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Modeling the Lost Foam Process with Defect Predictions—Progress Report: Lost-Foam Model Extensions, Wicking

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OVERVIEW

Recent experimental evidence has revealed some shortcomings in the original Lost Foam model developed within the ***FLOW-3D***® software. The particular shortcomings that appear to be significant include a gravity orientation effect and the possibility that eps residue is wicked into the foam coating. There is also evidence of faster foam degradation in regions where gas can easily reach the walls of the casting.

In this Progress Report we cover developments completed to represent the first two effects, i.e., eps wicking and gravity orientation.

WICKING

Observations indicate that eps residue does not flow along mold walls and back into the interior of a part to the extent that the original defect model predicts. Close examination of test castings indicates that there is some trapping of liquid residue by the coating placed on the foam. The trapping process appears as a wicking of the residue into the pores of the coating.

A second scalar quantity has been introduced to account for this wicking of defect material into the sand. Assignment of the wicked scalar is made by inputting *idfctw* as the index of the scalar used for this purpose. Once material is struck to the walls, it does not move with the flowing metal. This condition is satisfied by setting *isclr(idfctw)*=0, which is done automatically by the program.

The original defect model used a single scalar to accumulate defect material in proportion to the amount of foam that is degraded at each location along the metal front and then transport it with the moving metal. The new, second scalar can only gain defect material from the first scalar. In fact, it is assumed that the rate of accumulation for the second scalar in a computational cell is proportional to the product of the first scalar and the sand wall area located in that cell. The constant of proportionality is, therefore, a rate per unit time and unit wall area. This constant is a new input quantity, *dfctw*.

Walls on which defect material can be deposited must be obstacle boundaries, not mesh boundaries. If no defect material is to accumulate on a particular obstacle n, then the user must define a negative roughness for that obstacle (i.e., ROUGH(n) < 0.0).

It should be noted that scalars representing defect material are defined as microscopic densities. Thus, the amount of moving defect material in a cell having volume C_{vol}, open volume fraction V_f, and fluid fraction F is defined by the product,

$$SCLR(1)*F*V_f*C_{vol}.$$

The corresponding amount of defect material struck to a wall and in a cell having volume C_{vol} is

$$SCLR(2)*C_{vol}.$$

In this case there is no dependence on the fluid or obstacle volume fractions because this quantity is not carried with the liquid metal. (We have used scalar indices of 1 and 2 here, but these could be any indices the user selects.)

The exchange of defect material from the moving scalar to the stationary one is conservative of defect material (as defined by the above definitions).

This program addition has been inserted at the end of the Lost Foam routine **FOBHT**. It appears as a separate Do Loop over mold wall surface elements.

Illustrative Test Case

A simple test of this addition is offered by the Yao & Shivkumar plate test casting. To make the problem a little more interesting, we have placed a rectangular obstacle in the cavity opposite the in gate. Figure 1 shows the computed velocity field at t=2 s, just before complete filling, and at t=2.5s. The computed scalar defect material is also shown at the corresponding times, in which no wicking was allowed. For this case the defect source coefficient was taken to be 100.

A repeat of this test was made with the wicking turned on and with the exchange coefficient *dfctw*=100. Results are displayed in Fig.2, which shows contours of the moving scalar defect material at times 2.0s and 2.5s (top row). Corresponding contours for wicked scalar are in the bottom row of Fig. 2.

Comparison of the top row figures with those in Fig.1 shows that the amplitude of the defect material has been considerably reduced by losses to wicking. For instance, at t=2s almost half of the defect material has been lost, and at t=2.5s almost 75% has been wicked away.

It will also be noted that the maximum defect was previously located in the upstream corners of the cavity (i.e., left hand top and bottom corners), while in the case with wicking the maximum resides at the moving metal front.

At the end of the simulation wicked material is seen to exist at all portions of the boundary with the highest concentration at the upstream corners. Wicking has not prevented defect material from entering the interior of the casting, but it has greatly reduced the amount. Of course, this amount of reduction is closely tied to the input coefficient *dfctw*, which must be determined from experiments.

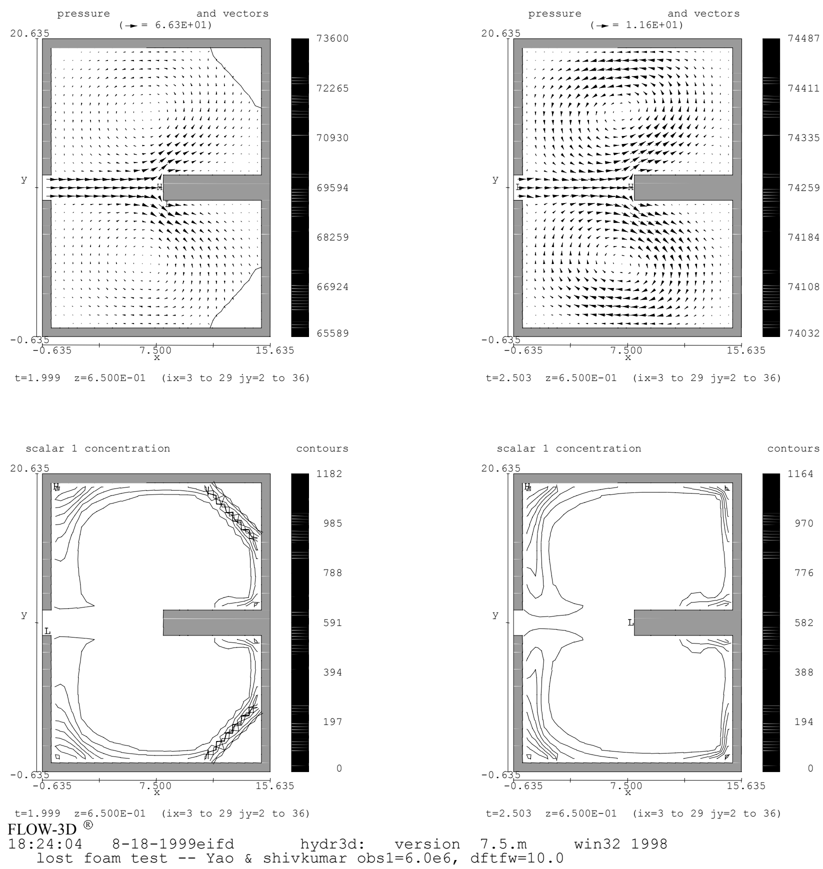


Figure 1. Original defect model results for a simple plate casting test. Velocities are shown at t=2s (top left) and t=2.5s (top right). Defect contours at the corresponding times are shown below.

GRAVITY ORIENTATION

A second observation made through X-Ray videos of test casts is that there appears to be an influence of gravity on the motion of the metal front. In particular, an upward moving front progresses more slowly than a downward moving front.

Previous tests for the influence of pressure on the motion of a metal interface indicated that the absolute pressure makes little difference (at least within the pressure range used in the tests). If this is true, then it is not the hydrostatic pressure associated with gravity that is causing the observed asymmetry in the front velocity.

What seems more likely is that the interface is subject to a Rayleigh-Taylor instability when heavy liquid metal lies above, in the sense of gravity, the gas-foam region at a front. Conversely, if the metal lies below the gas-foam region, then gravitational effects should smooth the metal interface.

To include this effect in the basic Lost Foam model, we have chosen to think of it as a kind of surface roughness that modifies the metal-to-foam heat transfer rate. When the metal-foam interface is in a stable configuration, the metal surface roughness is smaller than it would be without a gravity effect. The smoothing (stabilizing) tendency of gravity resists the formation of corrugations on the metal surface.

When the metal-foam interface is in an unstable configuration, surface disturbances grow and increase the effective area of the surface. Growth is limited because the overall pressure is usually large and constantly pushes the metal into the foam.

In neutral gravitational situations, the metal surface has some roughness because of the local turbulence generated by melting and vaporizing foam. It is this situation that we assume corresponds to the heat transfer rate that users must specify as the input *HOBS1*.

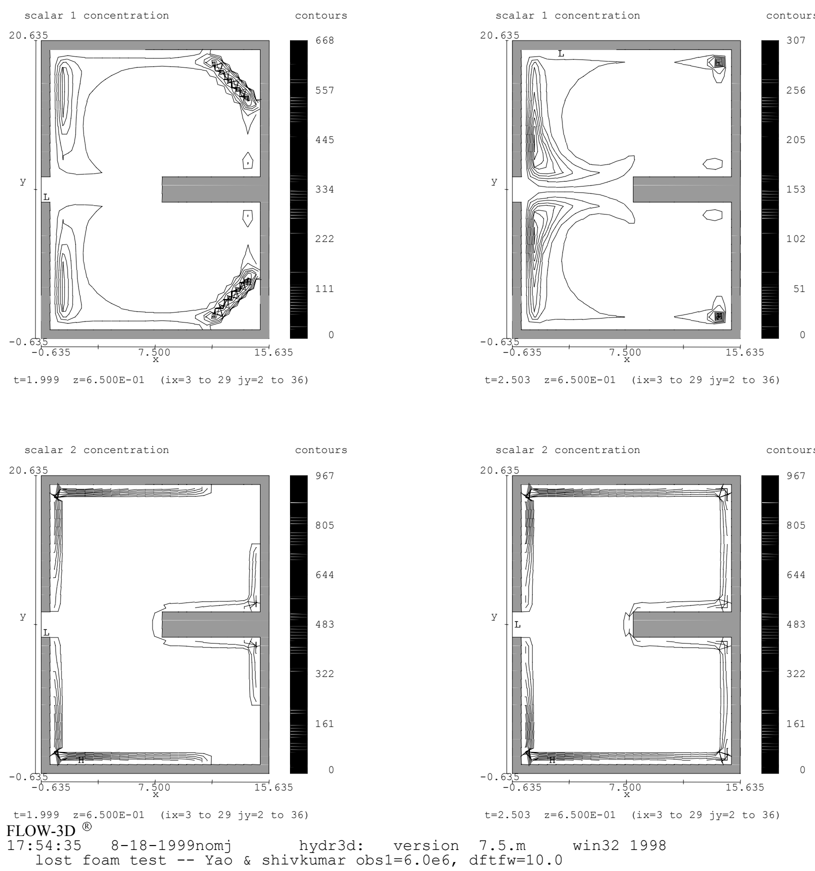
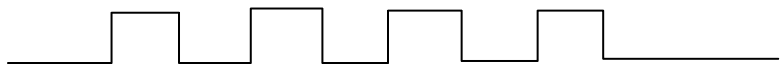


Figure 2. Defect concentrations for simple plate test at t=2s (top left) and t=2.5s (top right). Concentrations of wicked defect material are shown at the corresponding times in the bottom row.

Some idea of the expected magnitude of roughness variation that could result from surface corrugations can be estimated by thinking of the surface as a series of steps:



The horizontal segments always add up to the same horizontal width. The vertical segments account for an increase in surface area. However, this increase in area is only effective as long as the amplitude of the perturbations is not too large. At large amplitudes the heated gas can't easily flow to the foam, and the area for radiative heat transfer is proportional to the opening of the steps and not to their depth. The limiting ratio of height to width for the depressions to increase heat transfer is probably no more than about a factor of two.

Square perturbations would increase the surface area by a factor of two over that of a flat, horizontal surface. So this provides a rough estimate of the order of magnitude to expect from the "roughness" concept.

We postulate a simple algebraic factor that multiplies the user specified heat transfer coefficient, call it H_0. The multiplier must account for both stable smoothing of the surface as well as unstable roughening. The maximum influence of the factor on the heat transfer rate should not be more than about a factor of 2 between the minimum and maximum roughness values. A formulation for the net heat transfer coefficient having these characteristics is,

$$H = H_0\left(1 + \frac{(cgfob)V_g\,\mathrm{sgn}(g)}{V_g + V_{ht}}\right)$$

The function sgn(g) means the sign of g such that it is positive when unstable interface conditions exist. The factor *cgfob* has a suggested value of 0.5 but could be changed if necessary to get agreement with data. A positive value of *cgfob*, which is a new user input quantity, is used to activate the gravity-orientation effect on heat transfer.

The V_g and V_{ht} quantities are characteristic speeds. V_{ht} is the nominal speed, at which the metal front should move into foam,

$$V_{ht} = hobs1(nob)/rcobs(nob).$$

Where *nob* is the foam obstacle number, *hobs1* is its heat transfer coefficient, and *rcobs* is the product of the foam's density and specific heat.

The velocity V_g is a characteristic speed of gravity waves,

$$V_g = \sqrt{gl},$$

where g is the component of gravity most normal to the interface and l is a user specified length. Since l is associated with the foam, we use the foam obstacle roughness parameter, *rough(nob)* for this input length (the parameter *rough(nob)* is not otherwise used).

Having the heat transfer roughness proportional to the factor $V_g/(V_g+V_{ht})$, which varies between zero and one, is one way to account for the fact that if V_{ht} is very fast, then gravitational effects are less likely to be important. Of course, what's considered important depends on the length scale l appearing in V_g. If one uses a value of 0.1 cm, which seems reasonable for a surface corrugation, then the V_g is on the order of 10cm/s. This is consistent with typical metal front speeds of about 10 cm/s.

As formulated, the roughness incorporated into the heat transfer coefficient H can only vary the input value H_0 by a factor that varies between (1-A) and (1+A), where A varies between 0.0 and *cgfob*. In other words, when *cgfob*=0.5 this model puts the maximum range for H between $0.5H_0$ and $1.5H_0$.

Illustrative Test Case

A vertical plate geometry was set having 10 cm. square sides and a thickness of 0.5cm. The plate region was filled with foam, and an inlet was placed at the back center of the plate. A circular inlet was used with diameter 2.0 cm and inlet pressure of 50,000 dynes/cm^2.

To have a control test, we first set gravity to zero so that the plate should fill in a circularly symmetric way. This is the case as can be seen in the first (left) plot of Fig.3. With gravity on, but no roughness effect included in the heat transfer rate, the filling is nearly identical to the no gravity case.

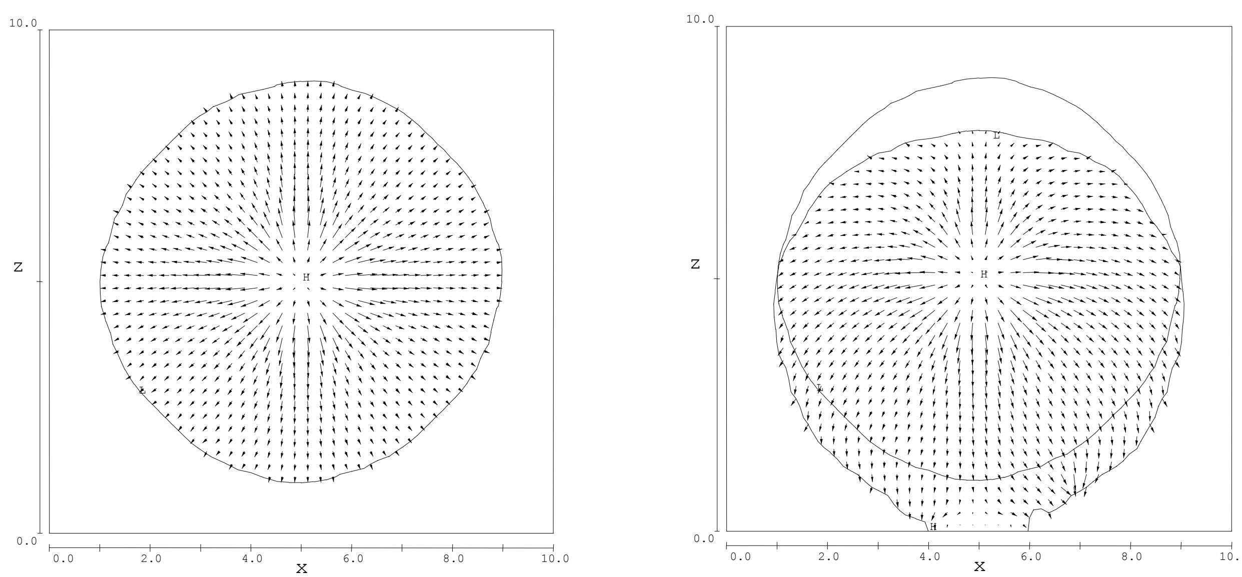


Figure 3. Filling of foam cavity at t=3s without gravity (left) compared with a case in which gravity is vertical (right). The asymmetry is caused by the new "gravity-orientation" addition to the heat transfer coefficient.

Finally, activating the roughness model with the 0.5 coefficient and a characteristic length of 0.1 cm, the results shown in the second (right) plot of Fig.3 were produced. We have overlaid the no-gravity result at the same time for comparison. As hoped, the bottom (unstable) portion of the metal front moves faster and the top (stable) portion moves slower. The sides continue to move at the same speed as in the no gravity case.

A somewhat more dramatic asymmetric effect can be achieved by replacing the *cgfob*=0.5 coefficient with a larger number. For example, a value of *cgfob*=2/3 gives the results shown in Fig.4.

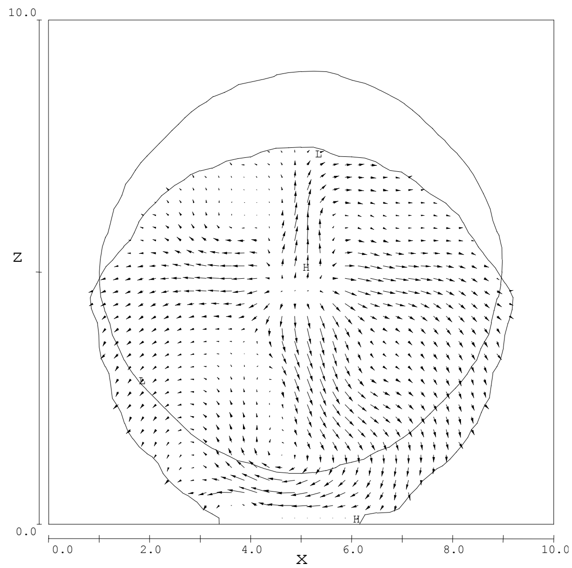


Figure 4. Filling of foam cavity at t=3s with enhanced gravity-orientation effect, cgfob=0.667. Compare with right plot in Fig.3.

The gravity-orientation effect is primarily an addition to the heat transfer coefficient subroutine **HFOBCL**. However, to make this work it is necessary to know the general direction of the normal to the metal-foam interface. We do this by finding the neighboring grid cell containing the largest amount of metal. This is done in routine **FOBHT** and the information is passed as another parameter to **HFOBCL**. The neighbor determination was already in **FOBHT** for another purpose, so it only required a little rewriting to accommodate the present extension.

SUMMARY

Two new features have been added to the Lost-Foam casting model. Both features were suggested by experimental evidence, and their addition should make predictions of the model more accurate. This interplay between modeling and experimentation is extremely desirable and is the most likely path to a successful program for understanding and controlling the Lost Foam process.