FIRST PRINCIPLES CALCULATIONS OF THE INTERACTION OF BLAST WAVES WITH AQUEOUS FOAMS

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Abstract. A series of two-dimensional hydrodynamic calculations using the two-dimensional Second-order Hydrodynamic Automated Mesh Refinement Code (SHAMRC) developed by Applied Research Associates, Inc. (ARA), was made with the objective of understanding the behavior of aqueous foams in the presence of a C4-generated blast wave. A full three-phase water equation-of-state was incorporated in the first calculation. Comparison of the results of the first calculation with experimental data collected by Sandia National Laboratories (SNL) indicated that the interaction was much more complicated than could be represented by a mixture of detonation products, air, and water in local temperature and pressure equilibrium.

Other models were incorporated in the code to examine the effects of thermal non-equilibrium between water and the gases and allowed for two-phase flow. The water droplets were allowed to slip relative to the gas velocity, providing non-equilibrium for the velocity distribution. These models permitted heated liquid droplets to be accelerated at high pressures and transported through and ahead of the decaying shock front. The droplets then exchanged momentum and energy with the foam ahead of the shock and preconditioned the medium through which the shock was propagating. This process had the effect of diffusing the shock front and its associated energy.

These relatively high resolution calculations develop numerical representations of the Rayleigh-Taylor instabilities at the detonation products/foam interface. This unstable interface plays in important role in understanding the behavior of the interaction of the detonation products with the foam. Figure 4 clearly shows the developing instabilities at the interface and an inward facing shock at a radius of 25 cm. The results of the calculations using the various models can be edited to provide the total energy exchanged between materials, the fraction of water vaporized, and the extent of detonation products as a function of time.

BACKGROUND

ARA SHAMRC has been used for predictions in a large variety of high explosive experiments. The "simple" free air detonation of a spherical TNT charge presents some challenging problems for a multi-dimensional computer code. Figure 1 shows a compendium of data from a variety of sources for the dimensions of several observed phenomena resulting from the detonation of a free air sphere of TNT. Results are scaled to 1 lb for convenience. The plot shows the radius of the primary shock, the position of the secondary shock and the fireball radius as a function of time. The data come from the sources cited. The CTH data are from an SNL calculation of a 1-lb sphere of TNT. The curves labeled SHAMRC are results from a recent ARA SHAMRC calculation of the same sphere.

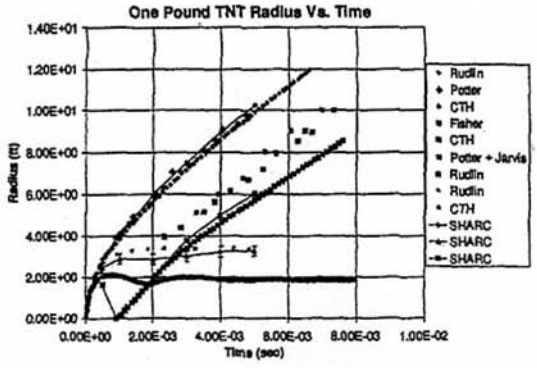

FIGURE 1. Comparisons of the radii of the primary shock, the secondary shock and fireball.

The largest discrepancy is between the fireball radius data and the CTH calculation. The light diamonds represent the observed edge of the detonation products from photographic coverage. The heavy line is composed of diamonds and represents the CTH results for the detonation products interface. For times greater than about 2 ms the CTH calculation is nearly a factor of two smaller than the observed data. The black line joining the black triangles shows the ARA SHAMRC fireball radius results. The SHAMRC calculation allows a numerical representation of Raleigh-Taylor instabilities at the TNT-air interface. The points plotted for the fireball radii are the averaged radii measured at several angles through the charge center. The error bars show approximately the extent of the mixing zone between air and C4 detonation products.

It is the much better definition of the fireball radius and the representation of the instabilities at the detonation products-air interface, which lead us to believe that SHAMRC is the superior tool for applications where the detailed flow field in the vicinity of high explosives is important.

EXPERIMENT AND FOAM EOS

The experiments consisted of a 1-lb or a 50-lb C4 hemisphere on the ground, covered by aqueous foam. The foams varied in nominal expansion ratio (ER) from 60 to 130. Instrumentation included

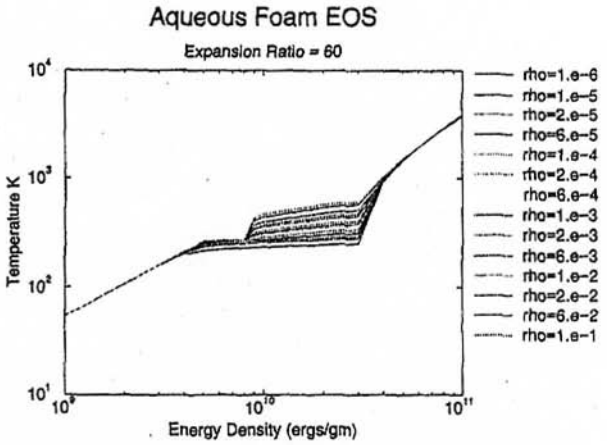

FIGURE 2. Temperature behavior for aqueous foam EOS.

overpressure and stagnation pressure gages placed from 18 inches to 10 ft in radius from the charge at intervals of 6 inches. All measurements used in this report were positioned within the foam.

Before proceeding with the hydrodynamic calculations, a set of calculations was carried out to exercise the EOS for aqueous foams. This EOS is a part of the SHAMRC library. The input parameters are the total density of a zone, the internal energy of the zone and the mass fraction of the zone that is water. The EOS then returns the pressure and temperature of the air-water mixture under the assumption that the materials are in temperature and pressure equilibrium. Figure 2 shows the temperature as a function of internal energy density for several densities. The relatively flat regions near 373 K is caused by the heat of vaporization of the water. The temperature is not constant because the pressure increases slightly during the heating process.

CALCULATION INITIAL CONDITIONS

Each calculation placed a 1- or 50-lb hemisphere of C4 on the axis of symmetry on a perfectly reflecting bottom plane. The charge was detonated at the bottom on the charge axis. Foam material with an expansion ratio of either 60 or 100 filled the remainder of the grid. One of four foam models was used for the foam material. The foam was initialized at a pressure of 12.2 psi, which corresponds to ambient atmospheric

pressure at an altitude of 5000 ft (Albuquerque's altitude).

The calculational grid contained 160,000 zones (400 in each direction). Initially, the zones were 0.02 cm for the 1-lb charge. Stations that recorded parameter versus time data were placed in the calculation along radials at angles of 0, 30, 45, 60 and 90 degrees and at 6-inch intervals, starting at 6 inches, to a distance of 10 ft. Two types of stations were used: Eulerian (fixed points in space) and Lagrangian (move with, but do not interact with the flow). Six calculations were run for a charge weight of 1 lb with variations in other parameters such as foam expansion ratio and foam model.

CALCULATIONAL RESULTS

The first calculation was for the case of a 1-lb TNT charge in an ER-60 foam. We naively thought that the problem was primarily one of getting the equation of state for foam correctly formulated, and doing the fully coupled hydrodynamic calculations with HE burn and air. Figure 3 shows the temperature distribution from this calculation at a time of 100 ms. The shock is moving through the foam at a radius of 27 cm. Immediately behind the shock is the unstable detonation products interface. The two-dimensional approximation to the Rayleigh-Taylor instabilities is clearly shown. An inward moving shock is forming on the interior of the detonation products and is currently at a radius of 23 cm. Figure 4 shows the temperature distribution at a time of 1 ms. The shock has progressed to a distance of just over 72 cm. The instabilities at the detonation products interface have grown significantly and indicate a mixing zone about 15 cm thick. The shock is well separated from the interface and propagating through the foam.

After the SHAMRC calculation was complete, we compared the results with the experimental data and found that the calculated arrival times were too early close in and as much as a factor of two too late at larger distances. The calculated pressures were an order of magnitude too high at all ranges. Clearly there was a lot more going on in the interaction of the foam with the blast wave

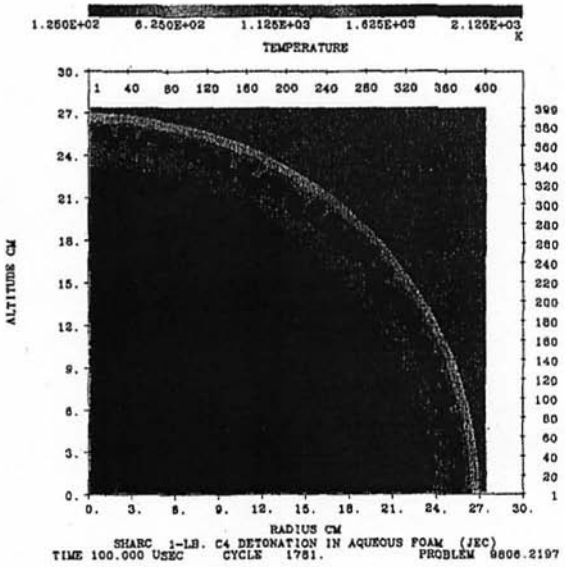

FIGURE 3. Temperature conditions at 100 μs from ER-60, EOS foam model.

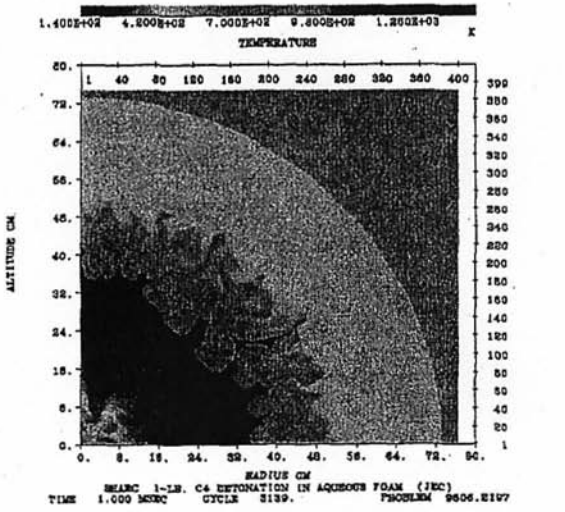

FIGURE 4. **Temperature conditions at 1 ms from ER-60, EOS foam model.**

than changes of phase, acceleration and heating of water. We had to answer the question, "what physical or chemical phenomena are we not modeling?" We then asked the question, "what happens if the water does not heat at all but is accelerated by the flow?" A model for the water was included which treated the mass and momentum of the water but did not allow it to heat during this process. The resultant arrival

times were too early at distances less than 4 ft, agreed well to a distance of 7 ft, and then were too late beyond 7 ft. Because this model removes less energy from the air, the pressures were increased about a factor of three and were further from the data rather than closer. Figure 5 is a plot at 1 ms from this calculation.

We developed a hypothesis that the water is formed into small droplets during shock passage and that the droplets are not in velocity equilibrium with the gases. We chose to model the water as 20% equilibrium water and 80% particulate or droplets, not in velocity equilibrium. We chose a single droplet size of 200 microns for the first such calculation.

The calculation was repeated with the particle size increased to 500 microns. We anticipated that the increased size of the water droplets would push them further ahead of the shock front, thus helping to explain the slow rise observed in the experimental pressure waveforms.

The size of the particle is also reduced by the shear forces associated with the blast wave. The model used to simulate breaking up the particles is the Wolfe and Anderson model (Ref. 1):

$$md = C\left[(\mu s^{1.5} D^{0.5})/(g^2 \rho^{0.5} U^4)\right]^{/3} \qquad (1)$$

where md is the mean particle diameter. As the effect of the Wolfe Anderson model on water droplets was not completely known, the minimum size for the particles was limited to 75 microns to avoid possibly vaporizing the particles too quickly. The shear effect was started at a difference in velocity of both 100 m/s and 10 m/s.

CONCLUSIONS

We have clearly demonstrated that inclusion of a full three-phase equation-of-state in the equilibrium approximation is a poor model for aqueous foam subjected to blast. We have demonstrated that droplets, which are allowed to slip relative to the gas flow, give a better approximation than the non-slip model. Further, we have shown that temperature non-equilibrium gives better results than the full equilibrium assumption. The change of phase energy is important at distances of a few charge radii but overestimates the energy absorption at larger distances.

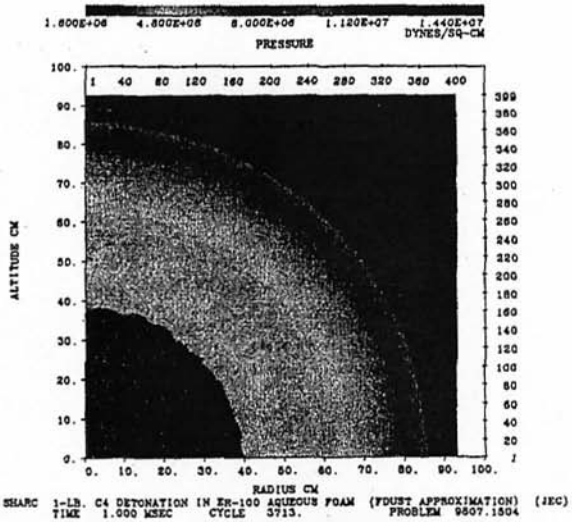

FIGURE 5. Pressure conditions at 1 ms from ER-100, non-equilibrium foam model.

The better agreement between calculation and experiment at the 50-lb level than at 1 lb is a mild indication that some non-equilibrium phenomena are present. At the larger scale, the non-equilibrium effects have more time to approach equilibrium and therefore give better agreement with the equilibrium model. This is true for both velocity and temperature equilibrium cases.

REFERENCES

1. Wolfe and Anderson, Proceedings, 5th International Shock Tube Symposium, April 1965, pp. 1145-1169.

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