joint exercise. In his letter here, he put forth the bottom line of his results (curve 1 of his Fig. 2). Meanwhile, he documented most other aspects of this computation in a limited distribution report given as his Ref. 7. This brings us to his second point that pits these results against ours.

We address curve 1 of his Fig. 2. We disagree also with curve 2, but this two-fluid case is really more than 2-yr-old technology, and we will not waste time on it here, while curve 3 represents an arbitrary variation that does not capture the essence of the differences in the two models. These differences are indeed numerous and important, and as summarized below, they do not reflect favorably on Fletcher's modeling approach.

1. The interfacial drag was modeled by Fletcher, using an old formula by Harlow and Amsden, as follows:

$$D_{ij} = \frac{3}{4}\epsilon_i\epsilon_j\rho_i\rho_j C_{Di,j}\frac{L_iL_j}{\rho_iL_j+\rho_jL_i}\left(\frac{1}{L_i}+\frac{1}{L_j}\right)^2|V_j-V_i| \ ,$$

where

$\epsilon$ = volume fractions

$L$ = length scales

$V$ = velocities of phases $i$ and $j$.

To our knowledge, this equation has not been used since, nor has it been compared to experimental data. In our model[2] we have adopted a flow-regime-dependent formulation due to Ishii and Zuber that has been experimentally verified and is in extensive use.

2. Fletcher assumes that the steam remains in saturation and allows no condensation. We emphasize that both steam superheating and steam condensation are seen to be very important in our computations.

3. Fletcher calculates the boiling rate $\dot{m}_s$ superposing radiation and film boiling heat transfer to the liquid by

$$h_{fg}\dot{m}_s = \epsilon_w\epsilon_p\frac{6}{D_p}\left[\sigma(T_p^4-T_w^4)+h_{FB}(T_p-T_w)\right] \ ,$$

where

$\epsilon_w, \epsilon_p$ = water and melt volume fractions, respectively

$T_p, T_w$ = melt particle and water temperatures, respectively

$D_p$ = fuel particle diameter

$h_{FB}$ = Bromley film boiling heat transfer coefficient

$h_{fg}$ = steam latent heat of vaporization.

In contrast, we use a flow-regime-dependent formulation as follows.[2] For a steam void fraction ($\alpha$, based on coolant volume) of <70% we assume we are in the bubbly or churn flow with sufficient water around each melt particle to maintain coolant saturation, to absorb all radiation emitted, and to yield film boiling in the sense of the Bromley correlation. For a steam void fraction >70%, we are in the dispersed water (droplet) regime with steam being the continuous phase. Thus, heat is transferred from fuel to steam by convection and from fuel to water by radiation. Thus, the steam is allowed to superheat and heat the suspended water droplets in it, which boil at saturation.

The impact of the above differences is illustrated in Fig. 1. Note that the curve marked "mimicking Fletcher's model" explains most of the discrepancy between Fletcher's high predictions and ours, although it does not quite match Fletcher's curve 1 in the latter portion of the transient shown. We will have to wait for the full documentation of his calculations before we can account for the remaining difference.

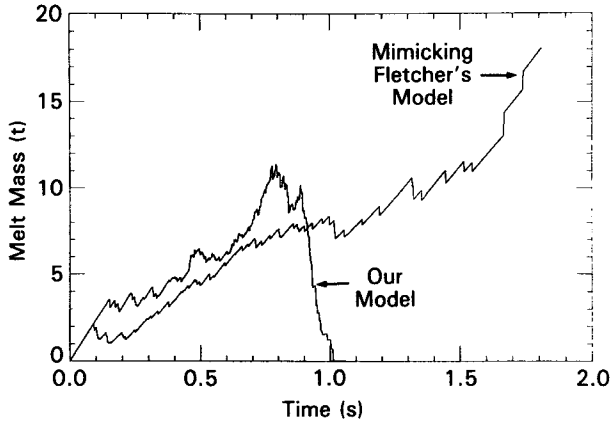


Fig. 1. The effect of constitutive law and model assumption limitations on Fletcher's predictions.

Much remains to be done, and we find it unfortunate that with such challenging tasks ahead we have to waste time in polemics.

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## Response to "Comments on Fuel-Coolant Premixing Modeling"

I want to provide some comments on the letters from Hopenfeld[1] and Fletcher and Thyagaraja[2] and relate them to the comments of Theofanous. I agree with some of the comments, but I want to focus on these comments in a particular order to emphasize how I think the fuel-coolant premixing issue can be investigated to move toward better agreement among researchers.

First, I agree with Fletcher that I should have included his model[3] in my summary Table I (see Ref. 4). If one were to do that and include the new mixing model incorporated into the IFCI code,[5] as well as the single calculation by Theofanous with his new model (ALPHA-PM, Ref. 6), then the table would look like Table I presented here.

If one reviews this table, it becomes immediately apparent

TABLE I

Advantages and Disadvantages of Current Mixing Models

| Model | Advantage | Disadvantage |
|---|---|---|
| Phoenics (Bankoff and Habib[14]) | Two-dimensional | No dynamic liquid breakup<br>Equal velocities and temperatures for coolant liquid and vapor |
| K-FIX (Theofanous) | Two-dimensional | No dynamic liquid breakup<br>Equal velocities and temperatures for coolant liquid and vapor |
| SIMMER (Bohl[15]) | Two-dimensional | No dynamic liquid breakup<br>Equal liquid velocities (fuel and coolant liquid) |
| TEXAS (Chu and Corradini[16]) | Dynamic liquid breakup<br>Three-field model with fuel Lagrangian and unequal velocities | One-dimensional |
| CHYMES | Two-dimensional<br>Dynamic liquid breakup<br>Unequal coolant liquid/vapor velocities | Equal temperatures for coolant liquid and vapor |
| IFCI | Two-dimensional<br>Dynamic liquid breakup<br>Three-field Eulerian model | Eulerian fuel field may allow numerical mixing |
| ALPHA-PM | Two-dimensional<br>Three-field Eulerian model | No dynamic liquid breakup<br>Numerical mixing by Eulerian fuel field |

that there are now a number of mechanistic computational models available to predict fuel-coolant premixing. Some progress on understanding the physics may be gained by continued theoretical comparisons. However, it is my strong opinion that simple well-planned mixing experiments are primarily needed to verify *any* of these predictions. To do this properly, instrumentation must be developed that can probe this multiphase mixture for local void fractions, liquid droplet diameters, and velocities. These requirements suggest that verification may take some time (years). Without such experiments, continued discussion of the mixing phenomenon and its details seems quite academic. In the absence of these experiments, I feel the most fruitful approach to identifying mixing limits is by looking toward overall effects that limit mixing. The best examples of this were the ideas first advanced by Fauske and Henry[7] for liquid fluidization limits and the extension work[8] I attempted.

My final comment focuses on the details of fuel-coolant mixing modeling. If I look at the details of Fletcher's results (above) and the new results of Theofanous[6] in his letter, there are large differences as well with some of the detailed predictions from the other models in Table I. Theofanous states in his response to my original letter that "Unfortunately, Corradini's discussion here is focused on models rather than on results! As noted in Part II and reiterated in our response to Berman, real progress in this area will be achieved when various results can be clearly compared and scrutinized." I do not think this statement is the proper way to view computational model comparisons in the *absence* of real data. We must not only scrutinize the *results* of calculations, but also the *models* that are used to produce these results. That is precisely why I am troubled by predictions without some concept of dynamic fuel fragmentation and multifield modeling. It is not good to only look at results because similar results without scrutinizing models may be completely fortuitous. This approach should always be taken until parametric analyses compared to real experimental data point out the importance or lack of importance of specific modeling choices.

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