (6)$$

$$Ku_g = \frac{\alpha_g v_g}{\left[\frac{g\sigma(\rho_f - \rho_g)}{\rho_g^2}\right]^{1/4}} \ge Ku_{g,crit}, \quad Ku_{g,crit} = 3.2 \quad (7)$$

3. Conclusion

We will look forward to decide the constitutive relations based upon the flow regime maps that are determined in this works. The constitutive relations will be used for the code under development.

Acknowledgement

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