THE BURNING RATE OF ALUMINIUM PARTICLES IN NITROMETHANE IN CYLINDER TESTS

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Aluminium is a common fuel component in propellants and explosives. There is a wealth of literature on Aluminium combustion in gases at relatively low pressure but limited data on combustion at high pressure (as in explosive detonation products). In this work we have carried out and analysed cylinder tests with Aluminium loaded Nitromethane with a view to assessing the burning rates in this regime. The analysis makes use of detailed numerical two phase flow modelling and new cylinder test experiments as well as existing experimental data from the literature. We conclude that, for systems of order the size of a standard cylinder test, one needs to use Al particles less than 5 microns in diameter if they are to significantly affect the ability of the explosive to do work on metal.

INTRODUCTION

Aluminium particles burning in a low pressure environment, e.g. air, typically exhibit a dependence of the burn time on particle size of the form [1, 2, 3],

$$t_b = \alpha d_0^2 \quad (1)$$

where t_b is the burn time, d_0 is the particle diameter and α is a constant. Typically the value of α is $4\times10^6 \mathrm{sm}^{-2}$. In the course of studying propellants and explosives it is of interest to study the burning of such particles in a high pressure environment such as occurs detonation. There is limited data available on this subject so a coupled modelling and experimental programme was instigated in the UK. We also make use of cylinder test data published by Baudin et al. [4].

The experimental data for this work was provided from Standard Cylinder Tests.

The mixtures considered here are Nitro-Methane (NM) combined with Aluminium particles (a spherical grade with a mean diameter of 10.5μm) at various loading densities.

We compare experimental results with predictions from two phase numerical models within a multi-material Eulerian Hydrocode. We consider the burn time of the Aluminium as a free parameter and use this to fit to experimental data.

EXPERIMENTAL DESCRIPTION

Copper cylinder expansion tests were carried out on nitromethane / aluminium (NM/Al) compositions containing 20, 30, 40, 50 and 60% by weight aluminium. The NM used was Analar grade and the aluminium particles were spherical, with a mean size of 10.5μm. The mixtures were prepared by adding 5% by weight of polyethylene oxide to the NM to thicken it, and thus help suspend the aluminium, and then adding the appropriate percentage of aluminium. The mixture was then mechanically agitated on a rolling machine for several hours to ensure a homogenous composition, before pouring into the copper cylinders.

The copper cylinders (304mm long, 25.4mm ID with a wall thickness of 2.6mm) were mounted vertically, sealed at the bottom end and initiated by a small booster pellet at the top. The overall expansion, at a distance of ca. 220mm from the initiation end, was viewed with a Cordin-132 streak camera writing at 5.999 mm/μs. An Argon flash bomb and diffusing screen were used to provide back-lighting. In addition VISAR was used to monitor the early expansion in greater detail, but these results will be reported in a future paper. The experimental arrangement is illustrated in Figure 1, which shows the copper cylinder, fibre optic (for VISAR), back-lighting screen, and flash bomb.

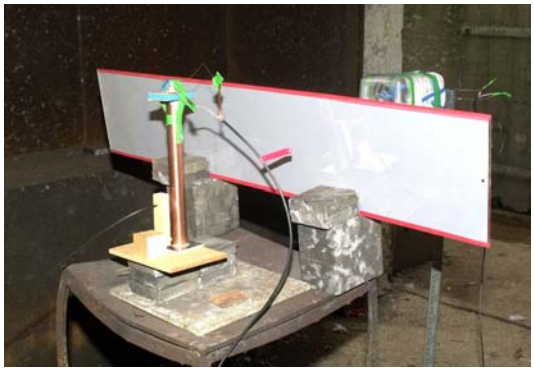

FIGURE 1. EXPERIMENTAL SET UP.

The streak records were analysed to provide the radius time plots shown in figure 2.

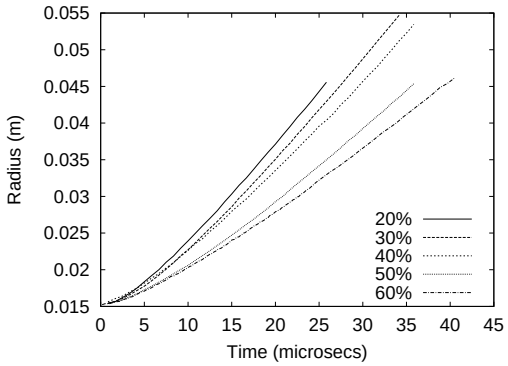

FIGURE 2. CYLINDER EXPANSION RADIUS-TIME PLOTS FOR VARIOUS PERCENTAGE MASS FRACTIONS OF 10.5 MICRON AL IN NITROMETHANE.

There is a decrease in expansion speed as we increase the particle loading density. There is a marked change between 40% and 50% loading which we should seek to reproduce in modelling.

We fitted these R-t curves via a non-linear least squares algorithm to a function of the form $R=at-bexp(-ct^d)$. Differentiation of this fit (this functional form was chosen since it tends to a constant speed at late times) gives us the velocity-time plots shown in figure 3.

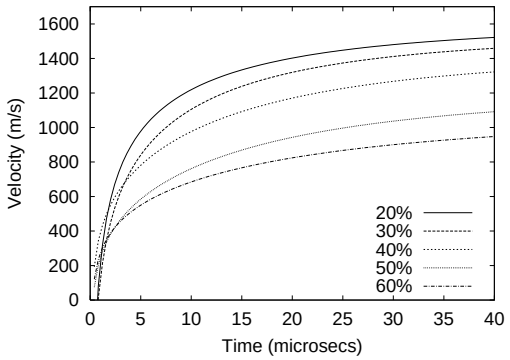

FIGURE 3. CYLINDER EXPANSION VELOCITY-TIME PLOTS FOR VARIOUS MASS FRACTIONS OF 10.5 MICRON AL IN NITROMETHANE.

Previous work by Baudin et al[4] considered 5 micron particles in a cylinder test. We compare our results for 10.5 micron particles at both 20% and 40% particle loadings in figure 4.

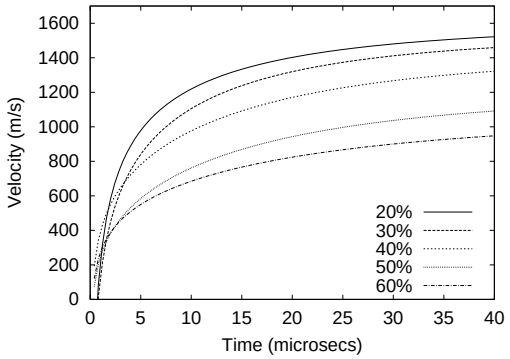

FIGURE 4. COMPARISON OF CYLINDER EXPANSIONS FOR DIFFERING AL PARTICLE SIZES.

We see the same basic trends in both cases but the 5 micron Aluminium gives an extra acceleration in both cases when compared with the larger particles. We wish to investigate these differences in more detail using numerical modelling.

NUMERICAL MODEL

We model these experiments using a two-dimensional, axi-symmetric hydrocode previously used in two-phase modelling of Aluminium Detonation [5]. In a previous paper Milne and Evans[6] used a simple programmed burn model coupled with an Aluminium burn model and the two-phase flow equations. In this paper the NM is modelled by Arrhenius kinetics in a model developed from bullet impact tests by Cook and Haskins[7]. The burn model considers the growth of an explosive burn as a series of coupled Arrhenius chemical kinetic steps. The rate of reaction is a function of the constituents, the temperature and the pressure. If sufficient energy is released then the explosive may burn to detonation. Alternatively, if the energy losses outweigh the energy released, the reactions may die out. Important features of the model are that it is temperature driven and that the chemistry is active throughout a simulation. That is, there are no arbitrary switches to control when the material should burn or detonate.

The unreacted Nitromethane is modelled by a Murnaghan Equation of state while the Nitromethane detonation products are treated as a JWL gas. In this paper the Aluminium combustion products are treated as gaseous. Work is currently in progress to consider improved representations of this material.

We should note that one limitation of our work in this paper is that we shall use the same model for Nitromethane to describe the Baudin et al mixture (NM +3% PMMA) and our experimental mixture with 5% polyethylene oxide but we do not anticipate major differences for this study.

DETONATION VELOCITY

The detonation velocity of NM Al mixtures has been reported recently both by Baudin et al[4] and Haskins et al[8]. We can use our numerical model in 1D mode to predict the infinite diameter detonation velocity for various mixtures of Al particles. We find the velocity deficit is dominated by the drag forces between the

particle and liquid at low loading densities. The inter-granular stresses dominate at higher loading densities.

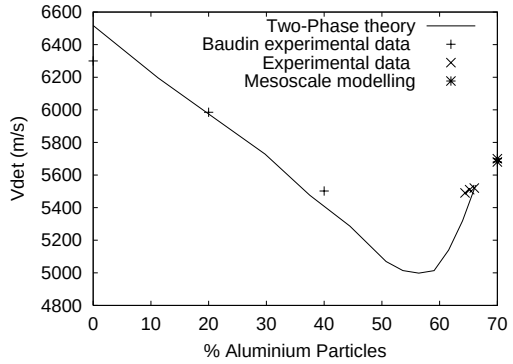

FIGURE 5. PREDICTED VARIATION OF INFINITE DIAMETER DETONATION VELOCITY FOR VARIOUS MASS FRACTIONS OF AL IN NM COMPARED WITH EXPERIMENTAL DATA.

This curve compares two phase flow predictions with data from a variety of experimental sources[4,8] along with direct mesoscale modelling of the detonation process at high loading densities (Milne[9]).

We find that, for the particle sizes being considered here, the detonation velocity is unaffected by burning. We thus use the same two phase model properties in 2D along with a burn model to compare with experiment.

BURNING RATE

In order to assess the particle burning it is necessary for the numerical model to incorporate a burn law. In this work we use a constant radial burn velocity law. Assuming the particles are spherical and burning occurs all over the surface simultaneously, the radius of the particle reduces at a constant rate. The rate of mass burnt per second is then proportional to the rate of change of the particle volume:

$$\frac{dV}{dt} = 4\pi r^2 \frac{dr}{dt} \qquad (2)$$

An alternative law often used in these models is to assume that the rate of change of the surface area of the particle is a constant. In this case the rate of change of volume is:

$$\frac{dV}{dt} = 2\pi r \frac{dr^2}{dt} \qquad (3)$$

In both cases we need to determine a characteristic timescale given by (1). In this work we treat this as a free parameter to compare with the experimental results.

We have repeated the earlier analysis[6] of the Baudin et al[4] experimental data using 5 micron Al particles and the Arrhenius kinetics for Nitromethane.

Our best fit to the results for 40% Al is shown in figure 6 below

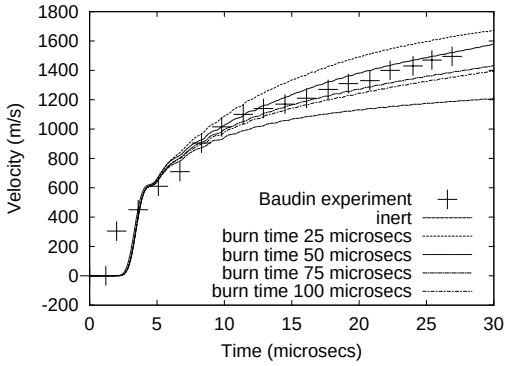

FIGURE 6 CALCULATION OF EFFECT OF BURN TIME ON CYLINDER EXPANSION VELOCITY FOR 40% LOADING OF 5 MICRON AL COMPARED WITH BAUDIN ET AL EXPERIMENT.

Inert particles give too slow an expansion compared with experiment. If we allow the Aluminium to burn in these calculations we see that the late time speed of the cylinder expansion increases and burn time decreases. We see here that the experimental results are bracketed by a burn time of between 50 and 75 microseconds

This burn time is similar to the time for the detonation wave to travel the length of the cylinder. Thus Al burning is taking place throughout the cylinder length even at late stages of the detonation. We can illustrate this by plotting Fraction of Al particles along the centre line of the cylinder which have reacted at late time in figure 7

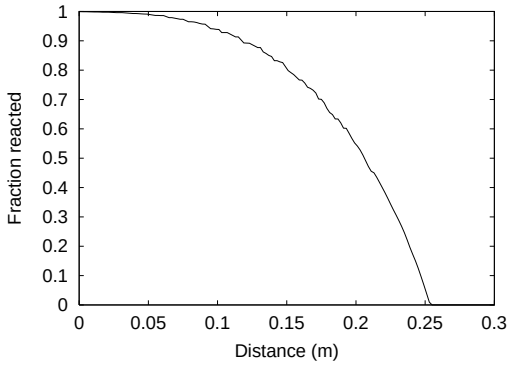

FIGURE 7. FRACTION OF AL PARTICLES REACTED V. DISTANCE ALONG CENTRE LINE OF CYLINDER.

Here we have used a burn time of 50microsec. The end of the cylinder is located at just over 0.3m on this figure. Here we see that as the detonation wave nears the end of the cylinder, only those particles at the start of the cylinder are fully burned

To apply this burn model to our 10.5 micron particles we should scale this burn time according to the d^2 law, giving a burn time of 220 microseconds. This is long compared with the characteristic timescale for the detonation along the cylinder. We thus consider inert particles as a first approximation in figure 8.

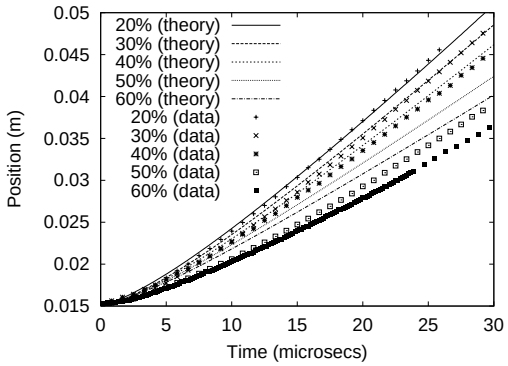

FIGURE 8. COMPARISON OF PREDICTED AND MEASURED CYLINDER EXPANSIONS FOR VARIOUS MASS FRACTIONS OF 10.5 MICRON AL IN NITROMETHANE.

Here we compare predicted and measured radius time plots. We see good agreement for low loading densities (20% and 30% by mass). As we increase the particle loading density the curves diverge. In all cases we see that the experimental curve is lower than the predicted curve in the early stages. As we saw in figure 6, allowing for any burning will only speed up the prediction and thus give more divergence.

The form of the divergence is that the predicted initial expansion is faster than the measured value. It is interesting to note that the predictions and measurements are tending to similar terminal velocities. We plot these values in figure 9.

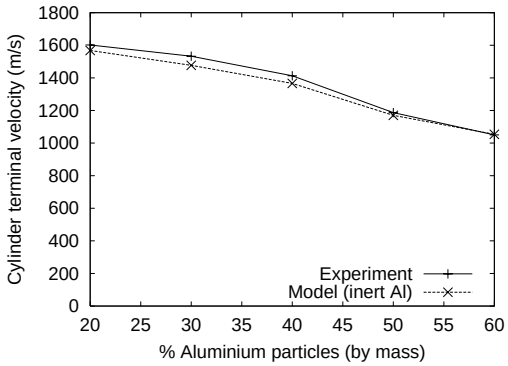

FIGURE 9. COMPARISON OF PREDICTED AND MEASURED CYLINDER TERMINAL EXPANSION SPEEDS

The agreement here is good with the same trend evident in both experiment and calculation.

We thus conclude that some effects other than Al combustion must be the cause of the discrepancies in the curve shapes of figure 8. Since the curves diverge most at high loading density we were led to consider the possibility of particle agglomeration. We have calculated the behaviour of the cylinder for 20 and 40 micron particles as an attempt to account for the possibility of agglomeration. We find that larger particles only exacerbate the differences.

Other factors which can affect the early time behaviour for inert particles are the drag between particles and detonation products or the inter-granular stresses. The values used in the numerical model have been developed from conventional theory and comparison with dispersion experiments (for late time drag effects) or detonation velocity measurements (see figure 5). We plan to revisit these aspects in future work where the detail afforded by the VISAR measurements we carried out in this series of trials will provide more insight.

DISCUSSION

By comparing modelling with published experimental data we find the burn time for 5 micron Al particles is of order the detonation transit time for a standard cylinder test (typically 50 microseconds). For the 10.5 micron particles considered in our new experimental work the burn time is longer and so Al combustion will have significantly less of an effect. These results can be used to determine what size of Al particles are needed to significantly affect the ability of the explosive to do work on metal. For systems of order the size of a standard cylinder test we clearly need to use particles less than 5 micron in diameter.

We find that our predictions are consistent with no significant burning of the 10.5 micron Al in the cylinder tests. We have good agreement between calculated and measured terminal expansion velocities over the range of loading densities considered. The predicted detail of the early expansion is in good agreement with experiment for low loading densities but poorer for high loading densities. We conclude that burning is not the cause of the discrepancy and see no evidence that agglomeration can explain these early differences. We plan to consider the effects of drag or intergranular effects in more detail in future work.

More data is required to allow detailed analysis to take place. To this end we plan to analyse the VISAR data recorded during this series of shots. We also plan to obtain more data on the effects of particles on detonation velocity.

ACKNOWLEDGEMENTS

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