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Influence of Different Parameters on the TNT-Equivalent of an Explosion

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Abstract: Emulsion explosives are used in a wide range of applications, amongst which some in closed vessels, where the properties at short range need to be known. A series of tests with spherical charges has been carried out to determine the TNT-equivalent at short range of an explosive emulsion based on both peak overpressure and impulse. Generally, the value is found to be constant over the considered range, with a value of 1 for overpressure and of 0.7 for impulse. In most common applications, explosive charges are not spherical. Experiments with cylindrical charges have been performed to study the influence of (1) the shape of the charge (length-to-diameter ratio) and (2) the location of initiation (central or at one end). At the considered range, increasing L/D increases the peak overpressure and the impulse perpendicular to the axis, but decreases these effects on the axis. The central initiation causes the largest effects on the centreline. The initiation at one end causes a shift in the location of the peak overpressure, but the highest impulse remains on the centreline.

Keywords: emulsion explosive, cylindrical charge, blast overpressure, blast impulse

Introduction

Emulsion explosives (which will be referred to as EE further in the paper) are widely used in quarries, for underground mining and tunneling, for civil works and for specific applications in detonation chambers, such as welding and cladding [1], or even destroying old chemical munitions [2]. For design, safety (transportation and storage), operations, etc., an amount of TNT-equivalent mass is generally needed.

Knowledge of the blast properties of the EE, especially at the short range, is important for the prediction of its effects and for determination of its TNT-equivalent [3, 4].

In first instance, the TNT-equivalent is considered as a property of a given explosive. The value depends on the nature of the explosive and the effect used for the comparison with TNT (Eq. (1)).

$$\text{TNT-equivalent of an } \underline{\text{explosive}} = f(\text{nature of explosive, effect}) \tag{1}$$

However, when assessing the effect of an explosion in a certain setup and in a certain environment, the TNT-equivalent should be considered as a function of combined parameters, which all could potentially have an influence on its value. Equation (2) summarizes some of the parameters which have a (potential) influence on the TNT-equivalent, placed in order of decreasing relevance:

$$\text{TNT-equivalent of an } \underline{\text{explosion}} = f(\text{nature of explosive, effect, distance, shape, initiation}) \tag{2}$$

These parameters have been investigated by numerous authors [3, 5-7].

In what follows, when the term TNT-equivalent is used, it shall be understood as the TNT-equivalent of an explosion, with all the parameters which can have an influence on its value.

Preliminary discussion

In Eq. (2), five parameters having a potential influence on the value of the TNT-equivalent were introduced.

1. The influence of the nature of the explosive is well documented [7, 8]. Each explosive has its specific properties with respect to TNT. Modern military explosives usually have TNT-equivalents higher than 1, while ammonium nitrate based EE are generally considered of less power and brisance than TNT.
2. The second parameter of major importance for the TNT-equivalent is the effect that is used for comparison with TNT, among others: the peak overpressure and the impulse of the blast wave, the brisance ($\rho \cdot VoD^2$), the

theoretical or experimental energy, the force (nRT), etc. [7-9].

3. The distance also plays a role for the TNT-equivalent assessment. Depending on the nature of the explosive and the effect used for comparison, the value for the TNT-equivalent can vary at short and long distance [5, 9].
4. The shape of the charge can play an important role as well. Often, in actual applications, explosive charges have a non-spherical or even unsymmetrical shape. Spherical charges lead to symmetrical effects, whereas elongated charges lead to asymmetry in the pressure field. Consequently, the TNT-equivalent depends on the angle around the charge [6].
5. Another potential factor that could influence the TNT-equivalent is the location of initiation. M. Held has found important effects on the side opposite to the initiation for one-end initiated cylindrical charges [10].

In the ideal case, when all parameters in Eq. (2) can be considered to be independent, Eq. (2) can be written as Eq. (3).

$$\text{TNT-equivalent} = f_1\,(\text{nature}) \times f_2\,(\text{effect}) \times f_3\,(\text{distance}) \times f_4\,(\text{shape}) \times f_5\,(\text{location of initiation}) \tag{3}$$

This study focuses on the functions f_1, f_4 and f_5, namely:

$\boldsymbol{f_1}$: The ammonium nitrate based EE is investigated and compared to TNT. This explosive has a lower brisance than the typical military explosives usually described in the literature.

$\boldsymbol{f_4}$: To investigate the influence of the shape of the charge, measurements at different angles around cylindrical charges have been carried out. Cylinders of two different length-to-diameter ratios have been brought to explosion. They are sufficiently different to distinguish shape effects between both of them. Cylindrical charges have already been the subject of studies [6], but the reduced distances were larger than in the current study and moreover the used explosives were of the military type.

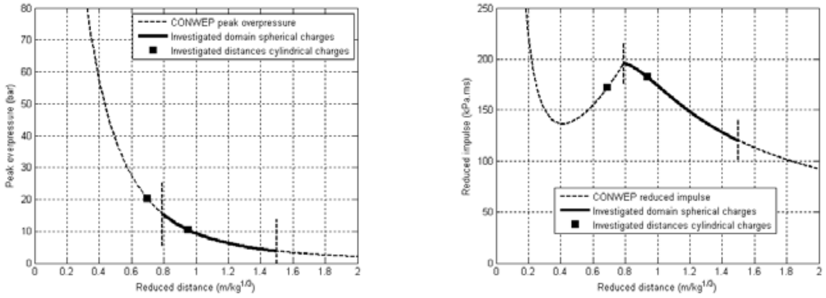
$\boldsymbol{f_5}$: Two different locations of initiation have been studied for the cylindrical charges: the central initiation and the initiation at one end. In [10], the effects around the one-end side initiated cylinder are compared to the spherical charges, but comparison between the central and the one-end initiation of cylinders has not been studied to see whether the effects observed in [10] are caused by the cylindrical shape or by the location of initiation. The spherical charges were always initiated centrally in this study.

For the functions f_2 and f_3, the investigations have been carried out for various values. These functions do not represent the properties of the charge, but rather define the domain of validity of the conclusions.

f$_2$: The two blast wave parameters of the peak overpressure and the impulse have been used for the calculations of the TNT-equivalent. These two parameters are very important when the response of a detonation vessel needs to be determined. In function of the natural period of the vessel and the duration of the loading, the peak overpressure, the impulse or both fully determine the vessel response [4]. For this reason, knowledge of both for the EE is important.

f$_3$: In this study, only the near-field has been considered, more particularly in the range between $Z = 0.79$ m kg$^{-1/3}$ and $Z = 1.5$ m kg$^{-1/3}$. This short range is of importance in detonation vessels having walls typically within these ranges of the explosive charge. For the spherical charges, a large number of reduced distances in this range have been tested. For the cylindrical charges, measurements have been performed at two reduced distances at the short range.

When the TNT-equivalent has to be determined, some reference value for TNT must be compared to. In this study, CONWEP has been used as a benchmark for the peak overpressure and the impulse for a spherical, aerial charge of TNT [8]. CONWEP contains widely accepted data for reduced distances from as small as $Z = 0.0531$ m kg$^{-1/3}$ up to as large as 40 m kg$^{-1/3}$ (Figure 1). As can be seen in Figure 1(b), the reduced impulse reaches a maximum value at $Z = 0.79$ m kg$^{-1/3}$. For smaller reduced distances, the calculations of the TNT-equivalent based on the impulse have proved to be very sensitive to measurement errors. Detailed examination has led to the conclusion that a measurement error of only 5% in the impulse can lead to errors in the TNT-equivalent of up to 200%. For this reason, the TNT-equivalent based on the impulse for reduced distances smaller than $Z = 0.79$ m kg$^{-1/3}$ has not been calculated.



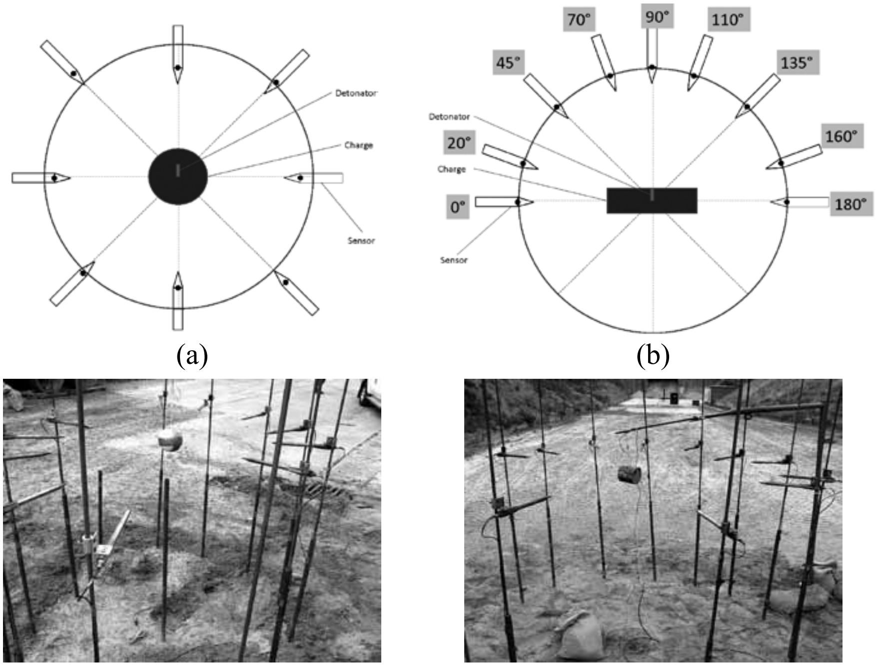
(a) (b)

Figure 1. The reference data for (a) the peak overpressure and (b) the reduced impulse from CONWEP with investigated ranges for the spherical and the cylindrical charges.

Experimental setup

Setup and instrumentation

Figure 2 shows the experimental setup with the position of the different blast sensors during the different tests with the spherical (Figures 2(a) and 2(c)) and the cylindrical (Figures 2(b) and 2(d)) charges. All the charges are placed at a height of 150 cm from the ground, in order to assure that they are aerial, without any reflections from the soil interfering with the measured pressures. Firing the shots under the same conditions as those for which CONWEP apply allows to compare the experimental results to the results for TNT calculated with CONWEP.



(a) (b)

(c) (d)

Figure 2. The detailed experimental setup with positions of the blast pencils and pictures for the spherical charges ((a) and (c)) and the cylindrical charges ((b) and (d)).

For the spherical charges, distances from the centre of the charge ranged from 50 cm to 200 cm (or in reduced distance from 0.43 m $kg^{-1/3}$ to 1.72 m $kg^{-1/3}$). Measurements around the cylindrical charges are performed at nine different angles (0°, 20°, 45°, 70°, 90°, 110°, 135°, 160° and 180°, see Figure 2(b)), of which the last four are redundant because of the symmetry in the case of central initiation. Pressures are measured at a distance of 80 cm and 110 cm from the centre of the cylindrical charges (or in reduced distance from 0.69 m kg$^{-1/3}$ to 0.94 m kg$^{-1/3}$). It is important to emphasize that the distance is taken from the centre of the cylindrical charge and not from its edge what makes the calculation of the reduced distance inevitably a little ambiguous. The line from the angles 0° to 180° is called the axis in what follows, while the line from the centre of the charge to the angle of 90° is called the centreline. Because of the difficulty of achieving good blast measurements at the considered short range, redundancy in the measured data has been obtained by firing multiple identical shots.

The pressure was measured with PCB blast pencil sensors which allow to measure incident blast overpressures up to 40 bar. The acquisition system allows for measurements at 10.10^6 Samples/s on four channels and at $2.5.10^6$ Samples/s on the eight other channels. A small electrode attached to the detonator is used to trigger the data acquisition. A part of the experiments has been recorded with a Photron SA3 high-speed camera at 3000 fps.

The explosive charges

The nature (f_1)

Table 1 presents the different types of experiments that were carried out. For the study of the influence of the nature of the explosive, spherical charges were used. The spherical shape of the charges was assured by use of plastic spheres with very thin but rigid walls which are assumed to have no influence on the blast waves (see Figure 2(c)). The EE used in most of the experiments consists of 80% ammonium nitrate, 10% water, 6% oil, an adequate emulsifier and a sensitizer. Two larger spherical charges of the EE have been fired as well in order to make sure there was no scale effect influencing the measurements and to confirm that the detonation of the small charges was good.

Table 1. Performed experiments

	Shape				
	Sphere	Long cylinder $L/D = 8.3$		“Square” cylinder $L/D = 1$	
		Initiation at one end	Initiation in the centre	Initiation at one end	Initiation in the centre
Emulsion explosive (1.6 kg)	✓	✓	✓	✓	✓
Emulsion explosive (4.5 kg)	✓				

The shape (f_4)

Experiments with two differently shaped cylindrical charges of the EE were carried out. There were short, thick cylinders (diameter: 12 cm, length: 12 cm, *L/D* = 1) and longer, thinner cylinders (diameter: 6 cm, length: 50 cm, *L/D* = 8.3). The charge of *L/D* = 1 will be referred to as the “square” cylinder further in this paper. It is considered to be short enough to become representative of a short cylinder, whereas the cylinder of *L/D* = 8.3 is used as reference for a long cylinder. Each of the cylinders has a mass of about 1.6 kg, the same as for the spherical charges, what allows for consistent comparison.

The location of initiation (f_5)

Finally two different locations of initiation were compared: the central initiation and the initiation at one end. For each of the configurations, cylinders of two different length-to-diameter ratios have been fired.

Results and Discussion

The nature of the explosive (f_1)

Experimental results

Figure 3 represents the decrease of the measured peak overpressure while increasing the reduced distance for the spherical charges of EE. The reference curve from CONWEP is drawn as well. Figure 3 shows a summary of 14 experiments. The peak overpressures for EE have a similar shape as the values for TNT. Scattering of the data is generally rather limited. The two shots of larger mass lead to results in the same range. This demonstrates the validity of laws of similarity (and the use of the “reduced distance”) for the EE tested.

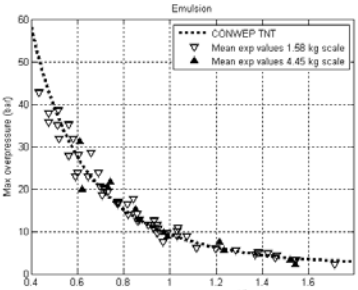


Figure 3. The peak overpressure in function of the reduced distance: the experimental data for the EE and the CONWEP curve for TNT.

The TNT-equivalent of the EE based on the peak pressure can be determined from Figure 3. The value amounts about 1 for the entire range of the reduced distance considered for the EE. Based on the impulse, the TNT-equivalent of about 0.7 can be found for the EE, a value which is independent of the distance for the considered range as well. Although some researchers found a distance-dependent value for the TNT-equivalent of some explosives [5, 9], this might be due to the large interval in distance that they considered.

These results show the importance of the function f_2 in Eq. (3), whereas the function f_3 has been found to be negligible in the short range. Table 2 summarizes the results from the experiments.

Table 2. Factor f_1 for peak overpressure and for impulse for the investigated EE

	TNT-equivalent	
	Peak overpressure	Impulse
Emulsion	1	0.7

Discussion

The EE characterized by less brisance than TNT, generates at short distance a blast wave that has peak pressures of the same magnitude as an identical mass of TNT. For impulse however, a mass of EE equals about 70% of that mass in TNT.

When applying these conclusions to Eq. (3), one notices the importance of the functions f_1 and f_2. In the considered range of distances, the influence of the function f_3 has been found to be negligible.

The shape of the charge (f_4)

In this section, the results for cylindrical charges initiated centrally are presented and discussed. For this case, the pressure distribution theoretically becomes symmetrical.

Experimental results

Figure 4 shows the experimental data for the peak overpressures at a distance of 80 cm obtained for a long cylinder. Some scattering in the data can be noticed but generally the expected symmetry is well remarkable in the measurements. In what follows, for all curves, the average value of all data at one angle will be used as the experimental result for that angle.

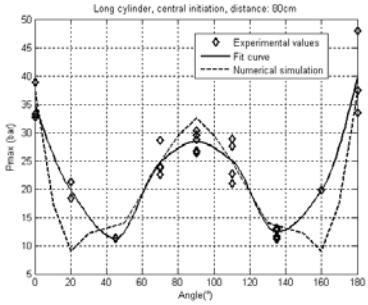
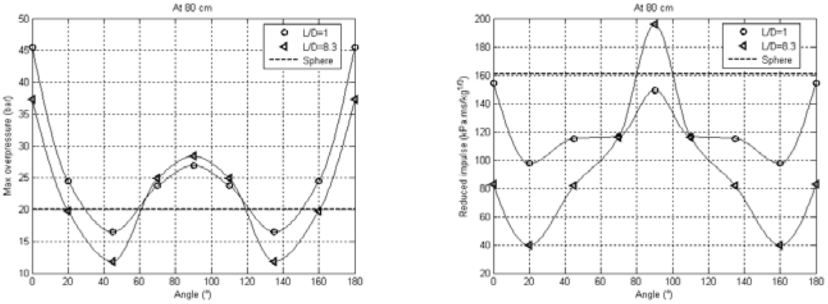


Figure 4. Example of the symmetrical measured pressure profile at a distance of 80 cm around the long cylindrical charge initiated centrally, with the result of the numerical simulation of the same case.

Figure 5 summarizes the results of the different tests for the peak overpressure (Figure 5(a)) and the reduced impulse (Figure 5(b)) at a distance of 80 cm. Both the pressure and the impulse are presented in function of the angle to the axis of the charge (Figure 2 for the definition of the angles). The influence of the shape of the cylinder is significant. With increasing length-to-diameter ratio, the overpressure at the angle of 90° increases and the overpressure at the angles of 0° and 180° decreases. This effect is independent of the distance, although it seems to become more pronounced at larger distances.



(a) (b)

Figure 5. The peak overpressure (a) and the reduced impulse (b) as a function of the observation angle for the centrally initiated EE charge at a distance of 80 cm; the dashed line represents the peak overpressure/impulse for an equivalent spherical mass of the EE.

Similar conclusions can be drawn for the impulses: more effect at the angle of 90° for the longest cylinder (*L/D* = 8.3) and more effect on the axis for the shortest cylinder (*L/D* = 1).

Figure 6 shows pictures taken with the high speed camera of shots with the central initiation. The largest effect on the centreline for the long charge is clearly visible, while the larger effect on the axis can be seen for the short charge.

(a) The cylindrical charge of *L/D* = 8.3 showing symmetry and a large effect on the centreline

(b) The cylindrical charge of *L/D* = 1, showing symmetry and larger effect on the axis

Figure 6. The images taken with the high speed camera for the centrally initiated cylindrical charges, at 1.3 ms after the initiation.

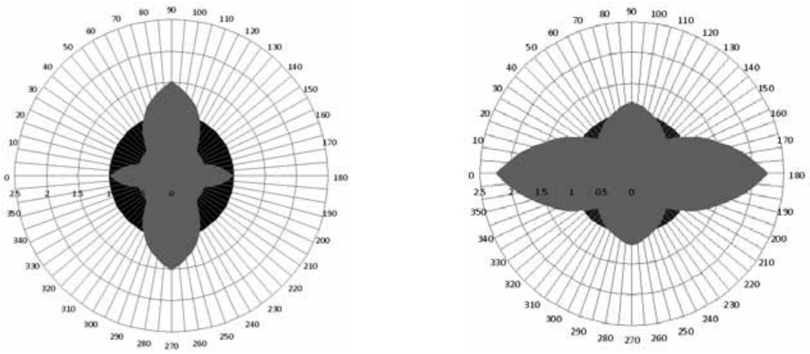
Numerical simulations

In order to confirm the experimental data, numerical simulations have been executed using Autodyn [11]. An axis-symmetrical 2D Eulerian grid is used to simulate the detonation of cylinders of EE. Virtual gauges are placed at every 10° angles. The results for the peak pressure of one case are shown in Figure 4, clearly showing the same trend as the experimental curves. This numerical confirmation increases confidence in both experimental and numerical results. Detailed discussion of the numerical simulations is not included in the scope of this paper.

Discussion

Figure 7 represents the ratio between the maximum overpressure of centrally initiated cylindrical charges at a distance of 110 cm and the maximum overpressure of a sphere at the same distance (represented by the circle with radius 1). The angles are defined as in Figure 2(b), with the angle 0° at the left, the angle 90° on the top, and so on. The "square" cylindrical charge has a less pronounced shape effect at the angle of 90° than the longer charge. A larger effect is produced on the axis of the cylinder (the angles 0° and 180°) by the "square" cylindrical charge than by the longer one. This seems somehow surprising, because of the definition of the distance from the charge. All distances have been measured from the centre of the charge. This means that, for the charge of

L/D = 8.3 of 50 cm length, the pressure gauge at a distance of 80 cm from the centre, is actually at a distance of 55 cm from the edge of the explosive charge. However, the effect of the cylindrical charge of *L/D* = 1 is more important at that point, although the pressure gauge is at a distance of 74 cm from the charge. This means that the effect is in reality even more important than the measurements seem to show.



(a) (b)

Figure 7. Summary of the maximum overpressures for (a) the long and (b) the "square" cylindrical charges at a distance of 110 cm (centrally initiated).

Note as well the presence of zones with weak effects (around the angles 45° and 135°). In these zones (the bridge waves [3]), the cylindrical shape also plays an important role, a reduction of the blast effects can be observed.

The TNT-equivalent can be calculated at each angle, as it has been done for each distance around the spherical charge. Table 3 gives values for the TNT-equivalent in the important directions around the charges. These results show the importance of the function f_4 in Eq. (3). Around the cylindrical charge and at short range, the TNT-equivalent value depends on the position of observation around the charge and the use of one single constant value is irrelevant.

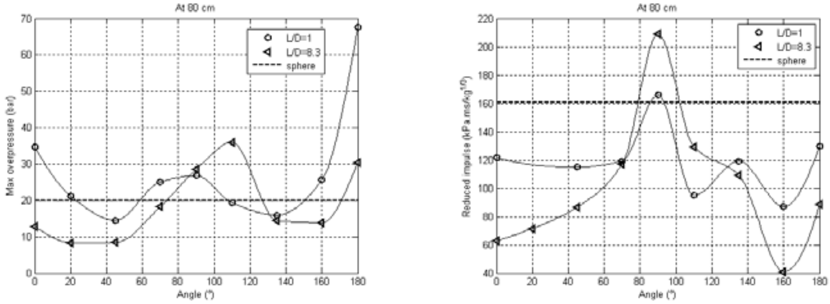
Table 3. Factor f_4 for the peak overpressure

	L/D = 8.3			*L/D* = 1		
Z (m.kg$^{-1/3}$)	0°/180°	45°/135°	90°	0°/180°	45°/135°	90°
0.69	2.39	0.44	1.56	3.33	0.70	1.44
0.94	1.02	0.47	1.80	3.21	0.74	1.28

The influence of location of initiation (*f*$_5$)

Experimental results

The location of the initiation influences the pressure distribution, certainly at the side where the initiation occurs. In the experiments where the initiation point is at one end, it is put at the angle 0°. The pressure at the angle 180° theoretically should not be influenced for the long charges, while for the short ones a certain increase in the pressure can be expected. Figure 8 (b) represents the reduced impulse in function of the angle to the axis of the cylinder. It shows that the position of the initiation does not have any important effect on the impulse: the maximum value is still measured at the angle of 90° but the distribution is not symmetric anymore around this angle. A small shift of the location of the maximum impulse might have occurred but if it is smaller than the angle of 20° (the resolution between two measurement points) it could not have been measured.



(a) (b)

Figure 8. (a) The peak overpressure and (b) the reduced impulse as a function of the observation angle for the one-end initiated explosive charge at a distance of 80 cm; the dashed line presents the peak overpressure/impulse for an equivalent spherical mass of EE.

Contrary to the impulse, the maximum overpressure differs more depending on the location of the initiation. As shown in Figure 8(a), when the detonation is initiated at one end, the angle of the maximum overpressure is moved from 90° to about 110° except for the case of the short cylindrical charge at a distance of 80 cm. We notice that the overpressure at the initiation side is lower too. There is no increase of the maximum overpressure on the opposite side for the long cylindrical charge. The peak pressure for the cylinder with *L/D* = 1 is higher at the opposite side of the detonator than for the central initiation. Similar effects have also been noticed in the numerical simulations and can be expected for the cylinders of small length-to-diameter ratios.

Figure 9 shows images of shots with the off-centre initiation, where the asymmetry can be clearly observed.

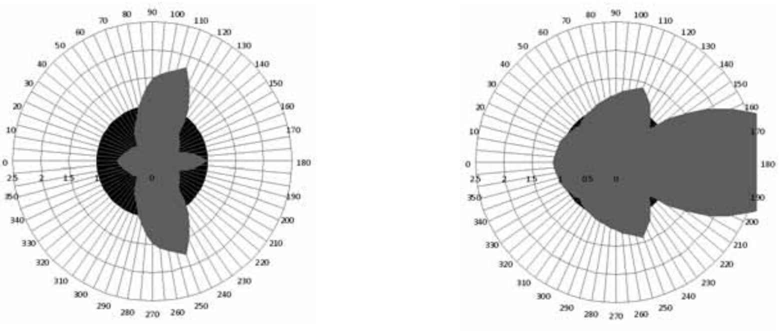
(a) The cylindrical charge of *L/D* = 8.3, showing asymmetry on the axis, but still the largest effect on the centreline

(b) The cylindrical charge of *L/D* = 1, showing clear asymmetry on the axis, and large effect on the axis

Figure 9. The images taken with the high speed camera for the cylindrical charges initiated at one end, at 1.3 ms after the initiation.

Discussion

Figure 10 represents the ratio between the maximum overpressure of the cylindrical charge initiated at one end at a distance of 110 cm and the maximum overpressure of the spherical charge (represented by the circle with radius 1) at the same distance. Clearly visible is the shift of the peak overpressure towards the side opposite to the detonator. Note as well the increased overpressure at that side for charges of small *L/D*, while that effect is not present for the charges of large *L/D*.



(a) (b)

Figure 10. Summary of the maximum overpressures for the long (a) and the “square” (b) cylindrical charges, initiated at one end, at a distance of 110 cm.

The influence of the function f_5 in Eq. (3) is found to be rather small in most of the zones around the charges, except for a few specific regions (on the axis, at the end opposite to the initiation, close to the centreline).

Conclusions

The spherical charges have allowed to determine the TNT-equivalent of the EE for both the peak overpressure and the impulse. The TNT-equivalent values for the overpressure and for the impulse have been found to be respectively 1 and 0.7.

The pressure around two types of cylindrical charges has been studied. In the case of the long thin cylindrical charges the strongest effect can be noticed in the centre, perpendicularly to the axis. For the short thick cylinders a stronger effect can be noticed on the axis. Changing the location of the initiation from the centre to one end does not have an important influence on the impulse distribution but the peak pressure shifts away from the 90°-line towards the side opposite to the initiation point. For the short charges, the effect on the peak pressure on the end opposite to the initiation can be important.

When calculating the TNT-equivalent value of the EE charge, the most important parameters among those studied at the short distance are the effect used to determine the TNT-equivalent and the shape of the charge.

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