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Numerical modelling of shaped charges with an elliptical liner

Modelowanie numeryczne ładunków kumulacyjnych z wkładkami eliptycznymi

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ABSTRACT: The article elaborates upon the numerical modelling of shaped charges equipped with various types of elliptical (trumpet-like) liners. Three various geometries of shaped charges with elliptical liners were modelled, which have been compared against a model of a traditional shaped charge with a conical liner. The charges were compared for maximum pressure during charge detonation, velocity of cumulative jet, kinetic energy obtained, as well as length of cumulative jet after a 15 µs interval. The modelling of shaped charges with elliptical liners was aimed at improvement of perforation job parameters in oil wells. Realization of the perforation job is a key element, enabling initialisation of production from a given reservoir of hydrocarbons. The purpose of perforation is the creation of a channel series, perpendicular to borehole axis, penetrating the wall(s) of the casing, cement layer and formation rock, in order to make a hydraulic connection of the borehole with the reservoir of hydrocarbons. The longest possible perforation channels are desired, which enable better completion of the reservoir. Currently, for a perforation job, shaped charges of axial symmetry equipped with conical liners made of copper powders are used, which enable achieving a cumulative jet velocity of 7000 m/s, which can penetrate up to 1 m of undisturbed rock in favourable conditions. The modelled shaped charges, featuring the elliptical liners, achieved much better values of pressure, maximum velocity, kinetic energy and channel length within the same time interval as compared to the results of modelling a cumulative jet created by standard shaped charge. However, it should be remembered that in order to confirm the effectiveness of target penetration by modelled shaped charges, their physical models should be fabricated and tested in ground-fields experiments.

Key words: perforation, shaped charges, elliptical liner, numerical modelling.

STRESZCZENIE: Artykuł został opracowany na podstawie wyników modelowania numerycznego ładunków kumulacyjnych z różnymi typami wkładek eliptycznych (trąbkowych). Zamodelowano trzy geometrie ładunków kumulacyjnych z wkładkami eliptycznymi, które porównano do modelu klasycznego ładunku kumulacyjnego z wkładką stożkową. Ładunki porównano pod względem maksymalnego ciśnienia podczas detonacji ładunku, prędkości strumienia kumulacyjnego, uzyskanej energii kinetycznej oraz długości strumienia kumulacyjnego po czasie 15 µs. Celem modelowania ładunków kumulacyjnych z wkładkami eliptycznymi była poprawa parametrów zabiegu perforacji w odwiertach naftowych. Wykonanie perforacji to kluczowy element, dzięki któremu możliwe jest zapoczątkowanie produkcji w danym złożu węglowodorów. Perforacja ma na celu wykonanie serii otworów prostopadłych do osi odwiertu, przebijających ścianki rur okładzinowych, cementu oraz skałę złożową, aby połączyć hydraulicznie otwór wiertniczy i złoże węglowodorów. Pożądane są jak najdłuższe otwory perforacyjne, które wraz ze wzrostem długości lepiej udostępniają złoże. Obecnie do perforacji wykorzystuje się ładunki osiowosymetryczne ze stożkowymi wkładkami kumulacyjnymi wykonanymi z proszków miedzi, które osiągają prędkość strumienia kumulacyjnego na poziomie 7000 m/s i penetrują do 1 m calizny skalnej przy sprzyjających warunkach. Zamodelowane ładunki kumulacyjne z wkładkami eliptycznymi osiągnęły znacznie lepsze wartości ciśnienia, prędkości maksymalnej, energii kinetycznej oraz długości po czasie dla strumienia kumulacyjnego w porównaniu do wyników modelowania strumienia powstałego z klasycznego ładunku kumulacyjnego. Należy jednak pamiętać, że aby potwierdzić skuteczność przebijania celów przez zamodelowane ładunki kumulacyjne, należałoby wykonać ich fizyczne modele i poddać je testom na poligonie doświadczalnym.

Słowa kluczowe: perforacja, ładunki kumulacyjne, wkładka eliptyczna, modelowanie numeryczne.

Introduction

A shaped charge is an explosive charge that locally focuses the effect of a detonation (Frodyma and Koślik, 2016). Contemporary shaped charges have a cumulative recess in the form of a concave, metallic hemisphere or cone (the liner). The explosive is located over the liner, and the whole unit is enclosed in a metallic housing. When the explosive is detonated, the metallic liner is compressed and pushed forward, creating the cumulative jet (Nowak and Smoleński, 1974; Walter, 1998). Shaped charges are

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used in military, civil and mining applications, e.g. perforation in boreholes for exploration of hydrocarbons (Kupidura et al., 1998; Wilk, 2008; Elbeih et al., 2018).

The explosives (shooting materials) are used in oil and gas mining mostly when making channels (perforation) between the casing string and hydrocarbon reservoir. During perforation, the perforator is run downhole and subsequently fired at the desired depth. Running the perforator downhole can be done via wireline or drilling string/tubing in the case of strongly inclined or horizontal boreholes (Frodyma and Wilk, 2007). Perforation is executed in order to initiate production from the borehole. The aim of this is the creation of a channel series in order to make a hydraulic connection of the borehole with the hydrocarbon reservoir. The perforation channels should be as long as possible, uniform, featuring adequate hydraulic conductivity, at a density from several up to a dozen or so per running metre (Habera and Frodyma, 2008).

The shaped charges commonly used for perforating boreholes comprise a liner in conical form. The liner is located in the centre of an axially-symmetrical shaped charge. Deformation of the liner under the action of explosive detonation is critical during the creation of a cumulative jet. Structures of liners are based on powdered metals, which provide a jet density sufficient for deep penetration without unwanted side effects, e.g. clogging perforation channels. Copper is most frequently used in the production of cumulative liners. The cumulative liner is underlined with explosives, most often Hexogen (RDX) and Octogen (HMX), i.e. explosives with a high velocity and detonation pressure (Perforating Services, 1993; Zygmunt et al., 2014; Kształt ładunków kumulacyjnych, 2020). The whole charge is enclosed in a metallic housing.

Computer modelling of complex shapes proved to be a very important tool for testing shaped charges, for which completion of analytical computations is impossible. This means that a given issue can be simulated in the computer, making the necessity of building a prototype needless, which greatly facilitates the design process (Shekhar, 2012; Feng et al., 2013).

Modelling of their set-ups is performed by means of, for example, the Finite Element Method (FEM), based on solving differential equation system with division on finite elements, for which the solution is approximated by specific functions, and completing the computations only for nodes of this division.

By means of FEM, it is possible to simulate the creation of a cumulative jet together with its most important parameters, such as: maximum pressure in the system, velocity of the cumulative jet together with kinetic energy created by the charge. It is possible to arbitrarily change the parameters in the course of modelling, e.g. thickness of the liner, its shape, the material used for its fabrication, as well as to select the explosive (Fedorov et al., 2015; Cheng et al., 2018).

Materials and methods

Analyses of the forming processes of shaped charges were performed by means of computer modelling in the Ansys software package, Ls-dyna and Autodyn modules.

The Ls-dyna is a system representing the geometrical structure. It was discretised with the use of grid adaptation tools, the so-called ALE method (Arbitrary Lagrangian-Eulerian), which is very well suited for description of fast changing phenomena, such as the impact of a shock wave on its surroundings or the creation of a cumulative jet. The elements are defined by eight nodes. Subsequently, each node, velocities and accelerations are transferred in all directions X, Y and Z.

Within the Ansys Autodyn software environment, construction of models was based on Euler's algorithms, and the geometry of individual systems was constructed on a finite element grid (mesh). The Euler's domain is a more stable computational system for very fast processes, such as explosion propagation, collision of jets, fragmentation of housing, etc., in which very high deformations occur, as compared to the Lagrange algorithms. In the case of description of such type, the discrete model is moved onto the background of a finite element grid.

For the mathematical description of phenomena occurring during an explosion and shock wave propagation, deformation and acceleration of liners, equations of state (EOS) were used, describing physical processes of conversion. In flow analyses (for highly non-linear dynamics), the description of materials should include equations of state, describing constitutive laws, characterising rapidly changing stress and strain. The Johnson-Cook model, combined with the Gruneisen equation of state (EOS), provides a very good description of materials under dynamical influences during the detonation process, such as creation of a cumulative jet (Habera et al., 2011).

Four models of shaped charges were prepared: traditional shaped charge with a conical liner made of copper, shaped charge with elliptical liner I, shaped charge with elliptical liner II, and shaped charge with elliptical liner II together with a lens.

The following material data was assumed for modelling all the charges: the enclosure of the shaped charge made of steel, the cumulative liner made of copper, with base diameter equal to 34.7 mm and 18 g mass, RDX phlegmatised explosive, 21 g mass for the traditional shaped charge and 26 g for shaped charges with elliptical liners.

Construction of the system was performed in the form of a spatial, axially-symmetrical body (3D) in the form of a single quarter. The model of the shaped charge was placed within a cylindrical space (air), 70 mm diameter and 135 mm height. The possibility of observing the jet being created and its front part over the distance of two calibres (69.4 mm) was assumed, starting from the base of the shaped charge/cumulative liner.

Furthermore, some model simplifications were assumed, not influencing proper functioning of the model and results of the analysis (simplifications concerned the geometry of housing - chamfering of edges and point-wise initiation of detonation).

All shaped charges, the numerical analyses of which are presented, have identical steel housings, dedicated for PRS 114 perforators (the type of housing in the case of ŁOKT-Fe-33-150 shaped charge, developed by Department of Shooting and Enviromnental Engineering – National Research Institute).

Shaped charge with standard conical liner

A standard shaped charge with a conical liner, having an apex angle $\alpha = 53°$ (Fig. 1), was assumed for modelling.

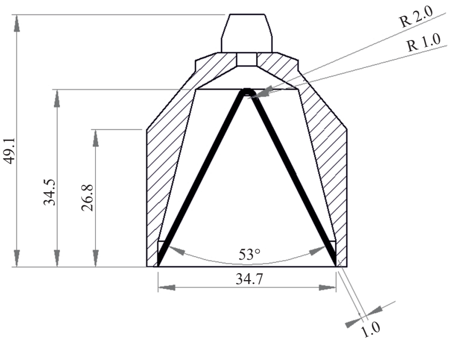

Fig. 1. Sectional view of traditional shaped charge with conical liner made of copper

Rys. 1. Przekrój przez klasyczny ładunek kumulacyjny z wkładką stożkową wykonaną z miedzi

Shaped charge with elliptical liner I

The shaped charge with an elliptical liner, having an apex angle $\alpha = 50°$ that expands progressively and forms a trumpet shape (Fig. 2), was assumed for modelling.

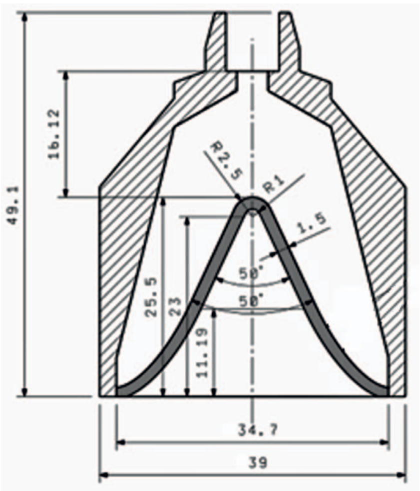

Fig. 2. Sectional view of shaped charge with elliptical liner I made of copper and individual dimensions of the charge

Rys. 2. Przekrój przez ładunek kumulacyjny z miedzianą wkładką eliptyczną I wykonaną z miedzi oraz poszczególnymi wymiarami ładunku

Shaped charge with elliptical liner II

The shaped charge with an elliptical liner, having an apex angle $\alpha = 31.8°$ that expands progressively and forms a trumpet shape (Fig. 3), was assumed for modelling.

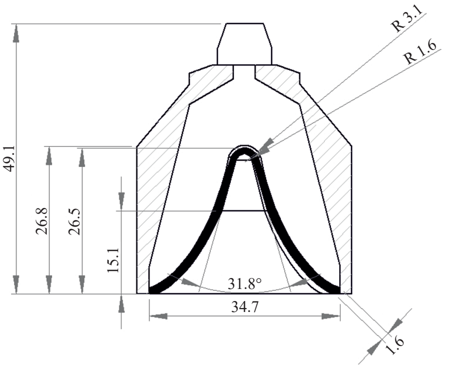

Fig. 3. Sectional view of shaped charge with elliptical liner II and individual dimensions of the charge

Rys. 3. Przekrój przez ładunek kumulacyjny z miedzianą wkładką eliptyczną II wykonaną z miedzi oraz poszczególnymi wymiarami ładunku

Shaped charge with elliptical liner II and a lens

The shaped charge with an elliptical liner, having an apex angle $\alpha = 31.8°$ that expands progressively and forms a trumpet shape (Fig. 4) was assumed for modelling. In the upper part of the charge, within the explosive mass, a detonation lens was modelled. Its application enables the obtaining of a toroidal shape of the detonation wave front and later enables the evolving of an adequate impact surface on the cumulative liner. The detonation lens was made of Teflon.

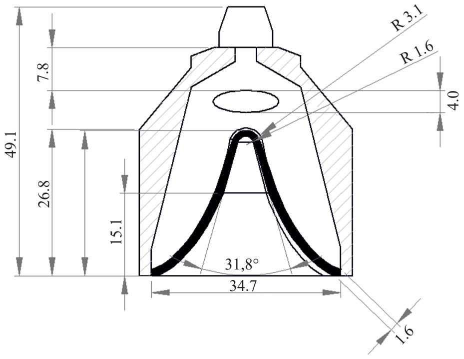

Fig. 4. Sectional view of shaped charge with elliptical liner II and the lens, along with key dimensions of the charge

Rys. 4. Przekrój przez ładunek kumulacyjny z miedzianą wkładką eliptyczną II oraz z soczewką z zaznaczonymi najważniejszymi wymiarami ładunku

Results and Discussion

As a result of modelling, some values were obtained and compiled in Table 1.

Table 1. List of most important parameters obtained during modelling of shaped charges

Tabela 1. Zestawienie najważniejszych parametrów uzyskanych podczas modelowania ładunków kumulacyjnych

Charge	Detonation of shaped charge	Maximum recorded velocity of the jet	Maximum recorded pressure of the jet	Kinetic energy of liner
	[µs]	[m/s]	[GPa]	[kJ]
Shaped charge with conical liner	4.8	6070	35.7	23.3
Shaped charge with elliptical liner I	4.8	6750	47.9	31.0
Shaped charge with elliptical liner II	4.8	7849	65.0	30.2
Shaped charge with elliptical liner II and a lens	4.8	7857	70.0	23.5

The analysis of data contained in Table 1 enabled the authors to observe that the modelled shaped charges with elliptical liners achieved much better parameters of the maximum recorded velocity of the cumulative jet, maximum pressure value of the cumulative jet and kinetic energy value of the cumulative liner (jointly the jet and the slug), as compared to a traditional shaped charge. All modelled shaped charges were detonated after a time of 4.8 µs. The shaped charges with elliptical liner II are characterised by the best parameters, influencing target penetration. Both the shaped charges achieved similar parameters of maximum jet front velocity, 7849 and 7857 m/s, respectively. The charges differ when comparing the achieved maximum pressure generated within the system. The maximum pressure for a shaped charge with an elliptical liner was 65 GPa, while for shaped charge with an elliptical liner and a lens, 70 GPa. Values of kinetic energy are also different in the case of these two shaped charges, but better values were achieved by the shaped charge with elliptical liner II without a lens, and this charge will likely have the best target penetration abilities.

The remaining charges exhibit slightly lower parameter than the shaped charges mentioned above. The shaped charge with elliptical liner I achieved a maximum jet front velocity equal to 6750 m/s, maximum jet pressure at 47.9 GPa level and kinetic energy equal to 31 kJ. The worst parameters were seen in the traditional shaped charge with a conical liner, which a generated maximum jet front velocity equal to 6070 m/s, maximum pressure equal to 35 GPa and kinetic energy at a level of 23.3 kJ.

The lengths (range) of individually modelled cumulative jets at a time of 15 µs are compared in Figure 5. The modelling of formation of the cumulative jet was carried out in air.

It has been found, when comparing the lengths of cumulative jets after 15 µs, that the best lengths were achieved by the shaped charges, which gained the best parameters during modelling: shaped charge with elliptical liner II (68% longer than the jet of the standard shaped charge) and shaped charge with elliptical liner II and a lens (80% longer than the jet of the standard shaped charge). The jet of the shaped charge with elliptical liner I was 42% longer than the jet of the standard shaped charge.

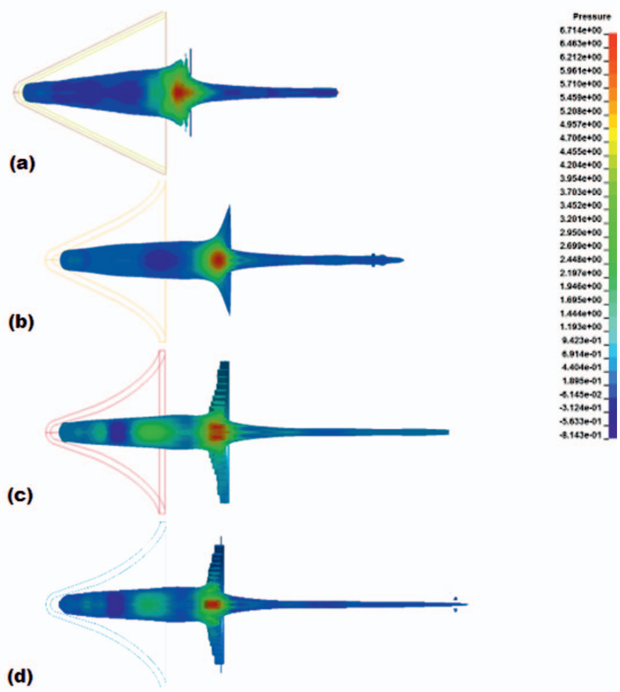

Fig. 5. Compared ranges of cumulative jets along with pressure envelopes after a time of 15 µs for modelled shaped charges: (a) traditional shaped charge with a conical liner made of copper, (b) shaped charge with elliptical liner I, (c) shaped charge with elliptical liner II, and (d) shaped charge with elliptical liner II together with a lens

Rys. 5. Zestawione ze sobą strumienie kumulacyjne wraz z konturami ciśnienia po czasie 15 µs dla zamodelowanych ładunków kumulacyjnych: (a) klasyczny ładunek kumulacyjny z wkładką stożkową wykonaną z miedzi, (b) ładunek kumulacyjny z wkładką eliptyczną I, (c) ładunek kumulacyjny z wkładką eliptyczną II, (d) ładunek kumulacyjny z wkładką eliptyczną II oraz z soczewką

Conclusions

The work included several numerical analyses, consisting of modelling various versions of axially-symmetrical shaped charges, the construction of which provides justified hopes for obtaining overstandard utilitary parameters, which translates to a significant increase in the target penetration ability (perforation channel sinking). The key parameters and quantities characterising the penetration ability of a cumulative jet were estimated in an analytical manner, namely: (a) pressure of the cumulative jet, (b) velocity of the cumulative jet, (c) kinetic energy of the cumulative liner. Consideration was given to three variants of shaped charges with elliptical liners, analysing their operation in the context of increasing target penetration abilities, and they were also compared with a traditional shaped charge equipped with a conical liner. It has been determined on the grounds of the analyses that all newly developed charges are characterised with increased operational parameters that influence target penetration: shaped charge with elliptical liner I, shaped charge with elliptical liner II, shaped charge with elliptical liner II with a lens. The parameters of these charges are as follows – (a) maximum recorded pressure in axis of cumulative jet action was 47.9, 65 and 70 GPa, respectively, (b) maximum velocity of the moving cumulative jet – its front part was 6750, 7849 and 7857 m/s, respectively, (c) kinetic energy of the liner was 31, 30.2 and 23.5 kJ, respectively. The parameters of the traditional shaped charge were as follows: maximum recorded pressure in axis of cumulative jet action was 35 GPa, the maximum velocity of the moving jet was equal to 5920 m/s, and the kinetic energy of liner was 23.3 kJ. The penetration abilities of the newly developed charges are certainly influenced by the base weight of a press moulded explosive, which amounted to 26 g, i.e. 5 g more than the modelled traditional shaped charge. Furthermore, the lengths of cumulative jets after an elapsed time of 15 µs were compared. The cumulative jet in shaped charges with elliptical liner I (42%) and elliptical liner II (68%) and the shaped charge with elliptical liner II and lens (80%) is significantly longer compared to the remaining shaped charges.

The modelled charges with a conical liner demonstrate better target penetration abilities, which directly translates into the creation of perforation channels having a higher volume, resulting in a better hydraulic connection between the reservoir of hydrocarbons and the casing string. However, in order to confirm these properties, it would be necessary to make physical models of these charges and subject them to testing.

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