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Research paper

The Shooting Tests of Target Perforating Ability, Performed on Cast Concrete Cylinders

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Abstract: In this paper, the first results of the applicability of shaped charges with a single liner, of a conical and of an axially-symmetric elliptical shape, are compared. The shaped charges were of an analogous type. The outer diameter and the height of the shaped charges were 39 and 42 mm, respectively. The mass of the explosive (flegmatized hexogen) in these charges was 27 g. The charges with the conical liner were commercially available. All liners used in these tests were made according to the same technology, as well as being of the same material, *i.e.* electrolytic copper. Two series of tests were carried out for shaped charges with the elliptical liner, *i.e.* 11 and 12 shots, with or without a distance plate between the shaped charge and the concrete shooting model (core), respectively. For comparison, 4 shots for each of these configurations were executed for commercial shaped charges with a conical liner. The distance plate was made of mild steel and its *dimensions were* 50×50×10 mm. All of the concrete cores used were uniform in the shape of a cylinder, with diameter 160 ±10 mm and height 1200 ±10 mm, and were prepared in a single-batch process. The tests were completed under outdoor conditions at ambient temperature.

X-ray computer tomography images, obtained with a measurement accuracy of 0.1 mm, were used to create 3D numerical visualisation of the perforation channels in the concrete cores created by *the* tested shaped charges. The 3D images allowed the depths to be measured, together with the volumes and degrees of uniformity of these channels. On the basis of these images, it was determined that the volume of the perforation channels created when using shaped charges with an elliptical liner were in the range 230-557 cm^3, while the volumes created by commercial shaped charges were in the range 105-201 cm^3. This is because charges with an elliptically shaped liner produced longer perforation channels than their analogues with conical liners.
The tested shaped charges enclosing a single liner of an axially-symmetric elliptical shape assures better opening of a hydrocarbon reservoir in the downhole conditions of oil and gas wells, as compared to its analogous traditional form, with a conical liner.

Keywords: shaped charge, axially-symmetric elliptical liner, hexogen, perforation channel, concrete, X-ray computer tomography, 3D numerical visualisation

Supplementary Information (SI) is available at:
http://www.wydawnictwa.ipo.waw.pl/cejem/Vol-17-Number4-2020/CEJEM_01119_SI.pdf

1 Introduction

Despite shaped charges being in service for over 100 years, the need to improve their parameters is still huge. In civil applications, *e.g.* in material engineering (explosive cutting) and in mining (*e.g.* perforation in boreholes in the mining of hydrocarbons – *i.e.* in the oil and gas industry) [1-4], improvements based on changes in the type of explosive material used are rather excluded. Two explosives, *i.e.* flegmatized both 1,3,5-trinitro-1,3,5-triazinane (hexogen, RDX) and 1,3,5,7-tetranitro-1,3,5,7-tetrazoctane (octogen, HMX), are mostly used as they assure high detonation velocities and pressures, and, when properly homogenized, allow acceptable penetration parameters to be obtained in engineering blasting work [5, 6]. Changes in the arrangement of the explosive charge are still possible, even involving liquids [7], but mostly, researchers have focused on improvements in the liner system, as it allows the cumulative jet velocity to be increased. In other words, the velocity of detonation of HMX- and RDX-based explosives applied in shaped charges reaches approximately 8000 m/s. More specifically, starting from the moment of the point of collision, at a pressure of over 100 GPa, on the axis, near the liner tip, parts of the liner are divided into two axial jets, a faster, cumulative one (which travels at approximately 7000 m/s), and a jet part creating the tail, which travels at approximately 500 m/s. On the basis of the developed computer simulations, *e.g.* Minin *et al.* [8-12], it could be possible to increase the velocity of the cumulative jet to values exceeding 10 000 m/s by way of the so called hyper-cumulation phenomenon.

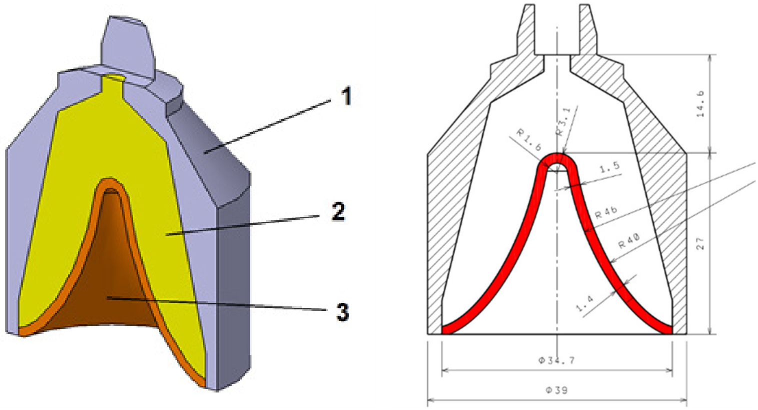
There are a few well known ways of achieving more effective perforation than are available today. Criteria other than deep penetration are also key factors, such as elimination of unwanted side effects, like clogging or deviating axes of perforation channels. However, usually at the beginning of an evaluation of new solutions in the area of shaped charges, the most important factor is the determination of the length of the perforation channel. This parameter depends significantly on the properties of the liner applied to the shaped charge. Commonly, axially-symmetrical shaped charges and their liners enclosed in the form of a cone are used, which is located in the centre of the charge. The most important methods for redesigning the liner system are based on:

- replacing the copper (usually used as the material of the liner), especially with materials of higher density,
- application of reactive liners, *e.g.* [13],
- modification of the shape of the liner, *e.g.* [14-17].

The aim of the present study was to confirm if the method based on the application of the tomographic measurement technique would allow the abilities of shaped charges to penetrate steel and concrete targets to be compared. Moreover, the purpose of this paper is to present the differences in performance characteristics between two types of tested liners for shaped charges, conical and elliptical, from the point of view of their applicability in the oil and gas industry.

2 Materials and Methods

On the basis of numerical analyses, performed for various concepts of shaped charges, charges having the best energetic parameters (a shaped charge with an elliptical liner) were selected and manufactured for these tests (Figures 1 and 2). Electrolytic copper was assumed as the liner material. The mass of the liner was 19 g for solid copper density (ρ = 8.9 g/cm^3), or 18 g for the density of a liner made of copper powder ρ = 8.4 g/cm^3. For the theoretical density of the explosive (flegmatized RDX), 1.891 g/cm^3, the mass of the explosive ought to be 31 g, however in the test conditions a density of 1.65 g/cm^3 was achieved and the mass of explosive in the shaped charge was 27 g.



(a) (b)

Figure 1. Elevation view (a) and cross-sections (b) of the cumulative charge selected for fire-ground testing: 1 – enclosure, 2 – explosive, 3 – liner

Figure 2. Experimental series of the tested elliptically shaped charges

Figure 3 illustrates the test arrangement used for the estimation of the perforation channel creation ability. It was estimated on the basis of direct measurement of the hole, created in effect by igniting (Figure 3, (a, b)) the shaped charge (Figure 3, (c)). The cumulative jet created from the shaped charge was directed vertically downwards, *i.e.* towards the concrete core (Figure 3, (f)), positioned on the ground. Each shaped charge was placed on a spacer (Figure 3, (d)) which was inserted between the charge and the top of either the concrete core or a mild steel plate. The spacer was a sleeve of cardboard with a height of 1 calibre (*ca.* 39 mm). Some shots were performed through an additional barrier in the form of a steel plate (Figure 3, (e)) of dimensions 50×50 mm and 10 mm thick. The type of the mild steel was St3. The steel plates were used alternately in a 2 of 4 shooting test series, presented in Table 1. The aim of using both the spacer and the plate was to simulate more realistically the conditions of firing in a perforating gun, in which some space (simulated by the spacer) is present between the charge and the well wall (simulated by the steel plate). The purpose of the use of a spacer was also to standardize the conditions during the cumulative jet penetration and to fix the cumulative jet inlet shape, and provides for the further possibility of measuring its diameter. The concrete cores (Figure 3, (f)) were prepared by casting into plastic tubes of 160 mm inner diameter and 1200 mm length. These cores were left for 30 days in order for the B-25 concrete to cure. Figure S1 (see SI) illustrates a view of the cores, alone and one core (No. 8) with the shaped charge attached.

The test series are listed in Table 1. 11 shots (Nos. 1-11) in Series EP, as well as 4 shots in Series CP (Nos. 24-27) were performed with the steel plate, whereas 12 shots in Series EW (Nos. 12-23), as well as 4 shots in Series CW (Nos. 28-31) were performed directly (with only the air-gap provided by the spacer) into the concrete target.

Figure 3. A view of a typical test arrangement, used for the steel-concrete target perforating ability test: electrical igniter (a), fragment of detonating cord (b), shaped charge (c), spacer (d), optional steel plate (e) and concrete core (f)

Table 1. Arrangement of firing tests and description of the test series

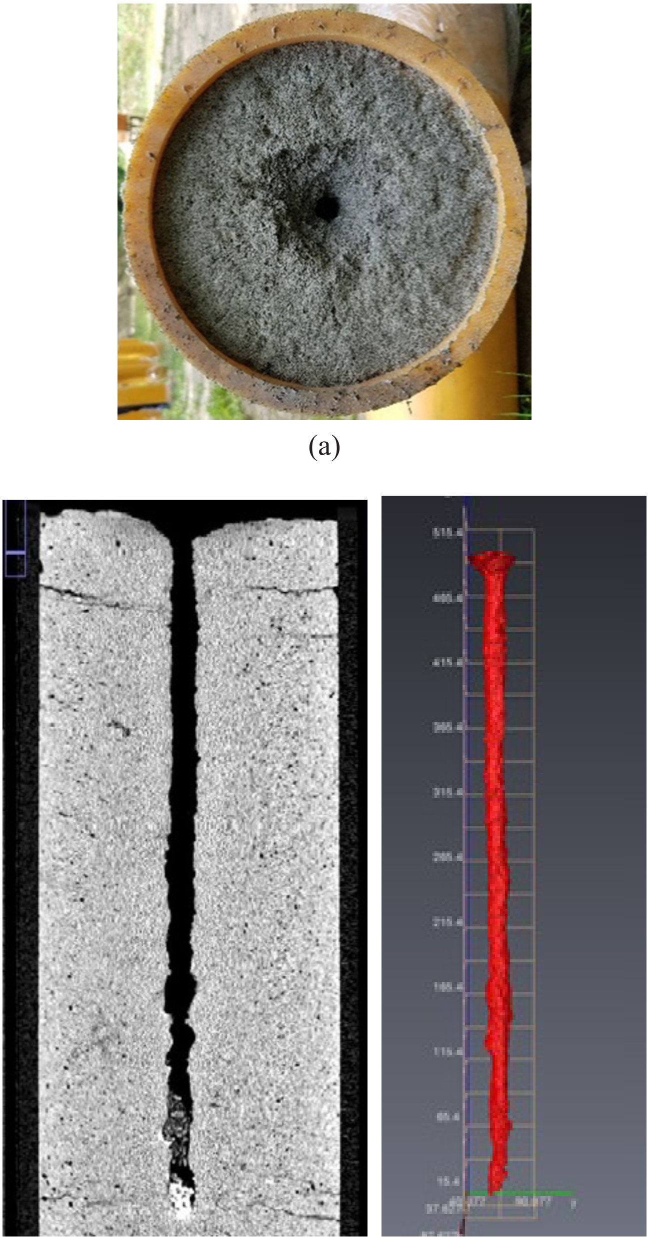
Test Nos.	Test Series			
	EP	EW	CP	CW
	Shaped charge with			
	elliptical liner, and		conical liner, and	
	with steel plate	without steel plate	with steel plate	without steel plate
1-11	YES	–	–	–
12-23	–	YES	–	–
24-27	–	–	YES	–
28-31	–	–	–	YES

In order to determine the depth and quality of the perforation channels, *i.e.* to visualize the geometry of the channel being created, the perforated concrete cores were subjected to X-ray computer tomography (XCT) scanning. The measurement accuracy of the applied XCT system was 0.1 mm. The XCT images were processed using specialized computer software into 3D images of the perforation channels, enabling the volumes of the channels to be computed. The results obtained for the concrete cores scanned with the XCT scanner include the length of the perforation channel, the minimum and maximum hole diameters, and the diameter averaged for the whole channel.

3 Results and Discussion

3.1 Images

The top view of a concrete core, the XCT image and the 3D view of the perforation channel for Tests Nos. 1, 12, 27 and 31, are shown in Figures 4-7, respectively. Figures S2-S11 (see SI) show the analogous results for Tests Nos. 2-11 (Test Series EP), respectively. Figures S12-S22 (see SI) show the analogous results for Tests Nos. 13-23 (Test Series EW), respectively. Figures S23-S25 (see SI) show the analogous results for Tests Nos. 24-26 (Test Series CP), respectively. Figures S26-S28 (see SI) show the analogous results for Tests Nos. 28-30 (Test Series CW), respectively.

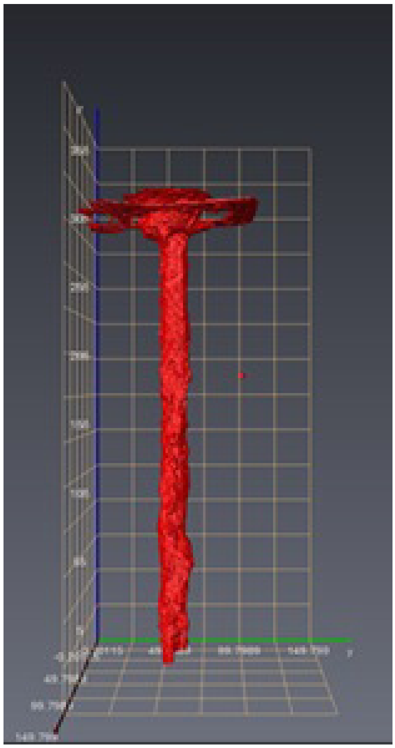


(a)

(b) (c)

Figure 4. Test No. 1 (Series EP): view from the top (a), XCT image of the perforated concrete core (b), and the 3D view of the perforation channel (c)

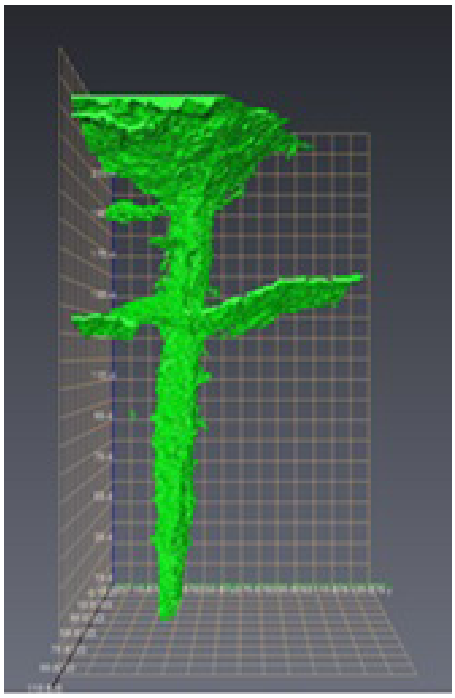
(a)



(b) (c)

Figure 5. Test No. 12 (Series EW): view from the top (a), XCT image of the perforated concrete core (b), and the 3D view of the perforation channel (c)

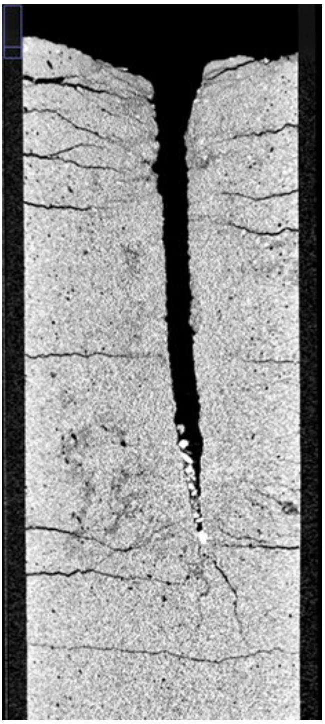
(a)

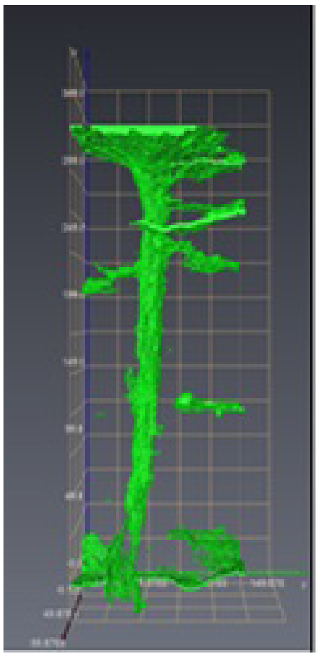


(b) (c)

Figure 6. Test No. 27 (Series CP): view from the top (a), XCT image of the perforated concrete core (b), and the 3D view of the perforation channel (c)

(a)





(b) (c)

Figure 7. Test No. 31 (Series CP): view from the top (a), XCT image of the perforated concrete core (b), and the 3D view of the perforation channel (c)

3.2 Lengths of perforation channels

Figure 8 shows the depths of concrete core penetration for all of the tested charges. During fire-ground testing using the standard shaped charges, the top concrete layer (*ca.* 3 cm) was crushed and detached from the concrete solid block. This phenomenon was included in the analysis, *i.e.* the lengths of the perforation channels for these charges were supplemented with the thickness of these detached parts.

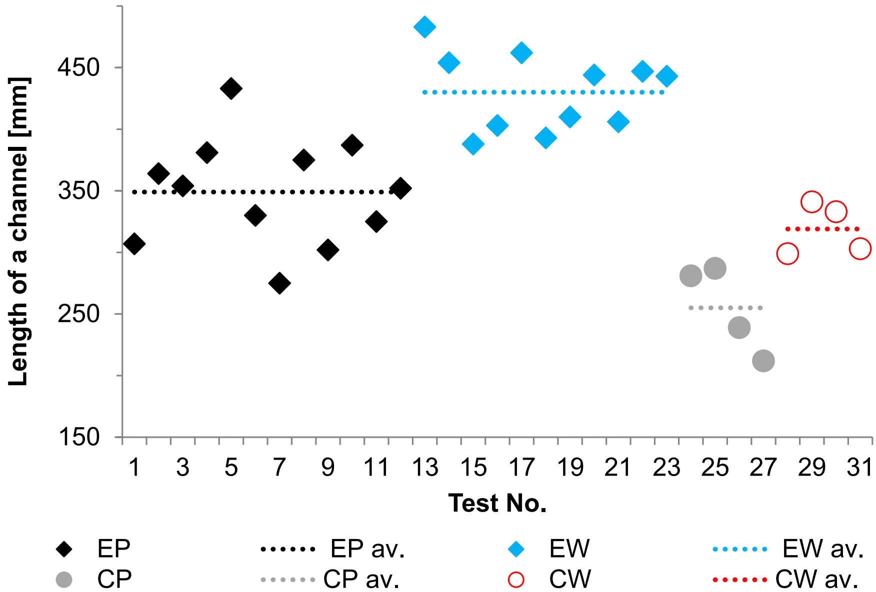


Figure 8. The lengths of the perforation channels measured from XCT images, for shaped charges with:
− elliptical liner (– with (EP, ♦) and without (EW, ♦) steel plate), and
− conical liner (– with (CP, ●) and without (CW, ○) steel plate), and calculated average values – dashed lines:
– EP av. = 349 mm, – EW av. = 430 mm, – CP av. = 255 mm, – CW av. = 319 mm), respectively

3.3 Diameters of perforation channels

As can be seen on the XCT radiographs, the sections of the individual perforation channels were not uniform; there were wider and narrower clearances of the channel, occurring in an irregular manner. The scale of this phenomenon was quantified in Figures S29 and S30 (see SI) and for average diameters in Figure 9. The penetrated steel plates are shown in Figure S31 (see SI). Two plates, located in the lower right corner of Figure S31 (a), are from the tests Nos. 24 (Series CP) and 28 (Series CW), and an additional series of 3 photos (Figure S31(b)), where commercial (reference) shaped charges were used for comparative purposes. For the shots executed directly into the concrete target, the results are presented in Figures 8 and S30 (see SI). The maximum penetration of the perforation channel was L_{max} = 483 mm, and the shortest channel was measured as L_{min} = 388 mm. A lower divergence of the results obtained in the whole series was also observed (Figure 10).

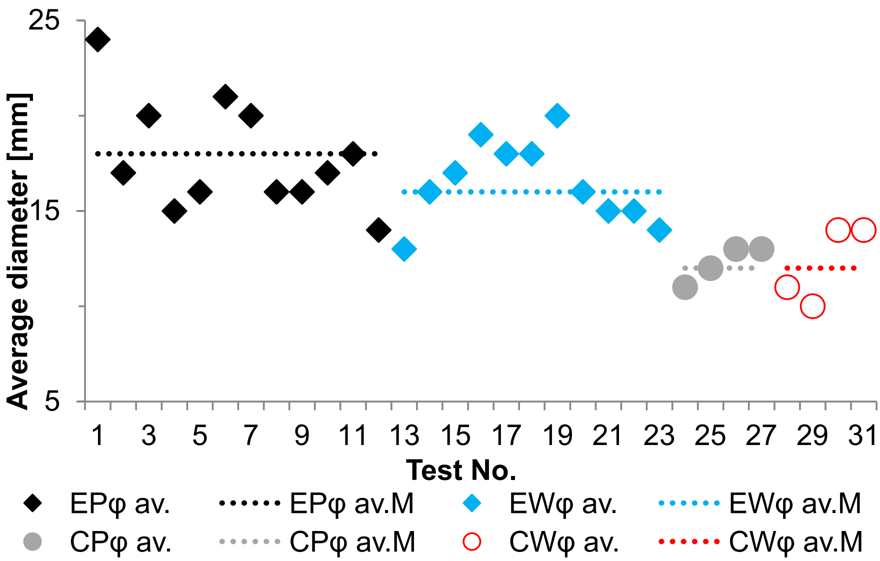


Figure 9. Average diameters of the perforation channels measured from the XCT images, for shaped charges with:
− elliptical liner (– with (EP, ♦) and without (EW, ♦) steel plate), and
− conical liner (– with (CP, ●) and without (CW, ○) steel plate), and calculated average values – dashed lines: – EP av. = 18 mm, – EW av. = 16 mm, – CP av. = 12 mm, – CW av. = 12 mm), respectively

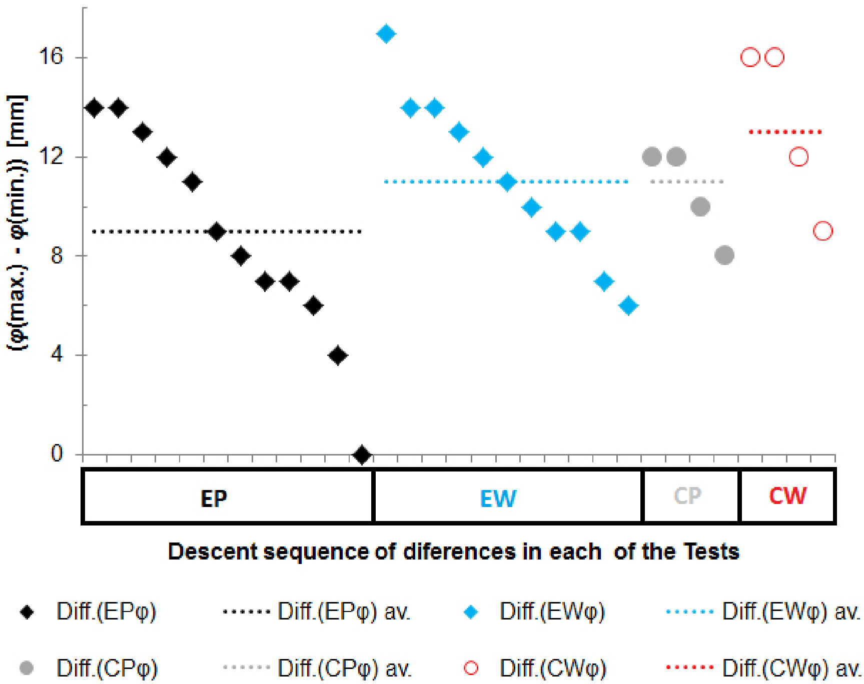


Figure 10. Dispersion of the diameters of perforation channels measured from the 3D images and the calculated average values – dashed lines: – EP av. = 9 mm, – EW av. = 11 mm, – CP av. = 11 mm, – CW av. = 13 mm), respectively

It has been noted during the analysis of the 3D photos of the created holes that the opening created as a result of using a shaped charge with an elliptical liner, has a shape similar to that from an irregular cylinder. The perforation channels created as a result of shaped charge action with a conical liner look different, they are closer in appearance to that from an irregular cone. Additionally, the channels created as a result of shaped charges with conical liners deviated from the axis of the concrete core. Another feature, clearly visible in the 3D photos of the channels created by using shaped charges with conventional liners, were extensive fissure zones at the inlet to the channel and sometimes in other locations, which was not observed in the cases where hybrid shaped charges were use. A common feature of all charges used was the inlet to the perforation channel, being funnel shaped.

3.4 Volumes of perforation channels

The volumes of the individual perforation channels are shown in Figure 11. The values for the channels created by application of shaped charges with an elliptical liner are considerably larger than the channels created using conventional shaped charges. It was concluded, on the basis of data obtained during tests with the new charges with an elliptical liner that it penetrated concrete cylinders much better, which, in relation to a hydrocarbon reservoir, would result in its better opening as compared to conventional shaped charges.

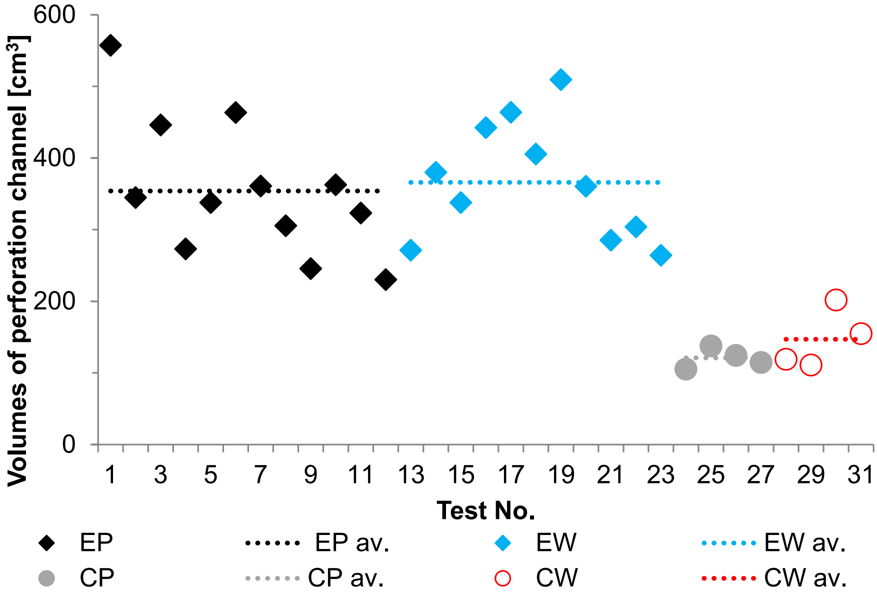


Figure 11. Volumes of the perforation channels measured from the 3D images for shaped charges with:
– elliptical liner (– with (EP, ♦) and without (EW, ♦) steel plate), and
– conical liner (– with (CP, ●) and without (CW, ○) steel plate), and calculated average values – dashed lines:
– EP av. = 354 cm^3, – EW av. = 366 cm^3, – CP av. = 121 cm^3, – CW av. = 147 cm^3), respectively

4 Summary

The results obtained for liners of both elliptical and conical shapes were compared on the basis of their influence on their perforation channel penetrating ability in concrete target stands. The results from computer tomography scanning of 31 concrete cores include the length of the perforation channel, the minimum and maximum diameter of the inlet hole, the averaged value for the whole sample population, as well as the volume of the individual perforation channels. For the shots executed directly into a concrete target, the maximum penetration of the perforation channel was observed as L_{max} = 483 mm, and the shortest channel in the series was L_{min} = 303 mm. A lower divergence of the results obtained was observed for the tests series with the steel plate. The perforation channels produced in the concrete core with the use of this additional metal target achieved depths in the range 211-433 mm.

By means of specialized computer software, the volumes of the individual perforation channels were calculated. The perforation channels created with using a conical liner had volumes in the range 105-201 cm^3. The perforation channels created using elliptically shaped charges, had volumes from 230 to 557 cm^3, which in 'downhole conditions' translates into better opening of a hydrocarbon reservoir. The most important observation that has been found in these results, is that the tested elliptically shaped charges produced longer perforating channels in firing tests executed into a concrete target, than its classical counterpart.

The lack of 100% repeatability can be justified by the fact that it was a prototype series. Because of this, further analysis of the elaboration process will continue and be verified under real conditions, that is on the fire-ground.

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