SESSION II

MASS FIRE AND RELATED TOPICS

SOME OBSERVATIONS ON THE EFFECT OF TURBULENCE MODELING IN NUMERICAL SIMULATIONS OF MULTIPLE-BURST FLOW FIELDS

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ABSTRACT

We describe some preliminary attempts to calculate the development of a simple class of axisymmetric multiple-burst environments. Our primary interest is in the intermediate time regime, during which the characteristic plume structures stabilize and begin to spread horizontally. Employing a standard two-equation description of turbulent entrainment, we find that the maximum extent of plume penetration into the atmosphere is sensitive to details of the turbulence modeling. Some interesting dynamic features of the plume stabilization process are also observed. These results are discussed together with supporting analysis and used to identify generic differences between single-and multiple-burst environments.

INTRODUCTION

Continuing developments in strategic-warfare technology toward more compact and accurate delivery systems have emphasized the importance of multiple burst scenarios to both military and civil defense planners. A prime example of this trend is the recent attention given the survivability of the proposed closely-spaced basing mode for the MX missile system. Clearly, any survivability assessment for this system must involve detailed examinations of a wide spectrum of threat scenarios that involve detonations spaced closely in both space and time.

One of the most important considerations for the viability of closely-spaced basing is the concept of fratricide, whereby a portion of the MX system survives because late-arriving reentry vehicles are incapacitated by weapon effects generated by earlier-arriving ones. Before an evaluation of fratricide can be attempted, the evolution and spatial characteristics of dust clouds and related aspects of multiple-burst flowfields must be known to some degree of accuracy. Thus, the purpose of this study was to see if realistic, but inexpensive, calculations of relatively late-time (tens-of-minutes) multiburst environments could be made with existing capabilities. Although a definitive answer to this problem was not obtained during the short period allotted for the study, we nevertheless have identified some interesting differences between single-burst and multiple-burst environments and the requisite modeling required for their realistic prediction.

PROBLEM DESCRIPTION

The intent of the work presented here is to make a preliminary analysis of the simplest multiple-burst problem — a sequence of near-surface bursts detonated at the same position, but delayed in time by a constant interval. In particular, we consider the successive near-surface detonations of one-MT weapons at an interval of twenty seconds.

The initial atmosphere for these calculations was taken to be isothermal, with both pressure and density falling off exponentially with height. The numerical grid was 26 km high by 14 km in radius. A total of 864 variable-sized zones were employed with the smallest zone size set at 0.25 km. Boundary conditions at the top of the atmosphere included a constant pressure condition, with unimpeded flow permitted across the boundary.* Radial boundary conditions were those of unimpeded flow. No attempt was made to describe the effect of water vapor, dust entrainment or radiation transport.

The code used in these calculations is the SIMMER-II code (1), developed at Los Alamos for nuclear reactor safety analysis. It is a derivative of the KACHINA code (2), and uses a form of the Implicit-Compressible-Eulerian (ICE) numerical solution technique. SIMMER has also been generalized for turbulent, reactive-flow applications. The version of the code used here contains the $k-\varepsilon$, two-equation description of turbulent mixing, unmodified for buoyancy effects. This simplification appears to be reasonable for the types of flow structures described here.

SOURCE CHARACTERIZATION

Because the time scale of interest for these problems is long compared with the time between bursts, our description of the individual detonations is necessarily limited to an approximate description of fireball development, rise, and interaction with the next burst. We found that an energy deposition rate of 2×10^6 J/kg-s over a cylinder 0.75 km high and 0.75 km in radius (about one-tenth the volume of the fireball's maximum size) existing for a total of two seconds produced a good approximation to a single, near-surface, one-MT fireball (see below). Whether this deposition produces an adequate description of fireball development in a perturbed atmosphere (i.e., after many bursts have occurred) is an unresolved issue.

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*All variables, except for pressure, are reflected across the top boundary. This is somewhat unrealistic for atmospheric problems where significant density gradients exist, and can give rise to unphysical effects near the boundary. Likewise, the constant pressure condition can also generate such disturbances. Our belief is that these perturbations do not significantly affect the primary flows generated by fireball buoyancy.

Figure 1 shows a comparison between a one-MT, surface-burst fireball density profile taken from Brode (3) at 2.6 s after detonation with a surface fireball density profile from the present study at 4.0 s after detonation. Recalling that, whereas the energy deposition in a real fireball is practically instantaneous, the deposition in this study occurs over a two-second period, we find the agreement remarkably good. Clearly, if the Brode calculation were extended to 4.0 s, even better agreement would be observed. This comparison could probably be improved by depositing the same total energy in a smaller time window; however, as the energy spike is sharpened, a much more dynamic expansion takes place, causing the calculation to take longer to run. We feel that the current formulation is a good compromise between accuracy and efficiency.

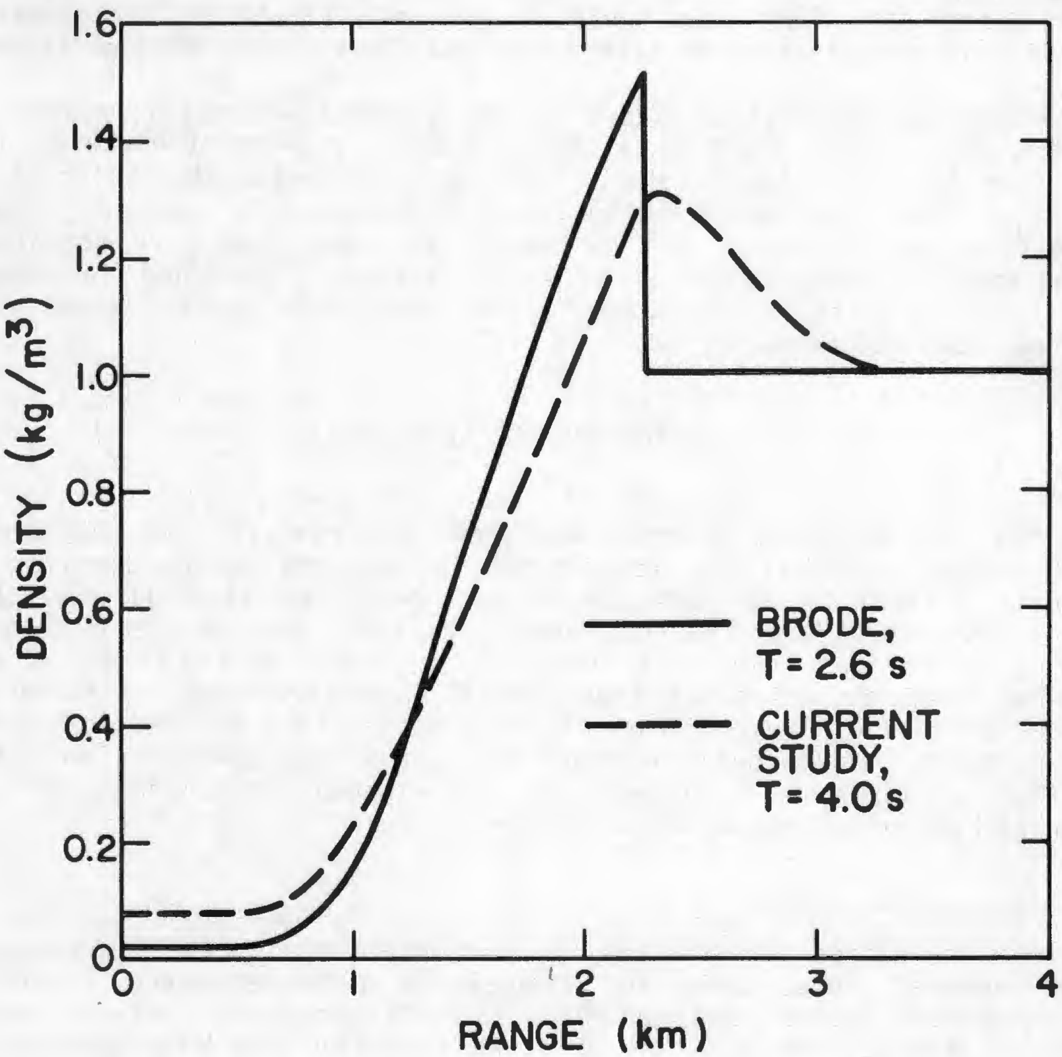

Fig. 1. Comparison of Fireball Density Profiles

PRELIMINARY STUDY

Before proceeding with the multiburst calculations, we wanted to test both the source characterization model and the general numerical formulation with a single-burst simulation. The early-time results from this calculation were discussed in the previous section. As the fireball forms and begins to rise, a classical vortex structure develops. Eventually the fireball reminant overshoots its equilibrium altitude, the vortex reverses, and a downward motion is initiated. In short, these reslts suggest a typical single fireball evolutionary sequence. No noticeable adverse effects attributable to boundary conditions were observed. Unfortunately, space limitiations prevent us from including graphical displays that form the basis of our comments and conclusions.

The next step was to proceed with the multiburst simulation. Naturally, during early times, these results were not dramatically different from the single-burst results. However, as soon as several detonations occurred significant differences were apparent. In fact, we observed the rapid development of a narrow plume structure that quickly penetrated the top of the calculational mesh. Further, high velocities generated in the plume were characteristic of very low entrainment rates.

PLUME STUDIES

The observation of a low-entrainment-rate plume in the multiburst calculation motivated us to investigate in more systematic detail the role of turbulence modeling in the development of such structures. To accomplish this economically, we lowered the energy release rate from 3 MT/min to 3 KT/min, and allowed the release to be continuous in time. Also, to improve resolution in the radial direction we reduced the radial extend of the problem from 14 km to 7 km. With these modifications, we hoped to keep all flow disturbances well within the calculational boundaries.

For reference, we first performed an effectively inviscid calculation of the 3 KT/min steady-release-rate case, starting from quiescent conditions. The quasi-steady-state result was a highly penetrating plume that extended to approximately 18 km in height with intense fallback occurring immediately outside the narrow upward moving core. The height at which horizontal spreading took place appeared to be in the range of 6-7 km.

This can be contrasted to the behavior of a high-turbulence-level case, where the initial turbulent dynamic viscosity was taken to be 0.01 kg/m-s and turbulent kinetic energy was set at $10^{-6} m^2/s^2$. As suggested in the next section, these initial conditions promote rapid generation of turbulence from the mean motion of the plume, and by inference significant entrainment. The result was a plume that penetrated to only about 11 km, with horizontal spreading occurring at about 6 km.

We subsequently investigated an intermediate case, where the initial turbulent dynamic viscosity was set at 0.001 kg/m-s. Here, the plume initially penetrated to heights close to those observed in the inviscid case, but then collapsed back down to about 14 km. The ultimate horizontal spreading height was again about 6 km. A detailed examination of the evolution of turbulent kinetic energy in the two turbulent calculations showed that the high-initial-turbulence-level case generated entrainment quickly, while the lower-initial-turbulence-level case did not generate significant entrainment for some time. Once it did, however, the turbulence levels were actually higher than in the former case.

AN EXPLANATION

The standard k-ε transport equations of Launder and Spalding (4) are

$$\frac{\partial \rho k}{\partial t} + \nabla.(\rho k v) = \nabla\left(\frac{\mu}{a}\,\nabla k\right) + 2\mu e^{ij}e^{ij} - 2/3\,\rho k \nabla.v - \rho\varepsilon \qquad (1)$$

$$\frac{\partial \rho\varepsilon}{\partial t} + \nabla.(\rho\varepsilon v) = \nabla\left(\frac{\mu}{b}\,\nabla\varepsilon\right) + \frac{c\varepsilon}{k} + 2\mu e^{ij}e^{ij} - 1/3\rho\varepsilon\nabla\cdot v - d\rho\varepsilon^2/k. \qquad (2)$$

The constants a, b, c, and d are of order unity. An important quantity in the above quations is the so-called eddy viscosity defined by the Kolmogonov relation, $\mu = c_\mu \rho k^2/\varepsilon$. The variable μ is generally orders of magnitude larger than the molecular viscous coefficient. The strain rate deviator tensor e^{ij} is defined by

$$e^{ij} = 1/2\,\left(\frac{\partial v^i}{\partial x_j} + \frac{\partial v^j}{\partial x_i}\right) - 1/3\,\nabla.v\,\delta^{ij}. \qquad (3)$$

A qualitative appreciation for these equations can be obtained by neglecting all spatial derivatives, letting c = d = 1, and taking ρ as a constant. We then have two ordinary differential equations:

$$\frac{dk}{dt} = c_\mu\,\frac{k^2 s(t)}{\varepsilon} - \varepsilon \qquad (4)$$

and

$$\frac{d\varepsilon}{dt} = c_\mu k\,s(t) - \frac{\varepsilon^2}{k}\,, \qquad (5)$$

where $s(t) = 2\,e^{ij}e^{ij}$. The solution to these equations is

$$T = T_i\,\exp\left[\,\int_0^t (\nu_i s(\tau) - \varepsilon_i)d\tau/k_i\right]\,, \qquad (6)$$

where T is any of k, ε, or μ, $\nu = \mu/\rho$, and the subscript denotes initial values.

Equation 6 suggests an explanation for the plume results described above. The growth rate of say μ, for a given mean shear s(t), is sensitive to the initial parameters ν_i and k_i. A large ν_i and small k_i will ensure that turbulence is generated very quickly. The calculations comprising the preliminary study were set up with low ν_i and relatively large k_i, so that turbulence never had a chance to develop, and essentially laminar, low-entrainment, behavior was observed. Exacerbating the problem was an effective numerical upper limit on the shear that could be developed due to the relatively large zone sizes employed.

We do not, incidently, claim that such behavior is necessarily physical. Certainly, problems exist in matching an inherently turbulent description in one region of the flow to a non-turbulent description in an adjacent region. Other entrainment models and/or much finer zoning, may prove to be more appropriate for the types of problems considered here.

CONCLUSIONS

These observations point to an interesting contrast between single- and multiple-burst simulations. Calculations of single-fireball dynamics do not appear to require entrainment modeling to achieve a reasonable degree of accuracy, probably because numerical diffusion is inherently present. On the other hand, it appears that multiple-fireball calculations, particularly of the type that give rise to narrow, plume-like structures, are much more sensitive to details in the turbulence modeling. This contrast is perhaps not so mysterious if we recall that most of the entrainment in plumes and jets occurs across their radial boundaries. At those boundaries very little radial motion is occurring, so that numerical diffusion is relatively ineffective in creating entrainment (5). Thus, some type of entrainment model is required to provide an adequate account of mixing in the plume-like structures so common to multiple-burst scenarios.

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