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Improved Choked Flow Model for MARS Code

MARS 코드의 임계유동모델 개선

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한국원자력연구소

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이 보고서를 “최적 열수력 계통분석 코드개발” 과제의 기술보고서로 제출합니다.

제 목 : **Improved Choked Flow Model for MARS Code**

MARS 코드의 임계유동모델 개선

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요 약 문

쌍곡형 2-유체 모델의 고유치해석에 의하여 얻어진 새로운 음속을 이용하여 MARS 코드의 이상임계유동 모델이 개선되었다. 본 임계유동모델은 열역학적 비평형성을 고려하여 유도된 2-유체 방정식의 고유치에 근거하고 있으므로 열역학적 평형의 가정 하에 유도된 Trapp-Ransom 모델의 열역학적 특성을 개선시킴과 동시에 기포류 영역에서의 음속에 관한 기존의 실험결과들과의 양립성을 확보하였다. 또한, Nguyen 등에 의해서 유도된 이상유체에서의 음속모델이 작은 기공율 영역에서 기체상에 대하여 보여준 것과 같은 비물리성을 가지지 않는다. 본 모델은 기존의 임계유동조건을 본 모델에 의한 것으로 대치함으로써 MARS 코드에 구현되었으며 모델의 검증을 위하여 Marviken (LBLOCA) 및 Typical PWR (SBLOCA) 문제를 계산하였다. Marviken 문제의 계산결과를 통하여, 경험적인 유출계수를 사용하지 않았을 경우, 본 모델을 사용하여 예측된 유출량과 실험결과와의 상대오차가 Trapp-Ransom 및 Henry-Fauske 모델을 사용하였을 경우에 비하여 현저히 작아짐으로써 냉각재 상실사고 시 유출량에 대한 MARS 코드의 예측성이 개선되어짐을 알 수 있었다. 또한 Typical PWR (SBLOCA) 문제의 계산결과에 의하면, 원자로계통의 과도상태모사에 있어서도 본 모델이 타당한 예측성능을 가지고 있음을 확인할 수 있었다.

Abstract

Choked flow calculation is improved by using a new sound speed criterion for bubbly flow that is derived by the characteristic analysis of hyperbolic two-fluid model. This model was based on the notion of surface tension for the interfacial pressure jump terms in the momentum equations. Real eigenvalues obtained as the closed-form solution of characteristic polynomial represent the sound speed in the bubbly flow regime that agrees well with the existing experimental data. The present sound speed shows more reasonable result in the extreme case than the Nguyen's did. The present choked flow criterion derived by the present sound speed is employed in the MARS code and assessed by using the Marviken choked flow tests. The assessment results without any adjustment made by some discharge coefficients demonstrate more accurate predictions of choked flow rate in the bubbly flow regime than those of the earlier choked flow calculations. By calculating the Typical PWR (SBLOCA) problem, we make sure that the present model can reproduce the reasonable transients of integral reactor system.

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1. Introduction

Accurate prediction of critical flow is of most importance in the safety analysis of nuclear plants, since it provides the transient boundary conditions during the depressurization transients initiated by a pipe break in primary or secondary systems and during the over-pressurization transients resulting in a relief of coolant through valves. Mass and energy discharge through the opening of pressure boundary affects the system thermal hydraulic responses, that is, phase changes and flow distribution in the system, and the mass inventory remaining in the system necessary to remove core decay heat. Safety significance of the critical flow model led to a development of various empirical and mechanistic models, such as Moody [1], Henry-Fauske [2], Trapp-Ransom [3] models, and so on. However, accuracy of these models is still in question especially during two-phase choking condition.

Choked flow condition is defined as the condition where mass discharge from a system becomes independent of conditions downstream, that is, the condition where acoustic signals can no longer propagate upstream. This occurs when the fluid velocity equals or exceeds the propagation speed. Thus, it can be said that choked flow condition strongly relates with the mechanistic property of a fluid flow governed by the sound wave propagation characteristics, that is, eigenvalues of the equation system.

In this study, the mechanistic choked flow criterion for bubbly flow has been developed for the purpose of enhancing the accuracy of critical flow model of MARS code [4]. The MARS code is a multi-dimensional thermal hydraulic system code developed by KAERI using RELAP5/MOD3 [5] and COBRA-TF [6] as backbones.

The critical flow model of the MARS code references that of RELAP5/MOD3 [5] and is based on Trapp-Ransom model [3]. The Trapp-Ransom model incorporated an analytic choking criterion for non-homogeneous, equilibrium two-phase flow. The two-fluid model for the conditions of thermal equilibrium is employed in the Trapp-Ransom model, which consists of overall mass conservation, two phasic momentum equations and the mixture entropy equation. The momentum equations include the interface force terms called virtual mass terms representing relative acceleration. They derived an analytic choking criterion that includes relative phasic acceleration terms and derivative-dependent mass transfer based on the characteristic analysis of this two-fluid model [3, 7, 8]. However, it should be noted that this criterion is derived based on the thermal equilibrium assumption, thus, may not be applicable when the thermal non-equilibrium effect dominates.

Characteristics of a two-fluid equation system can be represented by system eigenvalues. The real part of the system eigenvalues results the velocities of signal propagation along the corresponding characteristic path in the space/time plane and the imaginary part represents the rate of amplitude growth of the signal propagating along the respective path. In the Trapp-Ransom model, analytic form of sound speed was obtained by the characteristic analysis of non-homogeneous, equilibrium conditions and it under-predicted the sound speed in comparison with the experimental data in the bubbly flow regime [3]. Furthermore, the existence of the non-zero imaginary part of the system eigenvalues may result in the nonphysical, short wave length instability [9, 10, 11].

A new promising approach to removing the complex eigenvalues was proposed by some references: see Lee et al. [12] and Chung et al. [13, 14, 15]. We introduced new terms, that is, interfacial pressure jump terms based on the surface tension terms into the momentum equations. Although quantitative amount of these terms is relatively very small, they contribute to hyperbolicity of the equation system, even without the conventional virtual mass or artificial viscosity terms. And the analytically obtained eigenvalues represent comparable sound speed with the existing measured data as well as the analytic result produced by Nguyen et al. [16] for bubbly flow. In this study, we have developed a new choked flow criterion for the two-phase bubbly flow regime based on the hyperbolic two-fluid model. Then, new choked flow criterion has been implemented in the MARS code and assessed using Marviken critical flow tests [17].

We introduce the interfacial pressure jump terms in Section 2. Following the characteristic analysis of the system matrix in Section 3, we discuss how the new sound speed criterion is implemented in Section 4. Finally, in Section 5, we discuss the assessment results of new criterion using Marviken LBLOCA tests and Typical PWR SBLOCA test.

2. Hyperbolic Two-Fluid Model

Trapp-Ransom [3] investigated the impact of the virtual mass coefficient on the sound speed. Even with the 'zero' virtual mass coefficient, Trapp-Ransom model under-predicted the sound speed for the bubbly flow at low void fraction ranges, $\alpha_g < 0.5$. To preclude problems associated with the selection of a virtual mass coefficient, we exclude the virtual mass terms in the characteristic analysis and we only include the interfacial pressure jump term as follows.

The conservation laws provide one-dimensional two-fluid mass, momentum, and energy equations based on the area-averaged phasic properties.

Continuity:

$$\frac{\partial(\alpha_k \rho_k)}{\partial t} + \frac{\partial(\alpha_k \rho_k v_k)}{\partial x} = \phi_{c,k} \quad , \tag{1}$$

Momentum:

$$\frac{\partial(\alpha_k \rho_k v_k)}{\partial t} + \frac{\partial(\alpha_k \rho_k v_k^2)}{\partial x} + \alpha_k \frac{\partial p_k}{\partial x} + (p_k - p_i)\frac{\partial \alpha_k}{\partial x} = \phi_{m,k} \quad , \tag{2}$$

Internal Energy:

$$\frac{\partial(\alpha_k \rho_k u_k)}{\partial t} + \frac{\partial(\alpha_k \rho_k v_k u_k)}{\partial x} + p_k \frac{\partial \alpha_k}{\partial t} + p_k \frac{\partial(\alpha_k v_k)}{\partial x} = \phi_{i,k} \quad . \tag{3}$$

The notation α_k, ρ_k, p_k, v_k, and u_k denote volume fraction, density, pressure, velocity, and internal energy, respectively, where phasic component $k = g$ is for the gas and $k = l$ is for the liquid. We use the additive relation $\alpha_g + \alpha_l = 1$. The source terms $\phi_{c,k}$, $\phi_{m,k}$, and $\phi_{i,k}$ depend on algebraic forms, therefore, they are not alter mathematical property of the above differential equation system.

The interfacial pressure jump term on the left-hand side of momentum equation (2), $(p_k - p_i)\partial\alpha_k/\partial x$, is related with the surface tension as introduced by References [12]-[15]. Its salient feature is not that the pressure has a jump at the interface but that its gradient is continuous across the interface for bubbles in equilibrium. Consequently, we got the interfacial pressure jump terms as

$$(p_g - p_i)\frac{\partial \alpha_g}{\partial x} = L_m\left(1 - \frac{R_g}{2}\frac{\partial a_i}{\partial \alpha_g}\right)\frac{\partial \alpha_g}{\partial x} = C_i L_m \frac{\partial \alpha_g}{\partial x} \quad , \tag{4}$$

$$(p_i - p_l)\frac{\partial \alpha_l}{\partial x} = -L_m\left(1 + \frac{R_l}{2}\frac{\partial a_i}{\partial \alpha_l}\right)\frac{\partial \alpha_l}{\partial x} = -C_i L_m \frac{\partial \alpha_l}{\partial x} \quad . \tag{5}$$

We use the interfacial area density relation for the bubbly flow, $a_i = 3.6\alpha_g / D$, suggested by Ishii and Mishima [18]. The averaged bubble diameter D is generally obtained by using the Weber number definition, $We \equiv 2D\rho_l (v_g - v_l)^2 / \sigma$. However, if we simply assume that two radii R_g and R_l are equal to half of the averaged bubble diameter D, than the coefficient of interfacial pressure jump C_i becomes constant having an order of magnitude $O(10^{-1})$: see Chung et al. [14]. Since the fluid bulk modulus is $L_k \equiv \rho_k C_k^2$ and it holds that $L_g << L_l$, the mixture bulk modulus yields $L_m \approx L_g / \alpha_g$ as shown by Chung et al. [13, 15]. We assume here that the order of magnitude of the mixture bulk modulus with constant is almost equal to that of the gas by taking $\alpha_g \approx O(10^{-1})$ for bubbly flow, which gives then

$$C_i L_m = \rho_g C_g^2 \quad . \tag{6}$$

3. Sound Speed for Bubbly Flow

The eigenvalues of the equation system represent the wave speed of small-amplitude short wavelength perturbations as Whitham [19] indicated. For long wavelength disturbances, dispersion and source terms play a more important role while, for large amplitude disturbances, the nonlinear wave interaction is dominant. If the eigenvalues are all real, the initial value problem is well posed and stable against small disturbances.

In a matrix form, the mass, momentum, and internal energy equations become

$$\frac{\partial U}{\partial t}+G\frac{\partial U}{\partial x}=E \quad . \tag{7}$$

Using the definition $\left(\partial\rho_k/\partial p_k\right)_{s_k}=1/C_k^2$ and the identity $\partial p_g/\partial x=\partial p_l/\partial x$, the eigenvalues of matrix G in equation (7) are determined by a sixth-order polynomial equation:

$$P_6(\lambda)=(\lambda-v_g)(\lambda-v_l)\left[K_1\lambda^4+K_2\lambda^3+K_3\lambda^2+K_4\lambda+K_5\right]=0 \quad , \tag{8}$$

where the coefficients are expressed as functions of phasic properties:

$K_1=1$, $K_2=-2(v_g+v_l)$,

$$K_3=\frac{1}{\alpha_l C_g^2\rho_g+\alpha_g C_l^2\rho_l}\left\{\alpha_l C_g^2\rho_g\left[(v_g+v_l)^2+2v_g v_l-\frac{L_g}{\rho_g}-C_l^2\right]\right.$$
$$\left.+\alpha_g C_l^2\rho_l\left[(v_g+v_l)^2+2v_g v_l-\frac{L_l}{\rho_l}-C_g^2\right]\right\} \quad ,$$

$$K_4=\frac{2}{\alpha_l C_g^2\rho_g+\alpha_g C_l^2\rho_l}\left\{\alpha_l C_g^2\rho_g\left[v_g\left(C_l^2-v_l^2\right)+v_l\left(\frac{L_g}{\rho_g}-v_g^2\right)\right]\right.$$
$$\left.+\alpha_g C_l^2\rho_l\left[v_l\left(C_g^2-v_g^2\right)+v_g\left(\frac{L_l}{\rho_l}-v_l^2\right)\right]\right\} \quad ,$$

$$K_5=\frac{1}{\alpha_l C_g^2\rho_g+\alpha_g C_l^2\rho_l}\left\{\alpha_l C_g^2\rho_g\left[\left(C_l^2-v_l^2\right)\left(\frac{L_g}{\rho_g}-v_g^2\right)\right]+\alpha_g C_l^2\rho_l\left[\left(C_g^2-v_g^2\right)\left(\frac{L_l}{\rho_l}-v_l^2\right)\right]\right\} \quad .$$

The closed-form solution to the characteristic equation (8) gives a set of six real eigenvalues as listed in Table 1. The first two simple eigenvalues, λ_1 and λ_2, yield phasic convection velocities. Two eigenvalues, λ_3 and λ_5 with zero phasic velocities, i.e., $v_g=v_l=0$, represent the sound speeds of the gas and the liquid phase, respectively. The total sound speed of bubbly flow can be expressed in the following form weighted by void fraction as

$$C_t = \frac{\lambda_3 \lambda_5}{\alpha_l \lambda_3 + \alpha_g \lambda_5} \quad . \tag{9}$$

By applying the closed-form solution of equation (8), we can get

$$C_t = \frac{C_g C_l \sqrt{\dfrac{\rho_g C_g^2}{\alpha_l \rho_g C_g^2 + \alpha_g \rho_l C_l^2}}}{\alpha_l C_g + \alpha_g C_l \sqrt{\dfrac{\rho_g C_g^2}{\alpha_l \rho_g C_g^2 + \alpha_g \rho_l C_l^2}}} \quad . \tag{10}$$

For bubbly flow, the total sound speed agrees well with the experiment [20] in the void fraction range, $0 < \alpha_g < 0.3$, as shown in Figure 1. As an extreme case, the sound speed becomes that of a single-phase fluid when there is no bubble, i.e., $\alpha_g \to 0$. That is $\lim_{\alpha_g \to 0} C_t = C_l$, thus the two-phase flow result is clearly reduced to that of single-phase in the extreme case.

Nguyen [16] also derived the sound speed from the equations of continuity and momentum, considering a stationary wave front in a moving single-phase medium as

$$C_t = \frac{C_g C_l \sqrt{\dfrac{\rho_g \rho_l}{\alpha_l \rho_g C_g^2 + \alpha_g \rho_l C_l^2}}}{\alpha_g \sqrt{\rho_g} + \alpha_l \sqrt{\rho_l}} \quad . \tag{11}$$

He assumed that no phase change occurs during the propagation of sound wave and that the two-phase flow confined by a rigid wall. He also assumed that influence of the surface tension upon the pressure disturbance does not exist. Treating the interface of one phase as the elastic boundary of the other, a single-phase fluid surrounded by another fluid shows a dependency upon the bulk modulus of the other fluid, i.e. the sound speed decreases with an increasing elasticity of the other fluid.

However, Nguyen's model shows nonphysical results that the sound speed of gas dispersed in liquid is much greater than that of single-phase gas at the limiting case $\alpha_g \to 0$, as shown in Table 2. For this reason, some discrepancy between the present model and Nguyen's model in the range of small void fraction $\alpha_g < 0.02$ arises as shown in Figure 1. An increasing deviation with experimental data shown in the void fraction range $\alpha_g > 0.3$ is possibly due to the flow regime transition effect.

4. Implementation of Sound Speed Criterion

MARS code [4] is a multi-dimensional T/H (Thermal Hydraulic) system code being developed by KAERI for realistic simulation of light water reactor transients under the nuclear R&D program of the government. The first version of MARS was developed by unifying RELAP5 [5] and COBRA-TF [6] in the form of 1D and 3D modules of the code. For this, hydrodynamic models of both codes were implicitly integrated, and the T/H models and input/output features were unified. Then, the code was restructured and modernized using advanced FORTRAN 90 language for better user readability, code maintenance and user friendliness.

Now, the code operates on Windows system supported with on-line graphic user interface. Further improvements of the code are being carried out through the improvement of T/H models and numerical method. In addition, for a multi-purpose coupled safety analysis, the MARS was coupled with three-dimensional core kinetics code, MASTER, and containment analysis code, CONTEMPT4/MOD5. This enables a more realistic analysis of multi-dimensional system thermal hydraulics, where a strong feedback from core kinetics and containment response should be taken care of.

Following describes the implementation of new choking criterion in the MARS code.

One subroutine contains the two-phase choking criterion used as a boundary condition for obtaining flow solutions in the MARS code [4]. The implemented choking criterion imposes on the junctions determined to be in a choked state. If choking is predicted, equation (12) is then written in terms of new-time phasic velocities and solved in conjunction with a difference momentum equation derived from the liquid and vapor momentum equations: see Appendix A.

$$\frac{\alpha_g \rho_g v_g + \alpha_l \rho_l v_l}{\alpha_g \rho_g + \alpha_l \rho_l} = C_t \quad . \qquad (12)$$

It should be noticed here that the major difference between the Trapp and Ransom's choking criterion [3] and the present one is the adoption of the non-equilibrium sound speed C_t and the total mixture velocity v_t: We do not use the homogeneous equilibrium sound speed C_{he} of Trapp and Ransom model anymore. Furthermore, we use the total mixture velocity $v_t \equiv \frac{\alpha_g \rho_g v_g + \alpha_l \rho_l v_l}{\alpha_g \rho_g + \alpha_l \rho_l}$ derived by mass conservation instead of the Trapp and Ransom's pseudo-velocity, namely, $v_{pseudo} \equiv \frac{\alpha_g \rho_l v_g + \alpha_l \rho_g v_l}{\alpha_g \rho_l + \alpha_l \rho_g}$ in the equation (12): see Reference [21].

In the choked flow model of the MARS code [4], choking is assumed to occur at the smallest section of the flow field called throat. The choking criterion can be written in the following form derived by equation (10), which is similar to the single phase choking flow criterion and choking corresponding to a total Mach number of unity:

$$M_t \equiv v_t / C_t = \pm 1 \quad , \qquad (13)$$

In the choking test, the fluid velocity is compared with the local sound speed, which is based on the hydrodynamic conditions at the throat. It is noted that we only apply equation (13) with (10) for the calculation of Marviken tests in the initial bubbly flow regime.

If choking occurs, equation (13) is solved semi-implicitly with the upstream vapor and liquid momentum equations for v_g, v_l, and p_g at the point of flow choking [5]. Because the virtual mass terms have a significant effect on the wave propagation, we include only time derivative terms as momentum sources.

5. Marviken (LBLOCA) Choked Flow Tests

In order to validate the present choking criterion, three Marviken tests [17] are assessed using the MARS code. Those are Marviken test 24 (nozzle length-to-diameter ratio *l/d= 0.3*), test 6 (*l/d=1.0*), test 11 (*l/d=3.1*), and test 15 (*l/d=3.6*) with a fixed 30K subcooling solved by including the present sound speed criterion are compared with the experiments as well as the earlier solutions by Trapp-Ransom model [3, 5]. It should be noted that we set a discharge coefficient of 1.0 for all discharge periods for model assessment.

The Marviken tests [17] represent large-scale choked flow tests. The pressurized vessel with the total volume of 420m^3 inserted nozzles of various length-to-diameter ratio *l/d*, was used to provide data for the choked discharge flow rate of subcooled liquid, low quality two-phase mixtures, and steam. The vessel inner-diameter and height are 5.22m and 24.55m, respectively. Tests were initiated by failing rupture disks attached to the downstream end of the nozzle and then the subcooled liquid discharges from the nozzle. The water level was initially at 19.88m, 17.81m, 17.63m, and 19.93m for test 24, 6, 11, and 15, respectively, above the bottom of vessel, and the steam dome above water level was saturated at 4.96MPa for both tests 24, 4.95MPa for test 6, 4.97MPa for test 11, and 5.04MPa for test 15 as shown in Table 3.

During the tests, the subcooling at the nozzle inlet decreased from 60 to 35K in the first 0.5 second and then decreased gradually until saturated conditions were established at 25 seconds in the tests 25 and 15, and at 50 seconds in the test 6 and 11. Two-phase flow period persisted between 25 and 55 seconds in the tests 24, 11 and 15, and after 50 seconds in the test 6. Test data were determined from both pitot-static measurements at the discharge pipe. The transitions from subcooled to saturated bubbly flow are clearly shown in Figure 2 through 5. Following discharges of mixture of subcooled and saturated water, two-phase bubbly flow period is characterized by a steadily decreasing flow rate and pressure.

Figures 2 through 5 show the assessment results in comparison with experimental data and those by Trapp-Ransom model [3]. As shown in the figures, the critical flow rates calculated by the present model show good agreements with experimental data, whereas those by the Trapp-Ransom model under-predicts the experimental data. The under-prediction of the Trapp-Ransom model becomes more prevailing for smaller *l/d* ratio in which thermal non-equilibrium effect dominates. The present model also reproduces the timing of transition to single-phase vapor discharge in good agreement with experimental data, whereas the transition is prolonged a lot by the Trapp-Ransom model.

From the assessment results, it is concluded that the present model improves not only the accuracy of the two-phase flow rate but also the transition to single-phase vapor discharge even without the adjustment of discharge coefficient. Thus, MARS [4] uncertainty related with the critical flow is reduced, which will enhance the code predictability for reactor transient analysis. Such improvement mainly owes to the new choking criterion derived for non-homogeneous and non-equilibrium condition: see Reference [21]. As shown in Figure 6, the flow regime transitions from two-phase bubbly to annular flow occurs abruptly at time 55 seconds in the test 15 and at the 60 seconds in the test 24.

Comparing between test data, as shown in Figure 7, the results calculated by the present model and the Trapp-Ransom model show that the present model gives better results than the Trapp-Ransom model does during the two-phase bubbly flow discharges. The mass flow rate obtained by the Trapp-Ransom model is under predicted with discrepancies of maximum 29% for tests. But the relative errors given by the results calculated by the present model during the bubbly flow regime are smaller than those by the Trapp-Ransom model.

6. Typical PWR (SBLOCA) Test

This integral test is to simulate the 4-inch SBLOCA situation at the cold leg pipe from the normal conditions of the nuclear power reactor. Plant is composed as shown in Figure 8. A broken loop is modeled as a single loop but the other three loops are lumped into one loop. Total number of volumes is 139 and number of junctions is 142. The safety injection points, for examples, accumulator flow, high-pressure safety injection, and low-pressure safety injection, are connected to the outlet of volume 116 in the intact loop and the outlet of volume 212 in the broken loop. The break is located at the outlet of volume 212.

This test is calculated by using three models of the critical flow: namely, the present model, Trapp-Ransom model, and Henry-Fauske model. The break is occurred at 0.01 seconds after the transients, when the pressure of the pressurizer reached to 12.8MPa, the signals of reactor scram, reactor coolant pump trip, and steam generator main feed and main steam outlet trip are generated. Safety injection flow is initiated with 5 seconds delay after the pressurizer pressure reaches to 12.6MPa.

At the initial stage, the pressurized water is discharged into the ambient condition through the 4-inch break. As shown in Figure 9, the depressurization of system balance with the reduction of break discharge flow, the decay heat generation in reactor core and the secondary heat removal. After two-phase critical discharge following to the initial depressurization of the pipe, loop seal clearing in the broken loop at around 400 seconds makes the system pressure decreased. At about 600 seconds, reactor system pressure is decreased further due to the loop seal clearing in the intact loop and accumulator injection.

As shown in the Figures 9 through 12, the general trends are consistently agreed until the loop seal clearing occurs. After that, however, the calculated results are sensitive depending on the critical flow models as shown in the Figures 9 through 12. Although the results are not consistent during the accumulator injection, the present model can reproduce the results calculated by previous models like Trapp-Ransom and Henry-Fauske models.

7. Conclusions

A new choking criterion for bubbly flow has been developed based on the hyperbolic two-fluid model for non-equilibrium and non-homogenous flow. The hyperbolic two-fluid model employs the interfacial pressure jump terms in momentum equations derived using the notion of surface tension.

Total sound speed of two-phase mixture is analytically defined using the system eigenvalues obtained from the characteristic analysis of two-fluid equations system. It is found that this analytic sound speed agrees well with the existing experimental data and shows better prediction at extreme cases compared with the previous models of Nguyen and Trapp-Ransom.

New choking criterion has been implemented in the MARS code and assessed using Marviken (LBLOCA) critical flow tests. From the assessments, it is validated that the new choking criterion improves not only the accuracy of two-phase critical flow rate but also the transition to single-phase vapor discharge even without the adjustment of discharge coefficients.

By calculating the Typical PWR (SBLOCA) problem, we make sure that the present model can produce reasonable results in the transient simulation of integral reactor system. In conclusion, new choking criterion developed in this study improves the accuracy of two-phase critical flow, thus, enhances the MARS capability for the realistic simulation of thermal hydraulic system transients.

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Table 1. Eigenvalues in the bubbly flow regime

Flow Regime	Eigenvalues
Bubbly flow	$\lambda_{1,2} = v_g, v_l$ $\lambda_{3,4} = v_g \pm C_g$ $\lambda_{5,6} = v_l \pm C_l \sqrt{\dfrac{\rho_g C_g^2}{\alpha_l \rho_g C_g^2 + \alpha_g \rho_l C_l^2}}$

Table 2. Comparison of the effective sound speed in each phase

Sound speed	Present model	Nguyen's model
Liquid phase	$C_l \sqrt{\dfrac{\rho_g C_g^2}{\alpha_l \rho_g C_g^2 + \alpha_g \rho_l C_l^2}}$	$C_l \sqrt{\dfrac{\rho_g C_g^2}{\alpha_l \rho_g C_g^2 + \alpha_g \rho_l C_l^2}}$
Gas phase	C_g	$C_g \sqrt{\dfrac{\rho_l C_l^2}{\alpha_l \rho_g C_g^2 + \alpha_g \rho_l C_l^2}}$

Table 3. Marviken (LBLOCA) Tests Matrix

Test No.	Diameter (*mm*)	Length (*mm*)	*l* /*d*	Steam Pressure (MPa)	Water Level (*m*)
6	300	290	1.0	4.95	17.81
24	500	166	0.3	4.96	19.88
15	500	1809	3.6	5.04	19.93
11	509	1589	3.1	4.97	17.63

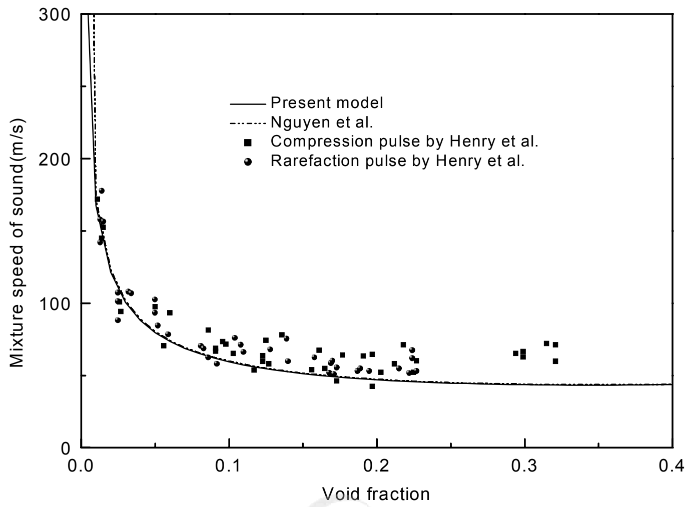

Fig. 1 Comparison of total sound speed for bubbly flow

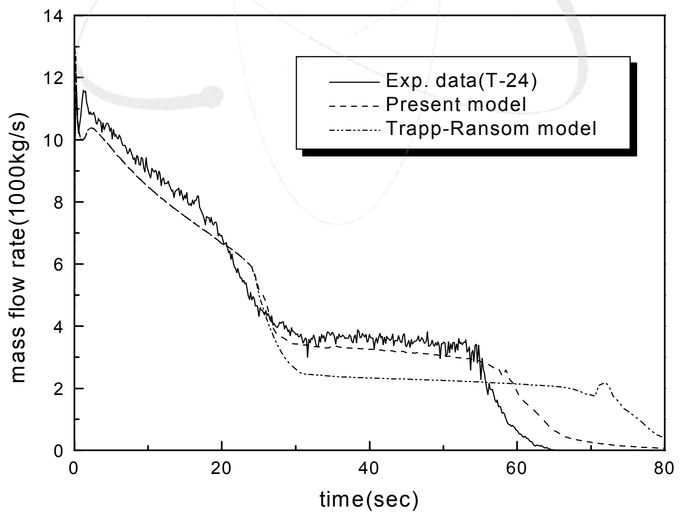

Fig. 2 Comparison between model predictions and measured data for Marviken test 24

(*l/d=0.3*)

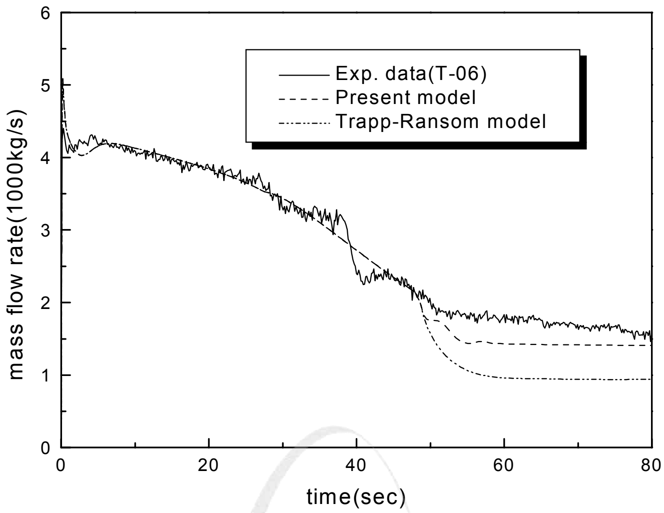

Fig. 3 Comparison between model predictions and measured data for Marviken test 6

(*l/d=1.0*)

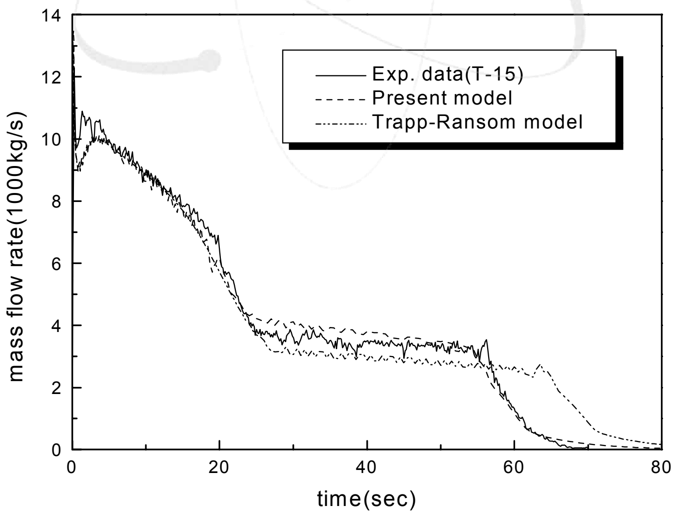

Fig. 4 Comparison between model predictions and measured data for Marviken test 15

(*l/d=3.6*)

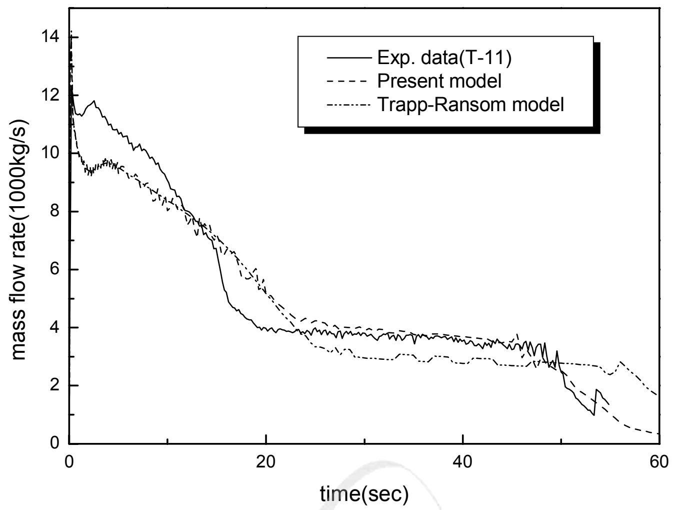

Fig. 5 Comparison between model predictions and measured data for Marviken test 11

(*l/d=3.1*)

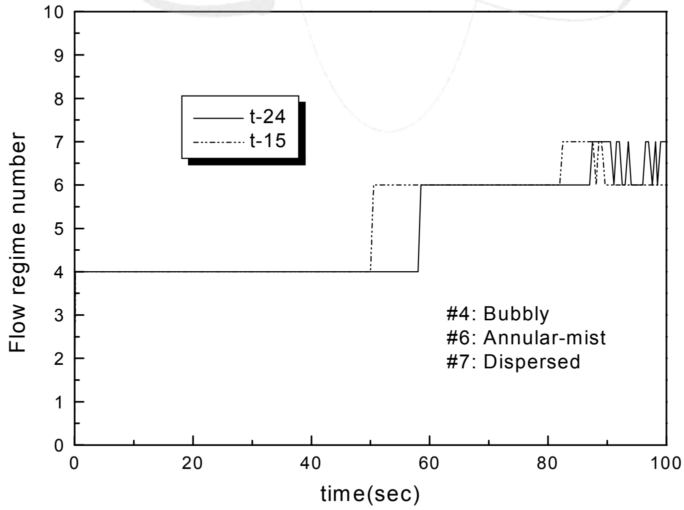

Fig. 6 Flow regime transitions during the Marviken tests 15 and 24.

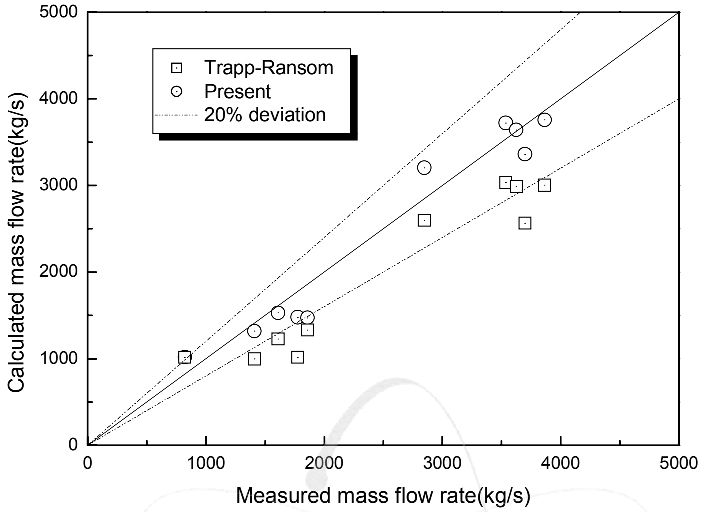

Fig. 7 Calculated mass flow rates for bubbly flow regime vs. experimental data

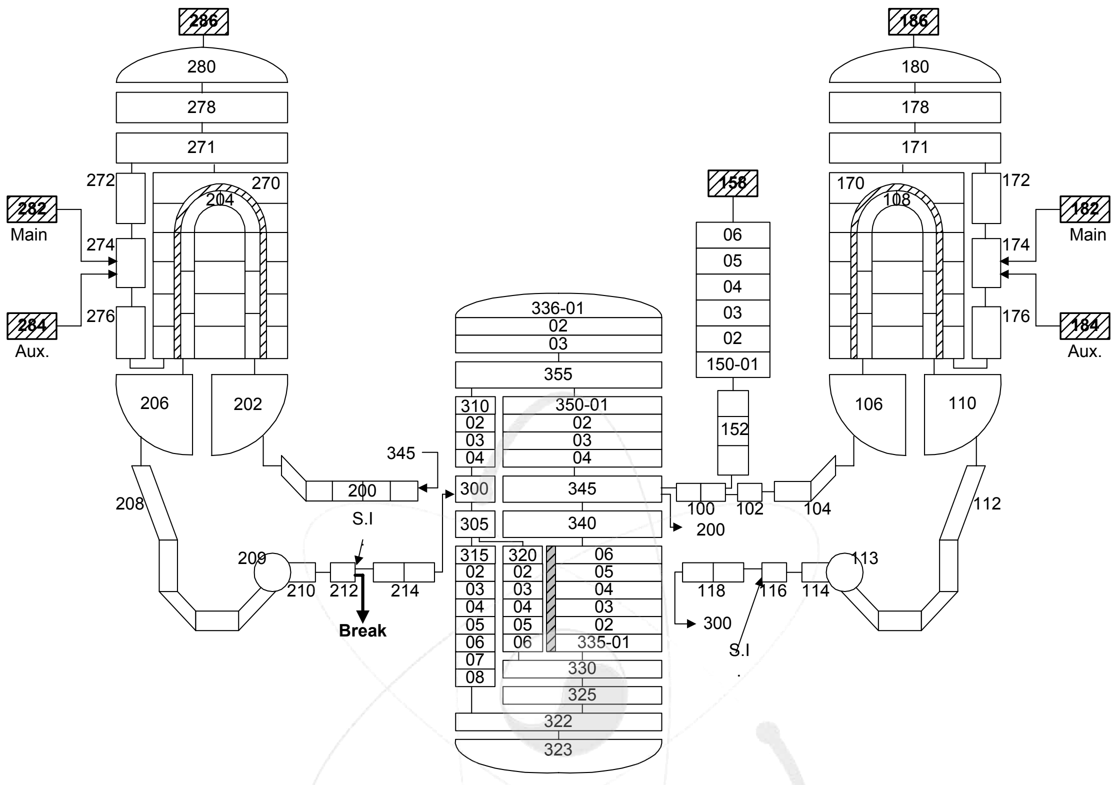

Fig. 8 Plant nodalization for Typical PWR (SBLOCA) test

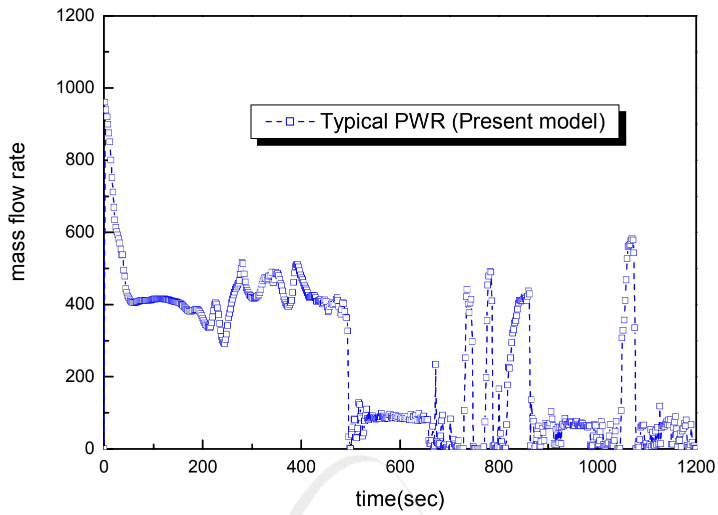

Fig. 9 Typical PWR (SBLOCA) problem calculated by using the present model with the old steam table

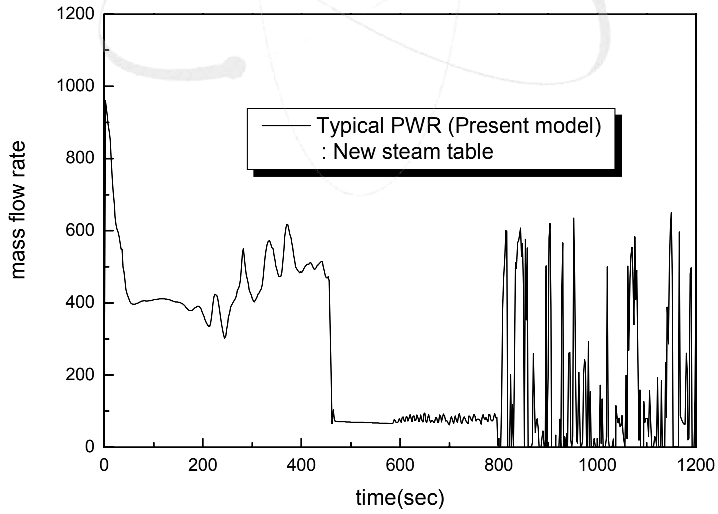

Fig. 10 Typical PWR (SBLOCA) problem calculated by using the present model with the new steam table

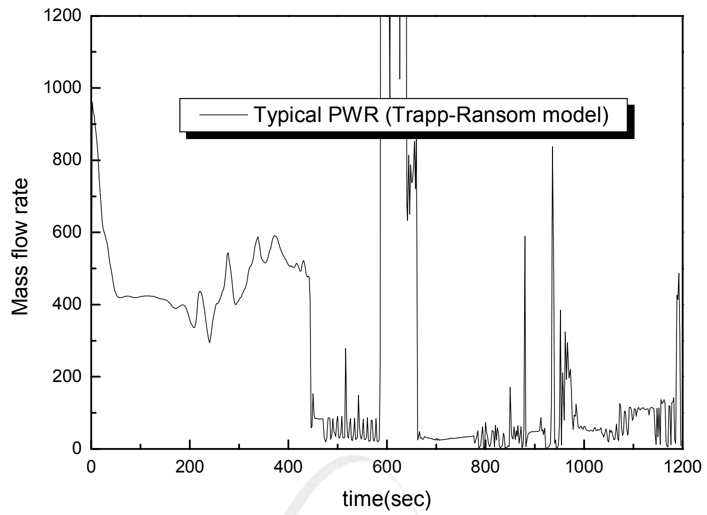

Fig. 11 Typical PWR (SBLOCA) problem calculated by using

the Trapp-Ransom model

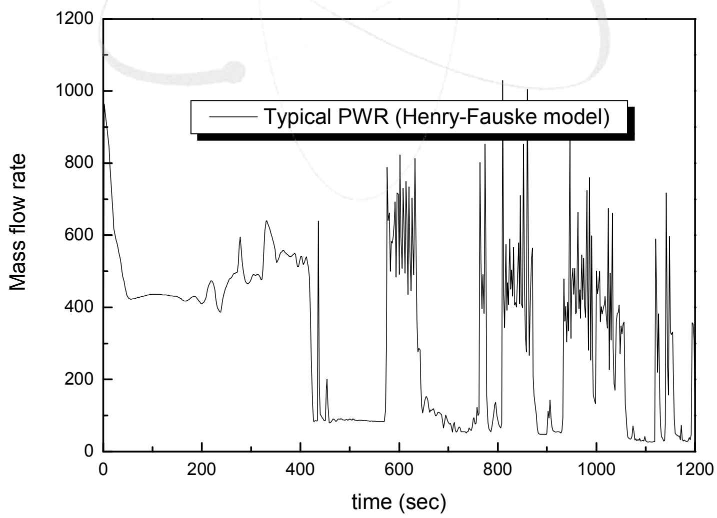

Fig. 12 Typical PWR (SBLOCA) problem calculated by using the Henry-Fauske model

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Abstract (15-20 Lines)

Choked flow calculation is improved by using a new sound speed criterion for bubbly flow that is derived by the characteristic analysis of hyperbolic two-fluid model. This model was based on the notion of surface tension for the interfacial pressure jump terms in the momentum equations. Real eigenvalues obtained as the closed-form solution of characteristic polynomial represent the sound speed in the bubbly flow regime that agrees well with the existing experimental data. The present sound speed shows more reasonable result in the extreme case than the Nguyens did. The present choked flow criterion derived by the present sound speed is employed in the MARS code and assessed by using the Marviken choked flow tests. The assessment results without any adjustment made by some discharge coefficients demonstrate more accurate predictions of choked flow rate in the bubbly flow regime than those of the earlier choked flow calculations. By calculating the Typical PWR (SBLOCA) problem, we make sure that the present model can reproduce the reasonable transients of integral reactor system.

Subject Keywords (About 10 words)

Two-phase flow, Critical flow model, Hyperbolic equation, Eigenvalue, Sound speed, LOCA