23RD INTERNATIONAL SYMPOSIUM ON BALLISTICS
TARRAGONA, SPAIN 16-20 APRIL 2007

BLAST STRUCTURE INTERACTION AND THE ROLE OF SECONDARY COMBUSTION.

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The effects of explosive blast on structures are of increasing interest to the weapon designer and the military end-user. For both the weapon designer and the military end-user the challenge is to maximise weapon effectiveness against a range of targets and minimise collateral damage. To meet these conflicting requirements it is therefore important to understand the physics and chemistry of the explosion process, in particular secondary combustion post detonation, which can significantly enhance the impulse on surrounding structures within the blast field.

The paper describes research by the weapons design team at QinetiQ to develop a number of numerical methods in the Eulerian hydrocode GRIM, to represent the combustion of the detonation products of explosives with the oxygen in the air. This release of energy can be significant and exceed the detonation energy. A number of simple scenarios are used to illustrate the importance of including this additional explosion energy source.

INTRODUCTION

The effects of explosive blast on structures are of increasing interest to the weapon designer and the military end-user. For both the weapon designer and the military end-user the challenge is to maximise weapon effectiveness against a range of targets and minimise collateral damage. To meet these conflicting requirements it is therefore important to understand the physics and chemistry of the explosion process, in particular secondary combustion post detonation, which can significantly enhance the impulse on surrounding structures within the blast field.

It is well known that for most explosives the energy released by the detonation process is less than the heat of reaction. It arises because the products generated by the explosion continue to react as they expand and cool, releasing or absorbing additional energy. TNT for example is 74% oxygen deficient, which implies that considerable additional energy is potentially available if there is sufficient air for the products to mix and react with.

The actual importance of this effect was recognised by the weapons design team at QinetiQ over 10 years ago, which showed that although this ‘after-burn’ energy does not contribute to the initial air shock, it does affect the blast wave impulse/pressure in the mid-distance range from the charge, which in turn affects the TNT equivalence [1]. Nash et. al. went on to demonstrate the importance of after burning in being able to accurately reproduce the experimental impulse measurements and the subsequent structural response of a building to an internal explosion [2, 3]. Since then an improved method to describe secondary combustion has been developed and the paper describes this model and illustrates its application in free field and internal explosions in building scenarios.

COMBUSTION MODELS

Simple Combustion Model

The initial combustion model was based upon free field explosion experiments and the observation that the fireball persisted for much longer times compared to that predicted by the QinetiQ Eulerian hydrocode GRIM. Numerical simulations of the blast field produced by cylindrical charges, whilst able to predict the initial peak pressure accurately, were unable to predict the arrival time of the reflected ground shock and its magnitude to the same degree of accuracy. This suggested that the velocity of sound in the products was too low, consistent with the persistence of the fireball in the experiment.

The secondary combustion energy was introduced into the GRIM simulation by adding additional energy into the products over a period of time, specified by the user. In the case of the explosive DEMEX [1], the secondary combustion energy was estimated as 8.7MJ.kg^{-1}, compared to a detonation energy release of 5.1MJ.kg^{-1}. Experimental data, for a 2.2kg spherical charge, showed the fireball to undergo a rapid expansion between 100μs and 1ms after detonation, suggesting this was the time over which after-burning occurred. Using a linear time dependent energy release Nash was able to accurately reproduce the reflected shock conditions. In the case of a 23.7kg charge adding the secondary combustion energy between 100μs and 30ms, based on the cube root scaling law, we were also able to bracket the experimentally measured impulse-distance behaviour [1]. Thus provided one has access to experimental fireball behaviour data the algorithm is surprisingly effective.

Whilst the simple algorithm is remarkably successful it does not capture the physics and chemistry of the combustion process and, being based upon free-field experiments cannot account for scenarios where the oxygen available for combustion is limited, e.g. a confined space. An advanced algorithm was therefore developed to reproduce these more complex blast scenarios.

Advanced Combustion Model

There are a number of competing physical processes that can be relevant to the combustion of detonation products expanding in air. Recently Muzychuk et al [4] proposed a model based on gaseous diffusion. Whilst they considered their model to provide a good fit to their experimental data, we do not consider diffusion to be the dominant mechanism in driving secondary combustion. As is well known the interface between the explosive products and the air is naturally Rayleigh-Taylor unstable and the resulting secondary combustion energy release is through turbulent combustion mixing of the products and oxygen in the air [5]. Whilst initially mixing of products and air might be driven by diffusion the subsequent rapid development of the surface instabilities will take over as the dominant mixing mechanism. A 1D spherical simulation, reported in [4] will not generate such flow field instabilities and as a result diffusion would be the only mechanism available for mixing and combustion.

As turbulent mixing is considered the governing mechanism a key requirement of the numerical scheme, therefore, is the ability to represent instabilities across interfaces. The advanced interface tracking scheme in GRIM has this capability.

The combustion model starts with the assumption that equilibrium chemistry is a realistic approximation. We can therefore write the chemical reaction in the form:

$$stoif.Fuel + stoio.O_2 \rightarrow stoip.\Pr oducts \qquad \textbf{Equation 1}$$

Where: *stoif*, *stoio* and *stoip* are the fuel, oxygen and final product stoichiometric coefficients respectively and *Fuel*, O_2 and *Products* their respective molar fractions.

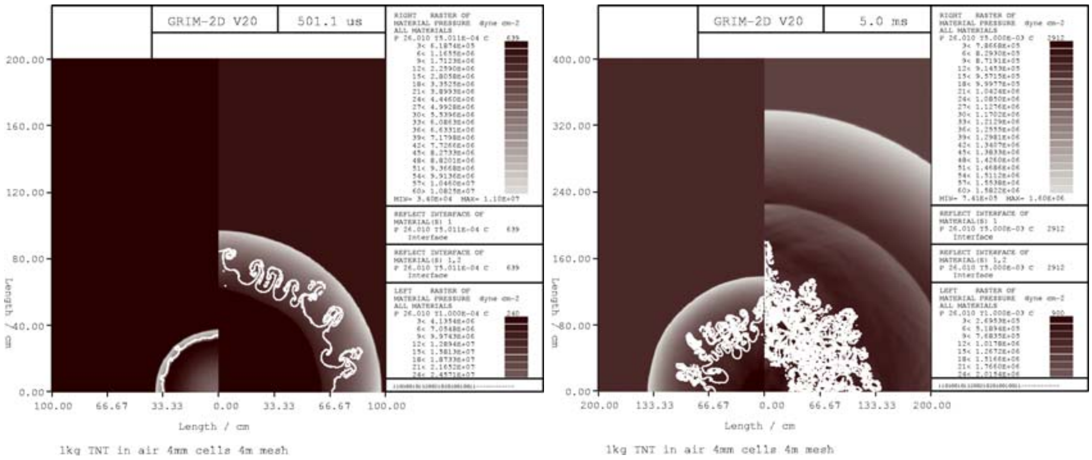
The detonation of TNT in air [5] can be represented by:

$$C_7H_5N_3O_6 + 5.33555 * O_2 \rightarrow 1.0 * \Pr oducts \qquad \textbf{Equation 2}$$

This implies that in the simplified scheme in GRIM, *stoif*, *stoio* and *stoip* become 1.0, 5.33555 and 1.0 respectively with molecular weights 227.0, 32.0 and 397.7376. The secondary combustion energy is then 10.392MJ.kg^{-1}.

In the algorithm, once the detonation wave has passed through the charge, mixed cells containing air and fuel are allowed to react to produce final products, releasing the appropriate amount of energy due to the reaction. The amount of energy released is thus dependent on the amount of air present and the degree of mixing. Figure 1 shows the development of the product air interface at 100μs, 500μs (figure 1a) and 1ms and 5ms (figure 1b) after detonation for a 1kg charge of TNT. The second shock wave is clearly observable in figure 1b at 5ms. The energy released as a function of time is shown in figure 2. The changes in slope are associated with the release waves from the product-air interface propagating back towards the origin and the negative phase in the pressure record. The bounce of the release wave to form the second shock wave for example generates the change in the energy release rate record at about 2.4ms as it propagates through the products-air interface increasing the degree of mixing.

Due to a lack of available experimental data the advanced model was validated against the gas dynamic turbulent combustion model of Kuhl et al. [5], using a 1kg TNT charge. Kuhl showed that the results of his simulations, in terms of the timing and the amount of energy released were dependent upon the spatial resolution of the numerical mesh. The GRIM simulations showed a similar trend as expected since a fine mesh is required to follow the turbulent mixing of the gases accurately, produce a better degree of mixing and hence a greater exothermic energy release.



a) 100μs (left) 500μs (right) b) 1ms (left) 5ms(right)

Figure 1. Development of product-air mixing between 100μs and 5ms

We also recognise that the ability of a 2D axis-symmetrical simulation to represent the 3D unstable product-air interface is limited. However, extensive unpublished research in the UK has demonstrated that the approach reproduces the essential physics.

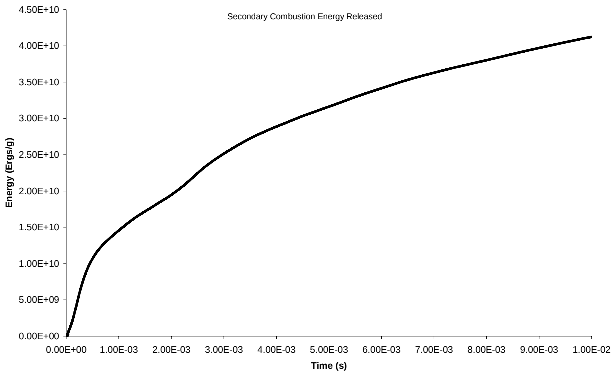


Figure 2. Secondary combustion energy release with time

EXPLOSION SCENARIOS

To illustrate the application of the algorithm two scenarios using a 1kg spherical charge of TNT are illustrated below; free field blast and an explosion in a 4m diameter by 4m high cylindrical room.

Free Field Blast

A 1kg spherical charge of TNT was created in an axis-symmetrical mesh and run with and without the advanced secondary combustion model. A series of data collection points, equivalent to experimental pressure gauges, were located at various distances from the centre of the charge.

The release of secondary combustion energy with time is shown in Figure 2. The effect of the secondary combustion energy release is show in Figure 3, which compares the first positive phase impulse against scaled distance with and without secondary combustion against CONWEP [6]. The simulations show that the secondary combustion energy release does not influence the primary shock front, since the enhanced local sound speed is below the shock wave velocity. The impulse however does show the effect of the secondary combustion energy release close in to the charge where the shape of the blast wave includes the products and rapidly changes with scaled distance. The impulse is, however, in less good agreement with CONWEP, a factor observed in our previous research [7].

Kinney and Graham [8] provide an analytic expression fitted to experimental data for the duration of a chemical explosion. Baker et al [9] represent this data graphically. These two relationships, shown in figure 4, do not agree with each other. The duration of the primary pulse was measured with and without secondary combustion using two definitions. In the first, due to Kinney, only the positive phase was used to define the duration. In the second the duration was defined up to the appearance of the second shock and includes the negative phase. The results show that the data provided by Baker and used in CONWEP includes the negative pulse in the definition of the duration.

Using these definitions the GRIM predicted positive phase durations are in very good agreement with Kinney. The effect of the secondary combustion can be observed to be restricted to a region close to Z=1. For Baker's definition of duration the simulations show the effect of the secondary combustion energy is to shorten the negative phase, increase the second shock pressure, and thus shortening the duration.

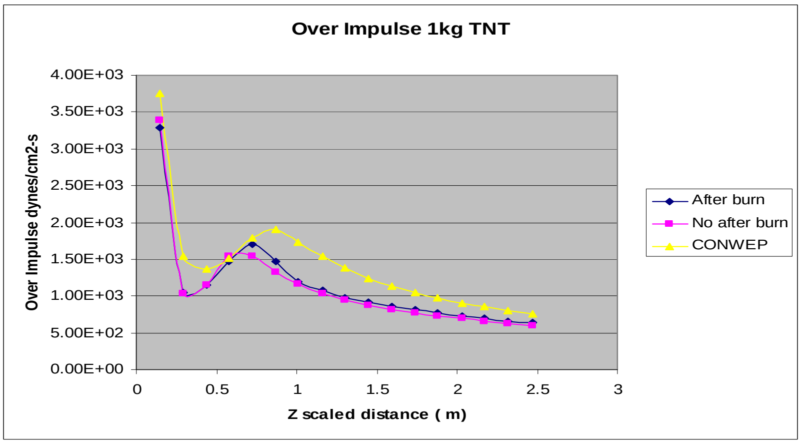


Figure 3: Over impulse with and without secondary combustion

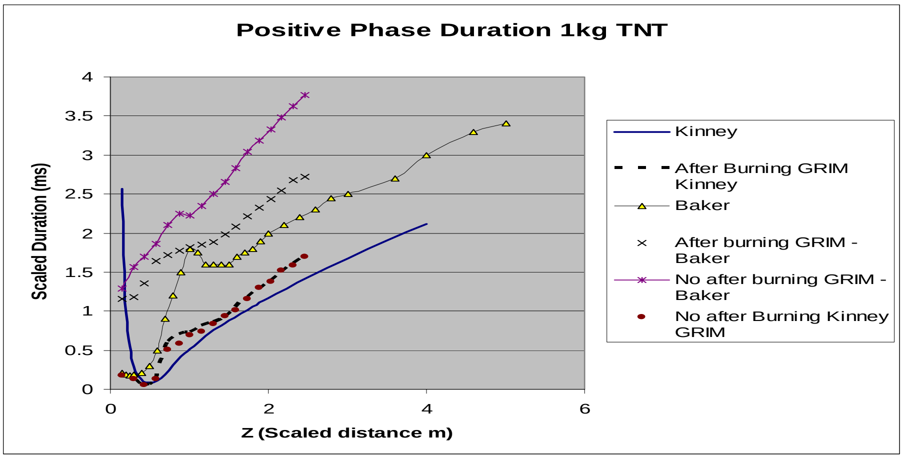


Figure 4: Blast wave duration: simulation and experiment

The simulation with secondary combustion suggests that a finer resolution will further improve agreement with experiment. It does confirm, however, that the anomalous shape in the duration is due to the shape of the blast wave close to the charge around Z=1.

Room Explosion

In the case of the room explosion the oxygen supply is limited by its volume. For this study however, the size of the room, 4m diameter, was such that there was sufficient oxygen available to allow the secondary combustion to run to completion, which the simulation predicts to occur some 38ms after detonation. The strong shock wave reflections from the walls of the room at various times increase the mixing of products with the air and hence the rate of secondary combustion, as illustrated in figure 5 at 5ms.

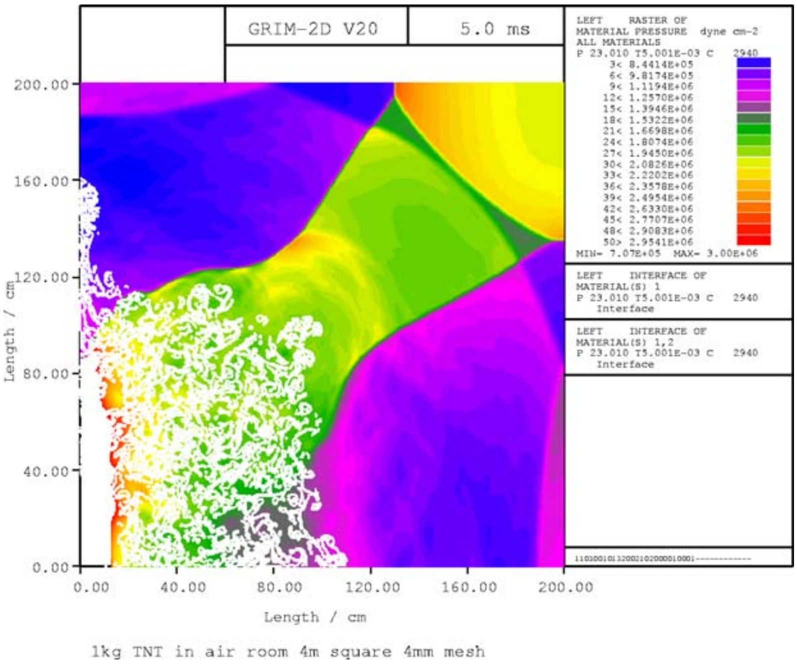


Figure 5. Overpressure time histories within a 4m room for 1 kg TNT

In free field the scaling length is the charge size. In the room, however, it is the volume of the room that determines the amount of oxygen and hence the energy that can be released, independent of charge size.

CONCLUSIONS

This paper has described the development of two methods to introduce secondary combustion into the numerical simulation of the formation and propagation of blast waves.

The predicted pressure, impulse and shock duration times are shown to be in excellent agreement with CONWEP and that differences can be accounted for by the use of different definitions of shock duration time.

The simulations have shown that the secondary combustion acts to enhance the impulse in the Z=1 scaled distance region, by reducing the negative phase duration and increasing the magnitude and arrival time of the second shock. The anomalous behaviour in the blast wave duration is due to the rapidly changing shape of the blast wave due to the involvement of the products and not secondary combustion as has been previously proposed.

Finally the effect of reflected shocks in controlling secondary combustion has been identified as an important factor in blast effects on structures and personnel.

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