A Stabilizing Numerical Scheme of the CUPID for a Fast Transient Two Phase Flow

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1. Introduction

A high resolution thermal-hydraulic code, CUPID[1,2], has been developed at KAERI for the application to a component-scale analysis of the reactor coolant system. Two-fluid three-field governing equations are discretized using an unstructured finite volume method (FVM). The solution algorithm is based on the semi-implicit method[3], where the momentum equation is solved explicitly and the pressure is calculated using the scalar equations.

In this paper, a fast and robust solution algorithm of CUPID is presented for the calculation of a fast transient two phase flow where the interfacial heat transfer coefficient changes sharply. The numerical scheme was verified by a calculation of a two-dimensional conceptual problem of a blowdown and refill event.

2. Governing Equations

A transient two-fluid three-field model was adopted for the application to a two phase flow of gas, liquid and droplet fields. The mass, momentum and energy conservation equations are separately established for the continuous liquid, entrained liquid and vapor fields. A thermal equilibrium is assumed between the continuous and entrained liquid fields. Thus, a merged single energy equation is used for the two liquid fields. For the non-condensable gases, the velocity and the temperature are assumed to be the same as those of the vapor and, thus, only the continuity equation is added to the conservation equations.

$$\frac{\partial}{\partial t}(\alpha_k\rho_k)+\nabla\cdot(\alpha_k\rho_k\underline{u}_k)=\Gamma_k \tag{1}$$

$$\frac{\partial}{\partial t}(\alpha_k\rho_k\underline{u}_k)+\nabla\cdot(\alpha_k\rho_k\underline{u}_k\underline{u}_k)=-\alpha_k\nabla P+\nabla\cdot[\alpha_k\tau_k]+\alpha_k\rho_k\underline{g} + P\nabla\alpha_k+M_k^{mass}+M_k^{drag}+M_k^{VM}+M_k^{non-drag} \tag{2}$$

$$\frac{\partial}{\partial t}[\alpha_k\rho_k e_k]+\nabla\cdot(\alpha_k\rho_k e_k\underline{u}_k)=-\nabla\cdot(\alpha_k q_k)+\nabla\alpha_k\tau_k:\nabla\underline{u}_k - P\frac{\partial}{\partial t}\alpha_k-P\nabla\cdot(\alpha_k\underline{u}_k)+I_k+Q''_k \tag{3}$$

$$\frac{\partial}{\partial t}(\alpha_v\rho_v)+\nabla\cdot(\alpha_v\rho_v X_{nc}\underline{u}_k)=0 \tag{4}$$

where, α_k, ρ_k, u_k, Γ_k, I_k are the k-phase volume fraction, density, velocity, interface mass transfer rate, and energy transfer rate, respectively. M_k represents the interfacial momentum transfer due to a mass exchange, a drag force, a virtual mass, and non-drag forces.

3. Implicit Calculation of the Interfacial Heat Transfer Coefficient

In the CUPID, the interfacial mass and energy transfer rates, Γ_k, I_k, are calculated using the interfacial heat transfer coefficients which are determined by the flow regime dependent interfacial area and the thermal hydraulic status of the working fluid. Numerical discontinuity of the interfacial heat transfer coefficient often occurs when the flow regime or the thermal hydraulic status changes. And this may cause numerical instability especially when one of the phase fractions is small. Under relaxation is usually applied to avoid large changes in the heat transfer coefficients. However, in this case, the solutions are dependent on the size of the time step. And sometimes, this under relaxation is not enough to stabilize the solution of a fast transient with a rapidly varying interfacial heat transfer coefficient.

In this study, the calculation is carried out in predictor and corrector steps where the interfacial heat transfer coefficient is treated in a nearly implicit way. Thus the under relaxation is not necessary in this method. In the predictor step, the pressure is predicted using the combined continuity equation as in the semi-implicit SMAC method [2]. Then the new time phase fractions are estimated by solving the continuity equations. Now the interfacial heat transfer coefficient is updated considering the interfacial area obtained from the estimated phase fraction of the continuity equation. In the next corrector step, the scalar conservation equations with new interfacial heat transfer coefficient are linearized as in the semi-implicit ICE method [1]. Finally the pressure is determined by substituting the scalar equation into the momentum equation.

With this method, the calculation time step size is increased significantly and the calculation is much faster than the previous result, despite the additional calculation of the pressure equation.

4. Decoupled Energy Equations

The energy equations are expanded in a non-conservative form as:

$$\alpha_v\left\{\rho_v-\frac{P}{\rho_v}\left(\frac{\partial\rho_v}{\partial e_v}\right)\right\}\frac{\partial e_v}{\partial t}=-\nabla\cdot(\alpha_v\rho_v e_v\bar{u}_v)+h_v\nabla\cdot(\alpha_v\rho_v\bar{u}_v)-P\nabla\cdot(\alpha_v\bar{u}_v)+ \frac{P_s}{P}H_{iv}(T_s-T_v)+\Gamma_v(h_v^*-h_v)-\frac{P-P_s}{P}H_{vl}(T_v-T_l)+\ddot{q}_v \tag{5}$$

$$(\alpha_l+\alpha_d)\left\{\rho_l-\frac{P}{\rho_l}\left(\frac{\partial\rho_l}{\partial e_l}\right)\right\}\frac{\partial e_l}{\partial t}=-\nabla\cdot(\alpha_l\rho_l e_l\bar{u}_l+\alpha_d\rho_l e_l\bar{u}_d)+h_v\nabla\cdot(\alpha_l\rho_l\bar{u}_l+\alpha_d\rho_l\bar{u}_d)$$
$$-P\nabla\cdot(\alpha_l\bar{u}_l+\alpha_d\bar{u}_d)+H_{il}(T_s-T_l)-\Gamma_v(h_l^*-h_l)+\frac{P-P_s}{P}H_{vl}(T_v-T_l)+\ddot{q}_l \quad (6)$$

Eqs. (5) and (6) are not linked with the continuity equations since the terms for the phase fraction change were already removed using the continuity equations. Thus, the correction step of the previous section is not necessary and the estimated pressure and phase fractions are their new time value. The calculations are about 3 times faster than the predictor and corrector method while the conservation of scalar is a little behind.

5. Results

The present method is verified against a two dimensional conceptual problem of a blowdown and refill. Initially a liquid water column is pressurized at 150 bar with a temperature of 300 ^{o}C. The width and height of the water column are 5 m and 10 m, respectively (Fig.1). A constant heat source of 20 MW is applied to the left bottom of the water column. And the same amount of heat sink applies to the right top. Flow boundary conditions for the blowdown and injection are installed at the left and right top. A single phase calculation is performed before the blowdown at 300 s to get a steady state condition of natural circulation is achieved. Then the water flows out from the water column to the atmosphere. Flashing occurs due to a rapid depressurization. A cold water (100 ^{o}C) injection starts when the pressure is below 100 bar.

The liquid water volume deceases as the blowdown proceeds and is recovered by the injected water later. The transient of blowdown and refill has been successfully simulated using the present stabilizing scheme, smac=3, while it was failed with the previous method, smac=2. Figures 2 and 3 show the liquid volume and total energy predicted by CUPID with present scheme. The mass and energy conservation error were less than 0.1 %.

5. Conclusions

A stabilizing numerical scheme of the CUPID code was proposed for a fast transient with a large change in the interfacial heat transfer coefficient. The new method has been successful for the calculation of a two dimensional blowndown and refill case where the two phase flow appears in a very complex pattern with flashing, evaporation and condensation. The calculation were stable with a large time step and the mass and energy conservation were satisfactory.

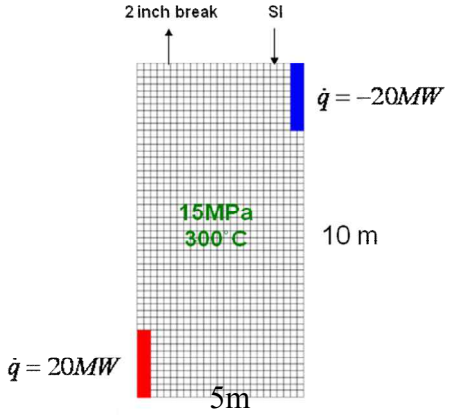

Fig. 1 Schematic of the blowdown and refill test

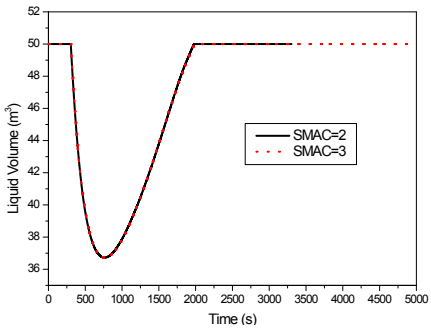

Fig. 2 Liquid volume of blowdown and refill test

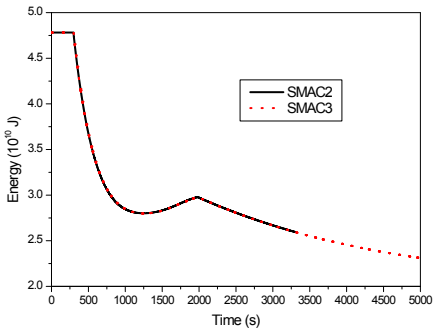

Fig. 3 Total energy of blowdown and refill test

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