Implementation and Assessment of Three-Field Modeling for MARS 1-D Code

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1. Introduction

The two-phase mixture of liquid water and steam has been analyzed using the two-fluid (or two-phase) representation in MARS 1-D module [1], as is done in most reactor system analysis codes. MARS 1-D code could also treat noncondensible gas as a part of the gas phase, assuming thermal and mechanical equilibrium with the steam. Soluble materials such as boron are included in the liquid phase. The two-phase modeling of the liquid/gas mixture flows, even though quite adequate in most flow conditions, wouldn't quite closely represent the flow where entrained liquid is involved, especially in the channel flow. The entrained liquid, in so-called annular mist flow, is known to have much higher velocity than the continuous liquid along the channel wall has. It is therefore believed more appropriate to treat the entrained liquid in a separate manner from the continuous liquid in such a flow.

In this study, the three-field modeling of the two-phase mixture is developed. The finite difference equations for the three-field equations thereafter are devised. The solution scheme has been implemented into the MARS 1-D code. To test the three-field implementation, several conceptual problems have been simulated using the new solution scheme.

2. Methods and Results

2.1 Three-field formulation

The thermal-hydraulic behavior of the two-phase mixture is predicted based on the multiphase field equations [2,3,4]. The equation set is known to be quite adequate especially where the volume and time averaged physical quantities could serve as major parameters for determining the physical phenomena of interest. The three-field formation of the mass, momentum, and energy equations are recast here. It is noted, however, that the thermal equilibrium between the entrained and continuous liquid is assumed for the energy equation formulation.

Mass equations (gas, continuous and entrained liquid):

$$\frac{\partial}{}(\alpha^g\rho^g)+\frac{1}{}\frac{\partial}{}(\alpha^g\rho^g v^g A)=\Gamma^g(=\Gamma^{l\to g}+\Gamma^{e\to g})$$

$$\frac{\partial}{}(\alpha^l\rho^l)+\frac{1}{}\frac{\partial}{}(\alpha^l\rho^l v^l A)=\Gamma^l$$

$$\frac{\partial}{}(\alpha^e\rho^e)+\frac{1}{}\frac{\partial}{}(\alpha^e\rho^e v^e A)=\Gamma^e$$

Momentum equations (gas, continuous and entrained liq.):

$$\begin{aligned}\alpha_g\rho_g A\frac{\partial v_g}{\partial t}+\frac{1}{2}\alpha_g\rho_g A\frac{\partial v_g^2}{\partial x}&=-\alpha_g A\frac{\partial P}{\partial x}+\alpha_g\rho_g B_x A-\alpha_g\rho_g A\,FWG\,v_g\\&-\Gamma_C v_g A+(1-\eta)\Gamma_E v_l A+\eta\Gamma_E v_e A-\Gamma_g v_g A\\&-(\alpha_g\rho_g A)\,FIGE\,(v_g-v_e)-(\alpha_g\rho_g A)\,FIGL\,(v_g-v_l)\\&-C_{v,ge}\alpha_g\alpha_e\rho_{m,ge}A\frac{\partial(v_g-v_e)}{\partial t}-C_{v,gl}\alpha_g\alpha_l\rho_{m,gl}A\frac{\partial(v_g-v_l)}{\partial t}\end{aligned}$$

$$\begin{aligned}\alpha_l\rho_l A\frac{\partial v_l}{\partial t}+\frac{1}{2}\alpha_l\rho_l A\frac{\partial v_l^2}{\partial x}&=-\alpha_l A\frac{\partial P}{\partial x}+\alpha_l\rho_l B_x A-\alpha_l\rho_l A\,FWL\;v_l\\&+\{-\eta(\Gamma_E v_e-\Gamma_C v_g)+S_E v_l-S_D v_e\}A+(\eta\Gamma_g-S_E+S_D)v_e A\\&-(\alpha_e\rho_e A)\,FIEG\;(v_e-v_g)-(\alpha_e\rho_e A)\,FIEL\;(v_e-v_l)\\&-C_{v,\mathrm{lg}}\alpha_l\alpha_g\rho_{m,\mathrm{lg}}A\frac{\partial(v_l-v_g)}{\partial t}\end{aligned}$$

$$\begin{aligned}\alpha_e\rho_e A\frac{\partial v_e}{\partial t}+\frac{1}{2}\alpha_e\rho_e A\frac{\partial v_e^2}{\partial x}&=-\alpha_e A\frac{\partial P}{\partial x}+\alpha_e\rho_e B_x A-\alpha_e\rho_e A\,FWE\;v_e\\&+\{-(1-\eta)(\Gamma_E v_l-\Gamma_C v_g)-S_E v_l+S_D v_e\}A+\{(1-\eta)\Gamma_g+S_E-S_D\}v_l A\\&-(\alpha_l\rho_l A)\,FILG\;(v_l-v_g)-(\alpha_l\rho_l A)\,FILE\;(v_l-v_e)\\&-C_{v,eg}\alpha_e\alpha_g\rho_{m,eg}A\frac{\partial(v_e-v_g)}{\partial t}\end{aligned}$$

Energy equations (gas and combined liquid):

$$\begin{aligned}\frac{\partial(\alpha_g\rho_g u_g)}{\partial t}+\left(\frac{1}{A}\right)\frac{\partial(A\alpha_g\rho_g u_g v_g)}{\partial x}&=-P\frac{\partial\alpha_g}{\partial t}-\left(\frac{P}{A}\right)\frac{\partial(A\alpha_g v_g)}{\partial x}\\&+Q_{wg}+Q_{ig}-Q_{gf}+\Gamma_{gl}h_g^*+\Gamma_w h_g'+DISS_g\end{aligned}$$

$$\begin{aligned}\frac{\partial\{(\alpha_l+\alpha_e)\rho_f u_f\}}{\partial t}+\left(\frac{1}{A}\right)\frac{\partial}{\partial x}\{A(\alpha_l\rho_f u_f v_l+\alpha_e\rho_f u_f v_e)\}&=-P\frac{\partial(\alpha_l+\alpha_e)}{\partial t}\\&-\left(\frac{P}{A}\right)\frac{\partial\{A(\alpha_l v_l+\alpha_e v_e)\}}{\partial x}+Q_{wf}+Q_{il\mathrm{g}}^B+Q_{il\mathrm{g}}^W+Q_{ieg}-Q_{fg}\\&-\{(\Gamma_l'')^B+\Gamma_e''\}h_f^*-(\Gamma_l'')^W h_f'+DISS_l+DISS_e\end{aligned}$$

The three-field formulations presented are similar to those for MARS 3-D module which originated from COBRA-TF, in a sense that the mass and momentum are treated separately for the entrained liquid and continuous liquid. The MARS-3D module also combines the entrained liquid and continuous liquid for the energy equation, assuming thermal equilibrium between the two. The three-field formulations for MARS-1D, therefore, are in line with the MARS-3D module, providing more consistent basis for coupling the two modules.

Numerical implementation of the aforementioned equation set followed the basic methodology MARS-1D is based on. All the non-linear terms are linearized to arrange the finite difference equation set into a linear matrix form with respect to the unknown arguments.

2.2 Assessment Results

The problems chosen for the assessment of the newly added entrained field consist of basic conceptual tests. Among the tests are gas-only test, liquid-only test, gas-only with supplied entrained liquid test, Edwards pipe problem, and GE swell problem.

The gas-only test and the liquid-only test are intended to confirm that the added field equation in the solution scheme shouldn't affect the behavior of the other remaining phases. The test results were produced with the new solver as desired, i.e. without any noticeable differences.

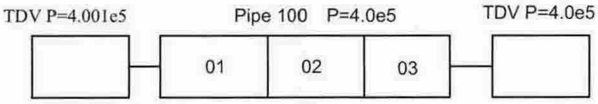
Gas-only test with supplied entrained liquid is performed to observe the behavior of the entrained liquid when gas is the only interacting substance inside the pipe (see Figure 1). Without the continuous liquid, the entrained liquid had to be added to the system via TDV. As seen from Figure 1, velocity development of the entrained liquid demonstrates the proper functioning of the interfacial friction between the gas and entrained liquid. Also, the entrained phase volume fraction (voide) profiles are seen to be consistent with the corresponding velocities to satisfy the continuity laws.

The Edwards Pipe Problem (see Figure 2) is tested to verify the sonic wave propagation along with the evaporation phenomenon accompanying the flashing event. The void fraction trend shown is seen to agree reasonably well with the dotted experimental data, even though the quantitative comparison might not be very important at this phase of the model development.

Finally, the calculation for the GE level swell test (see Figure 3) also confirms the sound integrity of the developed numerical frame. The experiment measured the water level change and void fraction distribution during depressurization from ~69.7 bar. Noting the very little discrepancy between results by the two-fluid and three-fluid solvers, it is seen that the newly developed three-fluid solver virtually doesn't display the effect of the added field where it shouldn't.

3. Conclusion

The three-field model has been implemented to the MARS-1D module, and tests have been performed to assess the integrity of the new numerical solution frame. Given the limitation of the current closure laws with respect to the added entrained field, the conceptual tests performed confirm the sound integrity of the three-field solver. Further work is planned for the implementation of more detailed and consistent models and correlations required for the whole three-fields involved.



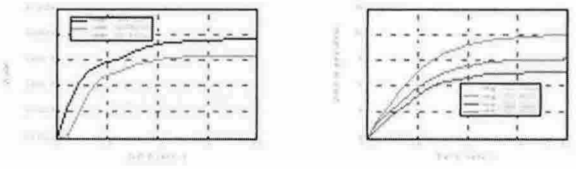


Figure 1. Gas-only test with supplied entrained liquid

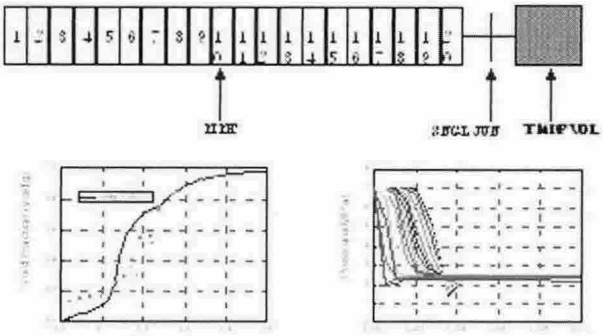


Figure 2. Edwards Pipe Problem

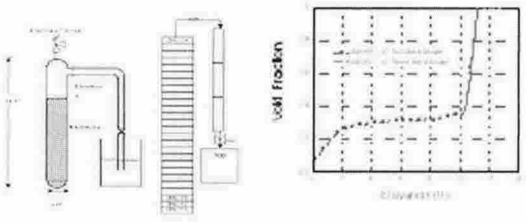


Figure 3. GE Swell Test

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