Development and Verification of a Semi-implicit Three-Field Pilot Code

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1. Introduction

The thermal/hydraulic behavior of a multiphase flow is predicted by solving the related governing equations. The equations are devised based on the mass, momentum, and energy conservation laws and physical models defining the thermal and mechanical interactions between the phases involved. A great deal of effort has been paid, during the past two or three decades, to solve the equations in an efficient and stable manner. A reliable methodology to obtain the solution of the equation set is essential, especially in a nuclear thermal/ hydraulic safety analysis where the consequences of the various hypothetical incidents are required to be within a predefined range of acceptance.

In this study, a semi-implicit solver is developed for a one-dimensional channel flow as three-fields. The three-field modeling of water is similar to a method employed in codes such as COBRA [2]. The three fields are comprised of a gas, continuous liquid and entrained liquid field. All the three fields are allowed to have their own velocities. The continuous liquid and the entrained liquid are, however, assumed to be in a ermal equilibrium.

2. Methods

2.1 Governing equations

The governing equation set for the three-field modeling of a two phase flow is based on the time-space average equations of a single-pressure two-fluid model [3]. The equations are:

$$\frac{\partial}{\partial t}(\alpha_v\rho_v)+\frac{1}{A}\frac{\partial}{\partial x}(\alpha_v\rho_v v_v A)=\Gamma_v \tag{1}$$

$$\frac{\partial}{\partial t}(\alpha_l\rho_l)+\frac{1}{A}\frac{\partial}{\partial x}(\alpha_l\rho_l v_l A)=-(1-\eta)\Gamma_v - S \tag{2}$$

$$\frac{\partial}{\partial t}(\alpha_e\rho_e)+\frac{1}{A}\frac{\partial}{\partial x}(\alpha_e\rho_e v_e A)=-\eta\Gamma_v + S \tag{3}$$

where η stands for the evaporation fraction from the entrained liquid, and the subscriptions v, l and d are for the vapor, continuous liquid and entrained liquid, respectively. Similarly, the momentum equation and energy equations for the gas phase are, respectively,

$$\begin{aligned}
&\alpha_v\rho_v\frac{\partial v_v}{\partial t}+\alpha_v\rho_v v_v\frac{\partial v_v}{\partial x}=-\alpha_v\frac{\partial P}{\partial x}+\alpha_v\rho_v B_x - F_{wv}(v_v)\\
&-\Gamma_E v_v+(1-\eta)\Gamma_E v_l+\eta\Gamma_E v_d\\
&-F_{vd}(v_v-v_d)-F_{vl}(v_v-v_l)\\
&-C_{v,vd}\alpha_v\alpha_d\rho_{m,vd}\frac{\partial(v_v-v_d)}{\partial t}-C_{v,vl}\alpha_v\alpha_l\rho_{m,vl}\frac{\partial(v_v-v_l)}{\partial t}
\end{aligned}\tag{4}$$

$$\begin{aligned}
&\frac{\partial(\alpha_v\rho_v u_v)}{\partial t}+\left(\frac{1}{A}\right)\frac{\partial(A\alpha_v\rho_v u_v v_v)}{\partial x}=-P\frac{\partial\alpha v}{\partial t}-\left(\frac{P}{A}\right)\frac{\partial(A\alpha_v v_v)}{\partial x}\\
&+Q_{wv}+Q_{iv}+\Gamma_{vi}h_g^{*}+\Gamma_w h_g^{'}+DISS_v+\ddot{q}_v
\end{aligned}\tag{5}$$

The momentum and energy equations for the continuous liquid and entrained liquid can be similarly obtained.

2.2 Finite Difference Equations

The differential equation set is integrated over the 1-diminentional node depicted in Figure 1.

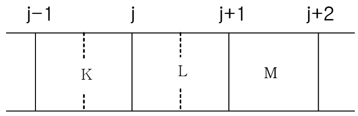

Figure 1. One-dimensional Nodes for the Pilot Code

The momentum equation for the vapor is in the form of

$$\begin{aligned}
&(\alpha_v\rho_v)_j^n(v_v^{n+1}-v_v^n)_j\big/\Delta t+(\dot{\alpha}_v\dot{\rho}_v v_v)_j^n\left[(\bar{v}_v)_L-(\bar{v}_v)_K\right]/\Delta x_j\\
&=-(\alpha_v)_j^n(P_L^{n+1}-P_K^{n+1})/\Delta x_j+\left[(\alpha_v\rho_v)_j^n B_x-F_{wv}{}_j^n(v_v)_j^{n+1}\right]\\
&+\left[-(\Gamma_E)_j^n(v_v)_j^{n+1}+\left\{(1-\eta_j^n)(\Gamma_E)_j^n\right\}(v_l)_j^{n+1}+\left\{\eta_j^n(\Gamma_E)_j^n\right\}(v_d)_j^{n+1}\right]_j\\
&-\left[F_{vd}{}_j^n(v_{v,j}^{n+1}-v_{d,j}^{n+1})+F_{vl}{}_j^n(v_{v,j}^{n+1}-v_{l,j}^{n+1})\right]\\
&-(\alpha_v\alpha_d)_j^n\left\{(C_{v,vd}\rho_{m,vd})_j^n\left[(v_v)_j^{n+1}-(v_v)_j^n-(v_d)_j^{n+1}+(v_d)_j^n\right]\right\}/\Delta t\\
&-(\alpha_v\alpha_l)_j^n\left\{(C_{v,vl}\rho_{m,vl})_j^n\left[(v_v)_j^{n+1}-(v_v)_j^n-(v_l)_j^{n+1}+(v_l)_j^n\right]\right\}/\Delta t\\
&+\frac{1}{2}\left[VISV_j^n\right]/\Delta x_j
\end{aligned}\tag{6}$$

It is noted that the old time step is used for the advection term, whereas the implicitness of the velocity is maintained for the source terms originating from both the phase change and the surface forces. The correlations for determining the phase change and the surface force, however, are based on the old time step.

The finite difference equations for the mass and energy equations are derived in a similar fashion. The equations are expanded for the time and space derivative terms before applying the finite difference method. This is merely for a convenience during the process of finite differencing. The *unexpanded* original forms are again used at the end the time step to minimize the mass error introduced by the linearization process of the densities and temperatures for a time step (n+1). The procedure for solving the finite difference equations are very similar to that used by the RELAP5/MOD3 code [4].

2.3 Models and Correlations

The governing equations for the mass, momentum, and energy equations require models and correlations for the interphase phenomena and interactions between a fluid and its surrounding structure. The interphase phenomena include heat and mass transfers, as well as a momentum transfer. The fluid/structure interaction, generally, includes both heat and momentum transfer. Assuming a adiabatic system, only a momentum transfer is considered in this study, leaving the wall heat transfer for a future study.

In this study, a void fraction and mass flow rate serve as the main flow conditions for categorizing the flow regimes as liquid, stratified, bubbly, slug, annular mist, mist, and vapor. The flow regimes are smoothed over the transition regimes for a continuous change of the model coefficients.

The major parts of the correlations for the interphase area concentration, friction, and heat/mass transfer were adopted from the TRAC code[5]. The wall friction model used is similar to the RELAP5/MOD3 model [4]. The entrainment and de-entrainment models, on the other hand, are based on the models discussed in [6-8]. The details of the models and correlations compiled for the pilot code are found in [9].

3. Results and Discussion

The integrity of the numerics and the model/correlations implemented in the pilot code is verified against several conceptual problems. These problems include:

1. Single phase liquid and vapor stagnation
2. Single phase liquid and vapor flow
3. Two phase liquid-vapor mixture
4. Liquid over steam problem
5. Fill problem of a vertical channel
6. Three-field two phase flow for interfacial drag
7. Subcooled spray flow
8. Manometer Oscillation by a u-tube simulation
9. Boil-off problem
10. Flashing problem

Each program was selected to verify a specific requirement or a capability of the pilot code. The subcooled spray flow problem demonstrates a special kind of flow condition observed in a pressurizer. The separate treatment of the entrained liquid, as opposed to the two-field model, allows for a more realistic behavior of the spray droplets. The schematic of the spray problem and the volume fraction of each three field at the bottom node are shown in Figure 2. The soundness of the solver is demonstrated. The improved model for a de-entrainment, however, is deemed necessary for a more realistic volume distributions.

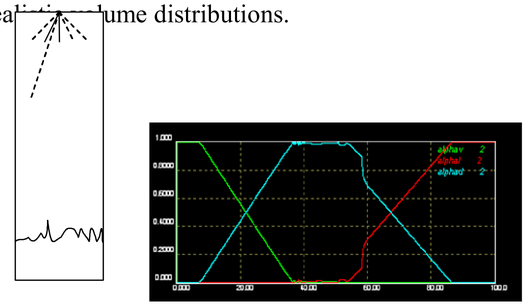

Figure 2. Spray and volume fraction transients

In the flashing problem, a highly pressurized liquid water is exposed to an atmospheric pressure condition, educing a highly transient evaporation phenomenon. Figure 3 shows the pressure and void fraction behavior during the initial 0.5 second, together with the MARS 3.0 results. Even though a quantitative comparison might not be very important at this stage of the development, the very similar simulation results are still noteworthy.

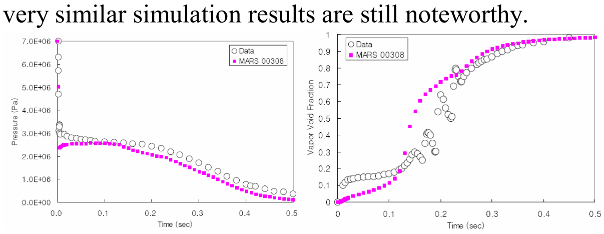

Figure 3. Pressure and Void fraction during a Flashing

4. Summary

In this study, a semi-implicit pilot code for a two phase flow is developed and verified. The two phase flow of water is modeled by a three field mass, momentum and energy equation set. The verification tests confirm the sound integrity of the numerical scheme as well as the model and the correlations implemented for the interphase phenomena.

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