Modification of MARS-KS field equations for considering hydraulic volume change due to blockage

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1. Introduction

During loss of coolant accident (LOCA) conditions, the degradation of fuel cladding integrity is accelerated as the loss of coolant accompanies the heat up of the fuel cladding. The resulting phenomena due to the degradation are ballooning and burst [1]. Under such conditions, the resulting geometrical changes cause flow blockage. The blockage of the flow channel degrades coolability and thus, it gives negative impact on the reactor safety.

Meanwhile, as one of the computational codes for reactor safety analyses, MARS-KS [2] has been utilized for best-estimate system analyses for reactor transient and accident conditions. For the best-estimate analyses, realistic system behaviors should be reflected. However, since MARS-KS adopts fixed volume condition, in which the hydraulic volume change cannot be implemented, it cannot deal with the flow blockage, realistically.

In order to consider the hydraulic volume change, the modification of the field equations of MARS-KS should be performed. In this study, the modification of field equations has been made to the mass, momentum, and energy equations, respectively, by employing the concept of porosity [3]. Through the following chapter, the modified field equations will be derived, and the modification will be verified using simple for single-phase flow conditions.

2. Derivation of field equations

Since MARS-KS adopts the control volume only with fluid volume, there is a need to modify the definition of the porosity, ε. In this study, the modified porosity is defined as Eq. (1), which corresponds to a fraction of the changed volume with respect to the original fixed volume.

$$\varepsilon = \frac{V-\Delta V}{V} \tag{1}$$

The volume change could be implemented by employing the modified porosity to each derivatives and source terms in the original field equations. The modified field equations are given from Eq. (2) to Eq. (7). This form of the filed equation enables the volume change as the porosity varies with respect to the time. Also, the original form of the field equation is preserved as the porosity is converged to the unity, which corresponds to the fixed volume condition. However, in the case of momentum equation, MARS-KS adopts expanded form, which is derived by expanding the derivatives in the left-hand side with respect to the phasic velocity. Under this condition, the porosity could be removed from the equation as it becomes the multiplier through the separation from each derivative. From this, it is clearly confirmed that there is no need to modify the momentum equation, and, therefore, the modification is necessary only to mass and energy equations, as the volume change is considered.

- Continuity equation

$$\frac{\partial}{\partial t}(\varepsilon\alpha_g\rho_g) + \frac{L}{V}\frac{\partial}{\partial x}(\varepsilon\alpha_g\rho_g v_g A) = \varepsilon\Gamma_g \tag{2}$$

$$\frac{\partial}{\partial t}(\varepsilon\alpha_f\rho_f) + \frac{L}{V}\frac{\partial}{\partial x}(\varepsilon\alpha_f\rho_f v_f A) = -\varepsilon\Gamma_g \tag{3}$$

- Momentum equation

$$\begin{aligned}&(\varepsilon\alpha_g\rho_g)\frac{\partial v_g}{\partial t} + \left(\varepsilon\frac{1}{2}\alpha_g\rho_g\right)\frac{\partial v_g^{\,2}}{\partial x} = -\varepsilon\alpha_g\frac{\partial P}{\partial x} + \varepsilon\alpha_g\rho_g B_x\\ &-\varepsilon(\alpha_g\rho_g)FWG(v_g) - \varepsilon(\alpha_g\rho_g)HLOSSG(v_g)\\ &+\varepsilon\Gamma_g(v_{gI} - v_g) - (\varepsilon\alpha_g\rho_g)FIG(v_g - v_f)\\ &-(\varepsilon C\alpha_f\alpha_g\rho_m)\left[\frac{\partial}{\partial t}(v_g - v_f) + v_f\frac{\partial v_g}{\partial x} - v_g\frac{\partial v_f}{\partial x}\right]\end{aligned} \tag{4}$$

$$\begin{aligned}&(\varepsilon\alpha_f\rho_f)\frac{\partial v_f}{\partial t} + \left(\varepsilon\frac{1}{2}\alpha_f\rho_f\right)\frac{\partial v_f^{\,2}}{\partial x} = -\varepsilon\alpha_f\frac{\partial P}{\partial x} + \varepsilon\alpha_f\rho_f B_x\\ &-(\varepsilon\alpha_f\rho_f)FWF(v_f) - (\varepsilon\alpha_f\rho_f)HLOSSF(v_f)\\ &-\varepsilon\Gamma_g(v_{fI} - v_f) - (\varepsilon\alpha_f\rho_f)FIF(v_f - v_g)\\ &-(\varepsilon C\alpha_f\alpha_g\rho_m)\left[\frac{\partial}{\partial t}(v_f - v_g) + v_g\frac{\partial v_f}{\partial x} - v_f\frac{\partial v_g}{\partial x}\right]\end{aligned} \tag{5}$$

- Energy equation

$$\begin{aligned}&\frac{\partial}{\partial t}(\varepsilon\alpha_g\rho_g U_g) + \frac{L}{V}\frac{\partial}{\partial x}(\varepsilon\alpha_g\rho_g U_g v_g A)\\ &= -P\left[\frac{\partial}{\partial t}(\varepsilon\alpha_g) + \frac{L}{V}\frac{\partial}{\partial x}(\varepsilon\alpha_g v_g A)\right] + Q_{wg}\\ &+\varepsilon\left[Q_{ig} + \Gamma_{ig}h_g^{\,*} + \Gamma_{wg}h_g^{\,\prime} - Q_{gf} + DISS_g\right]\end{aligned} \tag{6}$$

$$\frac{\partial}{\partial t}(\varepsilon\alpha_f\rho_f U_f)+\frac{L}{V}\frac{\partial}{\partial x}(\varepsilon\alpha_f\rho_f U_f v_f A)$$
$$= -P\left[\frac{\partial}{\partial t}(\varepsilon\alpha_f)+\frac{L}{V}\frac{\partial}{\partial x}(\varepsilon\alpha_f v_f A)\right]+Q_{wf}$$
$$+\varepsilon\left[Q_{if}-\Gamma_{ig}h_f^{*}-\Gamma_{wg}h_f{}'+Q_{gf}+DISS_f\right] \qquad (7)$$

3. Verification

3.1. Simple model for verification

For the verification, three-different simple models are made with respect to the single-phase flow condition. One is for the modified code calculation, and the others are for the original code calculations. Each model consists of a single channel without modeling the heat structure. For the modified code calculation, the volume change is modeled by reducing the porosity at the fifth node of the flow channel, as depicted in Fig.1. During the total calculation time of 50.0sec, the volume starts to change at 30.0sec. The volume change is made with the change rate of the porosity as 1/s until the reduced volume reaches 20% of the initial volume. Meanwhile, the remained two-different models are made for the comparison of the modified code with respect to original code. Each model is modeled with different flow channel conditions with respect to the volume changes at the fifth node, respectively. One models the flow channel before the volume change, and the other models the flow channel after the volume change. In order for the verification about the single-phase flow conditions, each model is employed to each case of vapor and liquid, respectively.

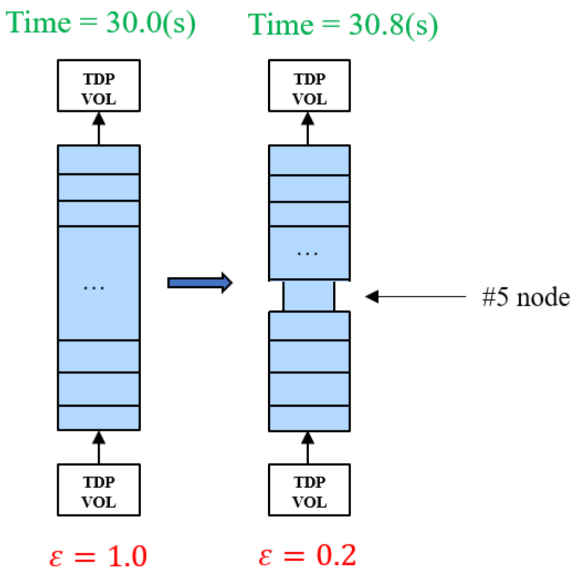
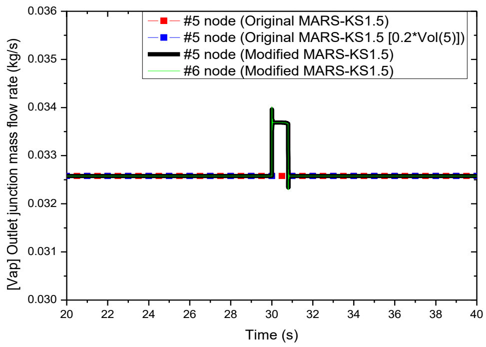


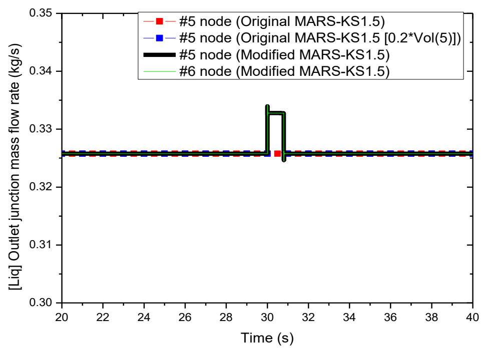
Fig 1. Scheme of volume change process in simple example for verification

3.2. Results

In total, six cases are calculated for the verification about the single-phase flow. As depicted in Fig.2, one of the most typical phenomena due to the volume reduction is further acceleration of the downstream mass flow during the period of the volume change. As the initial mass should be conserved, this leads to the additional mass transfer corresponding to the reduced volume. Furthermore, as the flow area decreases, velocity becomes accelerated, and this induces local pressure drop due to the increase of the dynamic head. These could be found through Fig.3 and Fig.4, respectively. Finally, the total system mass becomes reduced, which corresponds to the result of flow channel reduction, as depicted in Fig.5. For all the given variables, it is clearly shown that the results of the modification are converged to the original results in both cases of before and after the volume changes. This means that the derived modification is complete without physical and numerical problems.

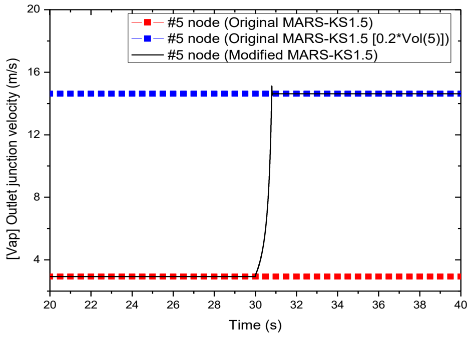


(a) vapor mass flow

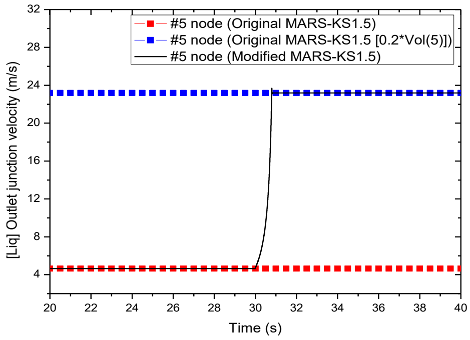


(b) liquid mass flow

Fig 2. Comparison of the calculated mass flow rate

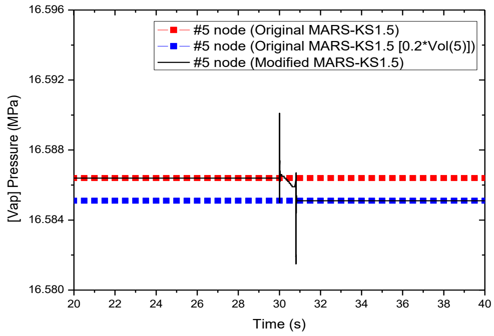


(a) vapor velocity

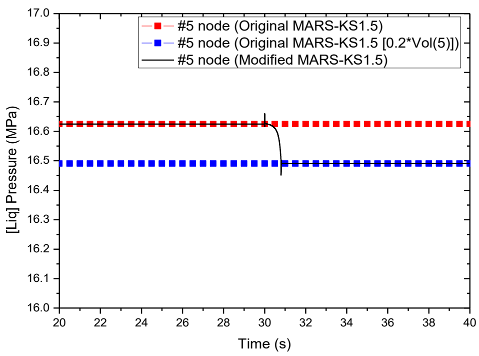


(b) liquid velocity

Fig 3. Comparison of the calculated phasic velocity

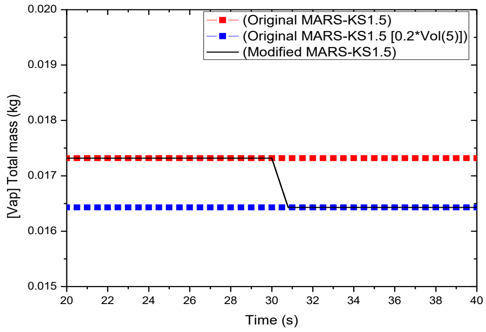


(a) static pressure of vapor

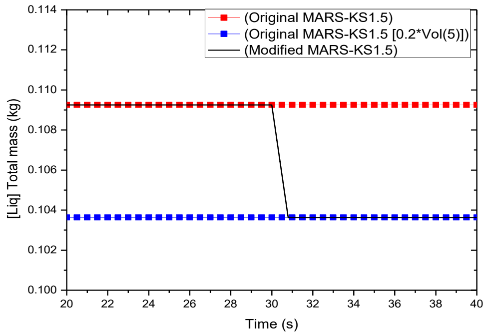


(b) static pressure of liquid

Fig 4. Comparison of the calculated static pressure



(a) total system mass of vapor



(b) total system mass of liquid

Fig 5. Comparison of the calculated total mass

4. Conclusion

The modified MARS-KS field equation to deal with the volume change has been verified based on the simple examples, which consist of single-phase vapor and liquid flow condition, respectively. The verification has been made by comparing the calculated results against the original code with and without volume changes, respectively. As a result, it is confirmed that there are no physical and numerical problems to each single-phase condition, as the calculated results of the modification are completely converged to the original results. As a future work, for further verification, two-phase flow with air-water and liquid-vapor conditions will be analyzed based on the identical simple-test. For the case of two-phase liquid-vapor condition, heat structure will be modeled, and the volume reduction due to the porosity change will be implemented through the expansion of the corresponding heat structure.

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