Effect of Virtual Mass Coefficient on Critical Flow Model for S-CO_2 system

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1. Introduction

A Small Modular Reactor (SMR) is considered as a promising future reactor technology. For SMR development, a Supercritical CO_2 (S-CO_2) is being considered as a coolant for reactor and power generation [1].

A Design Basis Accident (DBA) initiated by a loss of fluid, CO_2 becomes choked due to high pressure condition of S-CO_2 system. The choked flow with second phase appearance can occur under depressurization scenario of S-CO_2 system as seen in Fig. 1. Therefore, to assess the safety of S-CO_2 system for nuclear power application, safety analysis code needs appropriate critical flow model including single and two-phase for S-CO_2 system.

Prior to the development of critical flow model for S-CO_2, effect of each term in the model should be analyzed to determine whether or not it significantly affects the analysis result. In a critical flow model based on two-fluid model, terms with derivative affect the critical flow condition. In general, virtual mass term only has derivatives in the two-fluid model if the mass transfer term is modeled as relaxation type that has no derivatives. For this reason, the effect of virtual mass coefficient is examined and presented using sensitivity analysis in this paper for the S-CO_2 critical flow application.

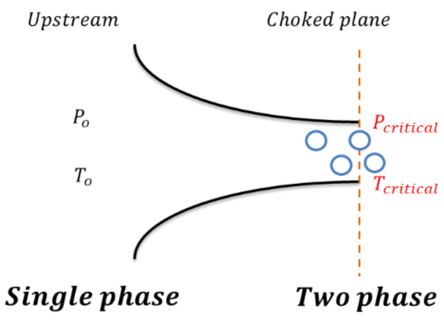

Fig. 1. Schematic of critical flow with appearance of the second phase [2]

2. Sensitivity analysis of virtual mass coefficient

2.1 Sensitivity analysis conditions

To identify the effect of virtual mass coefficient on the sound speed (i.e. critical flow velocity), following assumptions are used in two-fluid model.

1) Steady-state
2) Each phase has same velocity
3) Thermal-equilibrium
4) Only virtual mass term includes derivatives

The most general form of the 1-D virtual mass acceleration given by Drew et al. [3] is used with steady-state. Virtual mass term can be expressed as in Eq. 2.

$$a_{VM} = \left(V_l + (1-\lambda)(V_l - V_g)\right)\frac{dV_g}{dz} \dots + \left(-V_g + (1-\lambda)(V_g - V_l)\right)\frac{dV_l}{dz} \quad (1)$$

where
$$\lambda = 2(1-\alpha_g)$$

$$F_{VM} = C_{VM}\rho_m \alpha_g (1-\alpha_g) a_{VM} \quad (2)$$

where
$$\rho_m = \alpha_g \rho_g + (1-\alpha_g)\rho_l$$
$$C_{VM} : Virtual\ mass\ coefficient$$

Steady-state governing equation set of two-fluid model is described with Eq. 3. The sound speed is obtained by finding the velocity that satisfying the necessary condition for choking which is mathematically shown in Eq.4.

$$A(X)\frac{dX}{dz} = b(X) \quad (3)$$

$$\mathrm{Det}(A) = 0 \quad (4)$$

2.2 Sensitivity analysis results

Zuber et al. [4, 5] stated that the value of the virtual-mass coefficients is approximately 0.5 for highly dispersed bubbly and droplet flows and the value approaches zero for separated flows. If interactions between the dispersed phase bubbles or drops are included, values for the virtual mass coefficient have been estimated to be as large as four. Therefore, the range of virtual mass coefficient for CO_2 can be from zero to four.

Figs. 2-3 show the change in sound speed of two-phase CO_2 according to the void fraction with constant virtual mass coefficients. Since the mass transfer term is used in the form without any derivative, discontinuity does not appear on both sides and it is consistent with the speed of sound in each phase. This trend of change in sound speed can be seen in velocities of rarefaction waves in steam-water mixture at low void fraction measured by

Henry et al [7]. As shown in Fig. 4, the calculated sound speed seems to agree well with the experiment data.

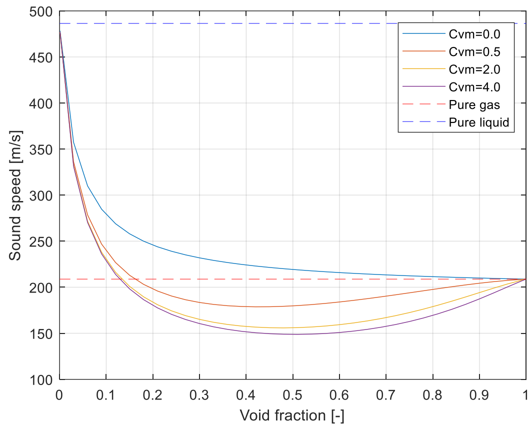

Fig. 2. Calculated two-phase sound speed of CO_2 at 4MPa

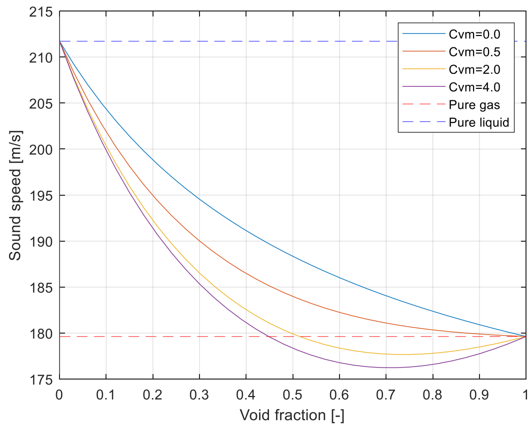

Fig. 3. Calculated two-phase sound speed of CO_2 at 7MPa

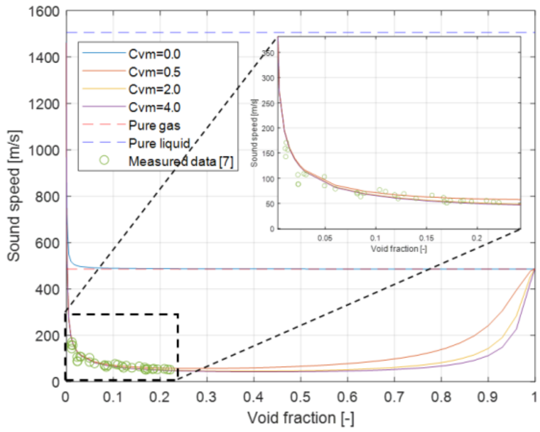

Fig. 4. Comparison of measured and calculated two-phase sound speed of saturated H_2O at 265 °F

It can be also identified that the sensitivity to virtual mass coefficient becomes larger as virtual mass coefficient is smaller. In addition, it can be seen that larger virtual mass coefficient leads to lower sound speed of two-phase. This result is consistent with the previous observation that smaller virtual mass coefficient will result in larger non-equilibrium effect on the velocity, and larger non-equilibrium effect increases the critical mass flux.

2.3 Comparison of correlations for virtual mass coefficient

The previous research works proposed correlations for virtual mass coefficient. Drew et al. [3] had no consideration of flow regime transition because they simply extended the correlation determined by Zuber. On the other hand, Wein [6] considered that the bubble coalescence causes the phases to separate and it reduces the virtual mass coefficient. To consider this point, the transition region is introduced and the virtual mass coefficient can have different values in three different regions (bubbly, transition and droplet). Fig. 5 shows a difference between the correlations. In particular, each correlation shows a different trend in the transition region, and for this reason, Figs. 6-7 show that the difference between the calculated sound speeds in the transition region is large compared to other region.

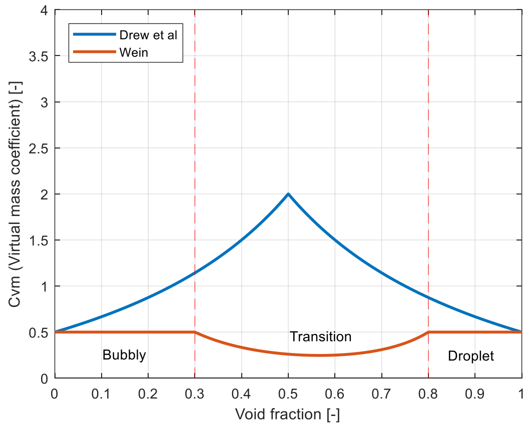

Fig. 5. Comparison of virtual mass coefficient correlations

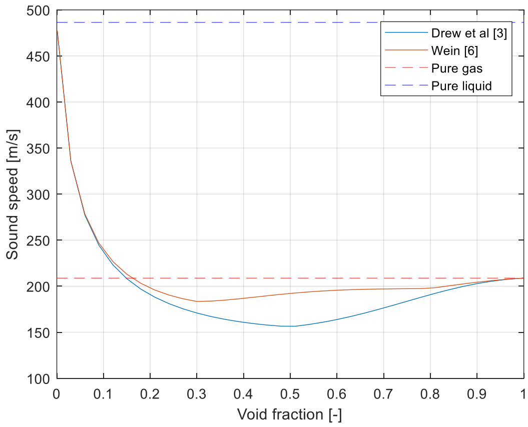

Fig. 6. Calculated two-phase sound speed of CO_2 at 4MPa

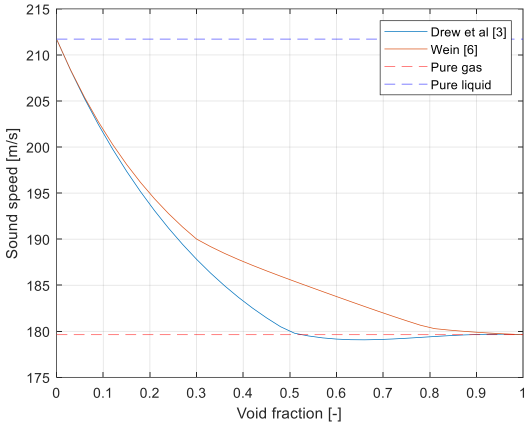

Fig. 7. Calculated two-phase sound speed of CO_2 at 7MPa

4. Summary and Conclusions

Sensitivity of two-phase sound speed for CO_2 in two-fluid model to virtual mass coefficient is analyzed. Two applicable correlations for virtual mass coefficient to the entire void fraction are compared for CO_2 flow conditions. From the analysis, it is confirmed that the virtual mass coefficient is a parameter that can have a significant influence on the critical flow mass flux. Thus, appropriate virtual mass coefficient should be determined for the CO_2 critical flow model.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT) (No. 2016R1A5A1013919).

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