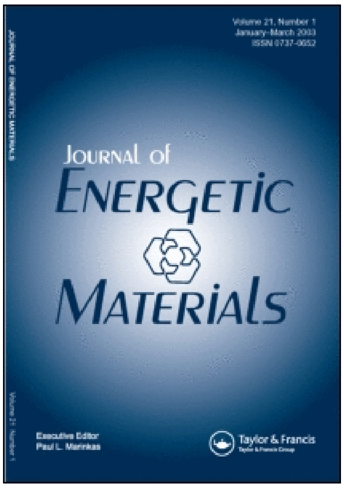

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AN INFLUENCE OF EXPLOSIVE GEOMETRY ON SHAPED CHARGE JET PERFORMANCE

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ABSTRACT

We have measured the velocities of the particles of a jet after breakup and found that the distribution contained an approximately constant velocity section of several particles immediately behind the tip. The jet was produced from a centrally initiated, 38 mm diameter conical shaped charge. Since the measurements were carried out after jet formation, the observation is not considered to be directly related to the inverse-velocity gradient effect that produces the tip particle. Comparison between calculated and measured jet penetration velocities show that the calculations assuming a uniformly stretching jet require modification to take account of the observation. A possible explanation for the origin of the non-ideal behaviour is that the short height of explosive between the detonator and liner (the explosive head height) produces a building detonation which strikes

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the liner with a varying impulse and curvature. Some support for the observation is found in earlier experimental work by DiPersio et al[1] and in a numerical modelling study by Coughlin[2].

INTRODUCTION

Conventional metal lined conical shaped charges collapse to produce stretching jets. The elongation is caused by the jet having a velocity gradient with the tip travelling faster than the tail. The process of jet formation is generally described by the Pugh, Eichelberger and Rostoker (PER) theory[3] and the early experimental verification of the velocity gradient was reported by Eichelberger and Pugh[4]. Although experimental and theoretical observations have led to several refinements to the PER theory (these have been summarised in an excellent review by Chou and Flis[5]) the velocity of the jet after formation is still considered to decrease linearly from tip to tail.

We have found that a centrally initiated, 38 mm diameter conical shaped charge produces a particulated jet whose tip and following few particles have a similar velocity and therefore do not form part of the uniform gradient. These particles will have an effect on penetration performance and should be considered in any analysis. Furthermore, a study into the cause of this non-ideal jet behaviour may assist in evaluating the role of boosters and wave shapers in shaped charges. This is particularly important where the weight of explosive is limited by overall system constraints. This note presents data illustrating the effect and the resulting penetration performance of the jet; the non-ideal behaviour is discussed in terms of the short height of explosive between the detonator and liner apex.

EXPERIMENTAL

The experiments were conducted using the 38 mm diameter shaped charge illustrated in Figure 1. The liner was flow turned and heat treated using oxygen free copper. The cast filling of Composition B was checked for quality using static, orthogonal radiography.

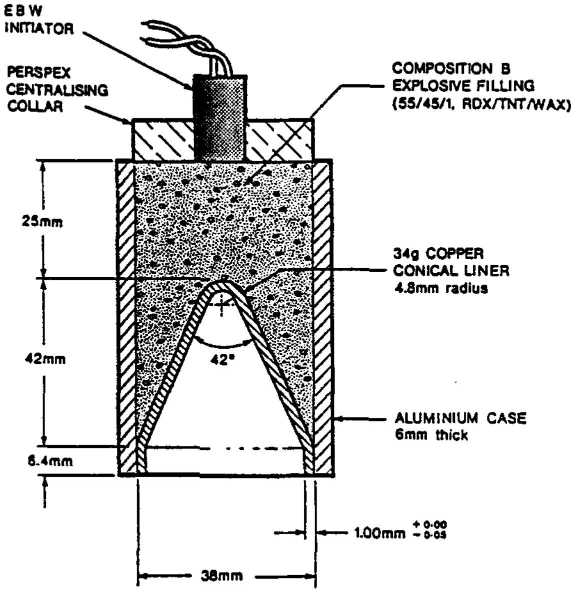

FIGURE 1

The 38 mm diameter shaped charge

Charges were centrally initiated with an Exploding Bridgewire Detonator. The velocities of the jet particles were determined by firing the shaped charges in air and using triple flash radiography to record their positions after allowing sufficient time for the jet to particulate. Measurements were carried out at both MRL and BRL. The jet penetration depth in mild steel at 76 mm standoff was about 175 mm.

The jet penetration velocities in mild steel were determined by firing the jet from 2 charge diameters standoff (76 mm) through a range of target thicknesses and using multiple flash radiography to measure the jet velocity about 15 to 30 mm from the exit surface of the target. The jet penetration velocity at the exit surface of the steel target was determined from[6]:

$$U_p = \frac{V_j}{1 + \gamma} \qquad (1)$$

where U_p the jet penetration velocity in steel

V_j the measured jet velocity in air

γ the square root of the ratio of the steel target and copper jet densities.

Flash radiography showed that the jet remained continuous while penetrating steel targets up to about 125 mm thick; at greater thicknesses the jet emerged from the steel in particulated form with the distance between the particles increasing with steel thickness (i.e. time of flight). The break-up time for the jet particles has not been measured but has been found to vary along the length of the jet.

RESULTS AND DISCUSSION

The MRL and BRL velocity measurements for the first 10 particles in the jet from 38 mm diameter shaped charges are listed in Table 1. Each velocity is the mean of two measurements taken from the triple flash radiographic records. Typical uncertainties in the velocity measurements were about ± 0.1 mm/μs.

TABLE 1

Velocities of the First 10 Particles in 38 mm Diameter Shaped Charge Jets

Particle Number	Jet Particle Velocity			
	MRL Measurements Charge 1 mm/μs	Charge 2 mm/μs	Charge 3 mm/μs	BRL Measurement mm/μs
1 (tip)	7.3	7.4	7.5	7.3
2	7.2	7.4	7.5	7.3
3	7.2	7.4	7.6	7.4
4	7.3	7.3	7.6	7.3
5	7.1	7.1	7.5	7.3
6	7.0	6.9	7.3	7.1
7	7.0	6.8	7.2	6.9
8	6.9	6.7	7.0	6.8
9	6.8	6.6	6.9	6.6
10	6.6	6.5	6.8	6.5

The results in Table 1 show that the first 4 or 5 particles have similar velocities but that the subsequent particles exhibit a normal shaped charge jet velocity gradient. The measured velocity gradient of the remainder of the jet particles not given in Table 1 was 0.1 mm/μs/particle which is typical of this type of shaped charge. Thus the general shape of the spectrum of velocities of the particles in the jet approximates that shown in Figure 2(a) rather than that for an ideal jet shown in Figure 2(b). The measurements showed no slowing of the particles up to a flight distance of at least 1 m.

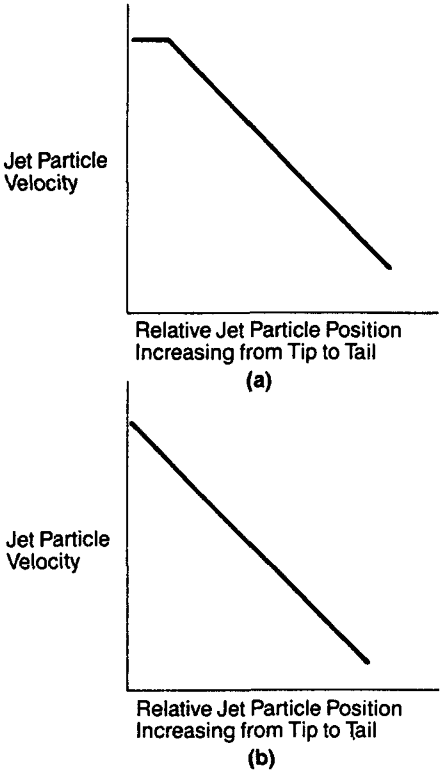

FIGURE 2

Spectrum of velocities of particles along the jet from the 38 mm diameter charge (a) and for an ideal jet (b)

Our measurements were undertaken after jet breakup and therefore the observation is not considered to be directly related to the inverse-velocity gradient effect reported by Kiwan and Wisniewski[7]. This inverse-velocity gradient occurs during the early stages of cone collapse where liner elements near the apex do not have sufficient distance to reach their final velocity before colliding on the axis. Thus on moving down the liner from the apex successive elements have further distance to travel and reach higher speeds; the resulting pile up forms the jet tip. The process is considered to stop when the liner elements can attain their final collapse velocity. Subsequent elements then reach progressively lower velocities due to the changing explosive/liner mass ratio.

We have estimated the effect of the constant velocity section at the front of the jet on the penetration characteristics in steel. This was carried out by comparing the calculated penetration rate using the data in Table 1 to the calculated value assuming a normal velocity gradient in the jet and to the experimentally determined values. The results are listed in Table 2. The results are presented as jet velocities, V_j, rather than penetration velocities in steel, U_p, since this data more easily demonstrates any inconsistencies between the values.

TABLE 2

Measured and Calculated Jet Velocities in Air after Penetrating Steel Targets for the 38 mm Diameter Shaped Charge at 76 mm Standoff

Steel Thickness	Jet Velocities		
	Measured	Calculated	
		Modified DiPersio/Simon Equation	DiPersio/Simon Equation
mm	mm/μs	mm/μs	mm/μs
13	7.0	7.30	6.58
19	6.6	6.93	6.23
25	6.3	6.59	5.94
38	6.2	6.01	5.41
52	5.4	5.48	4.93
60	5.3	5.21	4.69
75	4.7	4.78	4.30
100	4.2	4.20	3.79
127	3.7	3.73	3.36
138	3.3	3.56	3.21
154	3.2	3.34	3.01
166	2.9	3.20	2.89

The calculation for the jet with a normal velocity gradient used the relationship developed by DiPersio and Simon[8] for determining the velocity of a stretching jet at a given depth of penetration in an incompressible target, i.e.,

$$V_j = V_{tip} \left[\frac{Y + S}{S}\right]^{-\gamma} \qquad (2)$$

where V_{tip} the measured jet tip velocity,

Y the depth of jet penetration in steel or thickness of steel target,

S the standoff from the virtual origin position of jet formation to the start of penetration of the target.

The virtual origin assumption[9] considers that all jet elements formed from the collapsing liner originate from one position in space and time. It has proved to be a very useful concept for the study of shaped charge jet penetration[10]. The position of the virtual origin is located along the liner axis back from the base and has not been experimentally determined for the 38 mm diameter charge. However, a value of 20 mm has been estimated using data for the BRL 81 mm shaped charge for which the 38 mm charge is an approximate half scale. Adding this value to the standoff distance of 76 mm gave S equal to 96 mm.

Our calculation for the jet with a constant velocity section was carried out by modifying equation (2) with the addition of a term for the penetration of the sum of the lengths of the constant velocity particles; it was then assumed the remainder of the jet penetrated in the normal manner. In this approach we assumed that other than the tip segment, the particles were of constant volume and stretched until particulation. The change in length of the particles from the approximate standoff position of the penetration

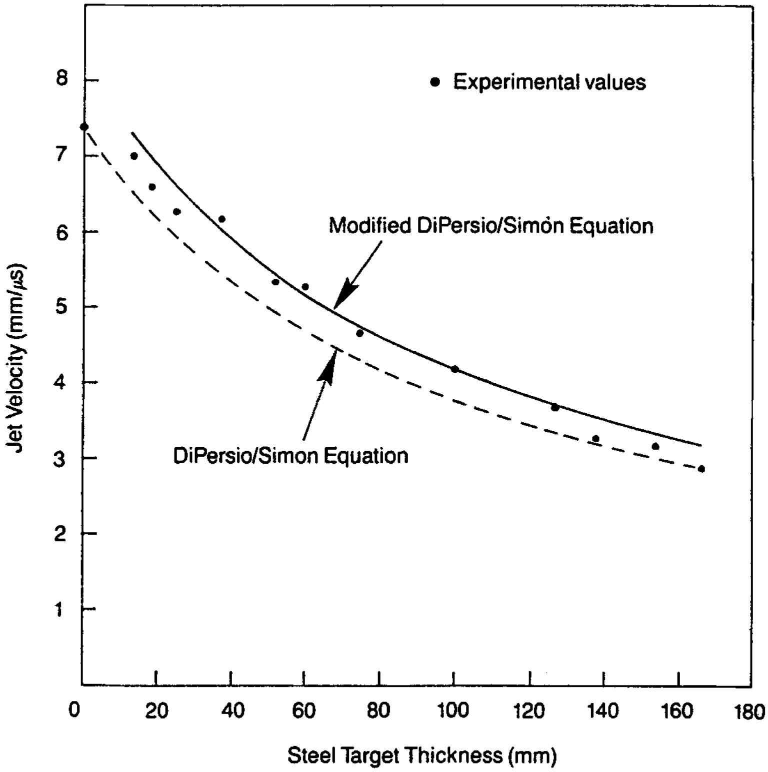

FIGURE 3

Comparison between measured and computed jet velocities after penetrating steel for the 38 mm diameter shaped charge at 2 charge diameters (76 mm) standoff.

in steel to particulation was estimated using flash radiography to record the concomitant change in radius. Thus the length of the particles for estimating their penetration in steel, x, is given by:

$$x = x'\left[\frac{r'}{r}\right]^2 \qquad (3)$$

where x' and r' the length and radius respectively of the particles after breakup,

r the radius of the jet at the approximate standoff position for penetration in steel.

The cumulative length of the particles, x, penetrates a depth, P, which is defined by[6]:

$$P = \frac{x}{\gamma} \qquad (4)$$

Thus the remaining jet penetrates Y-p but the standoff has been increased to S+P. Therefore equation (2) can be modified to take the form:

$$V_j = V_{tip}\left[\frac{Y + S}{S + P}\right]^{-\gamma} \qquad (5)$$

The results are listed in Table 2 and plotted in Figure 3 and show good agreement between the experimental values and the calculated values which take account of the constant velocity particles behind the jet tip, equation (5). The calculated values using the DiPersio/Simon relationship, (2), give a significant underestimate of the jet velocity other than for the deepest penetration.

An explanation for the origin of the non-ideal behaviour of the particles following the jet tip may be associated with the short run of explosive between the detonator and liner apex (the explosive head height) and be related to the varying curvature and impulse hitting the liner from the building detonation. Our flash radiographs show the detonation front has marked divergence on striking the liner apex and straightens up as it passes down the liner surface.

This type of explanation is supported by some results from a study by DiPersio, Simon and Martin on jets from scaled conical liners[1]. The study determined the performance of jet particles from 3 scaled centrally initiated, Composition B filled conventional shaped charges. The explosive head heights for the charges were 26, 39 and 52 mm; the smaller charge was therefore similar to our 38 mm diameter charge. The velocities of the jet particles in the tip region of the smallest charge exhibited non-ideal behaviour and are reproduced in Table 3. The results from the other two charges were not tabulated in the original report but were presented graphically; they show that the irregularity in jet velocities was less marked for the middle size charge and was not evident in the largest charge. DiPersio et al noted the irregular velocities and believed the trend to be real but did not comment further. Thus in Table 3 it is also difficult to ascertain whether particles 2 and 3 were travelling faster than the tip or whether the results were within experimental error.

TABLE 3

Jet Particle Velocities from the Study by
DiPersio, Simon and Martin[1]

Particle Number	Jet Velocity mm/μs
1	7.61
2	7.73
3	7.77
4	7.56
5	7.44
6	7.40
7	7.27
8	7.23

Support for the proposition that changing detonation wave shape can produce a non-ideal velocity distribution along a jet is given in a computational study by Coughlin[2] using the BRLSC code. Coughlin studied the effect of point initiation, plane wave detonation and circumferential initiation on the velocity gradient from a conventional 150 mm diameter shaped charge. The head height of the explosive was 25 mm, similar to our 38 mm diameter charge. There was no burn routine in the code and hence detonation buildup was assumed to be instantaneous. In the point initiation case the detonation front formed a circular diverging arc (similar to that observed on the flash radiographs of our 38 mm charge) while the plane wave produced a straight horizontal front and the circumferential initiation produced a converging conical shaped front. After 40 μs the velocity spectrum for circumferential initiation exhibited a smooth decrease from tip to tail. In the plane wave case at the same time the velocity along the jet showed a slight decrease. However, the point initiation case at 40 μs produced a jet with a velocity maximum about half way along and the study indicated it was only slowly moving towards the tip region.

A general conclusion from Coughlin's study is that a diverging detonation front striking a conventional liner may exhibit non-ideal behaviour and produce a jet with an irregular velocity distribution.

Further investigations will evaluate the effects of explosive head height and detonation front curvature on the distribution of velocities along particulated jets. This will be undertaken with charges with half and three times the head height of the normal charge (illustrated in Figure 1) and for a circumferentially initiated charge. It is anticipated that the long head height charge will approximate a plane wave detonation impact on the liner. These results will be compared to hydrocode calculations.

CONCLUSION

Multiple flash radiographic measurements have shown that the jet from a centrally initiated charge with a 25 mm explosive head height exhibits a range of particle velocities that has an approximately constant velocity section behind the tip rather than the ideal behaviour of a linear decrease from tip to tail. We have determined that a simple modification to the DiPersio/Simon relationship for computing penetration rate for a uniformly stretching jet produces good correlation with experimentally determined values in steel. Evidence is presented for attributing the non-ideal behaviour to the short head height of explosive in the charge which is the subject of further study.

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