2. Показано, что скорость схлопывания $w_с$ соответствует среднему значению скорости точек перегиба $w_п$ (датчики на внутренней поверхности КО) и экстремумов $w_э$ (датчики на внешней поверхности КО).

3. Установлено, что численные расчеты скорости схлопывания удовлетворительно совпадают с данными инженерной методики работы [1] только для кумулятивных зарядов без корпуса. Для кумулятивных зарядов с корпусом численные расчеты и данные инженерной методики существенно отличаются друг от друга для области основания облицовки.

4. Предложена поправка в формулу расчета времени прихода боковой волны разрежения для инженерной методики работы [1], пропорциональная времени двойного пробега ударной волны по толщине корпуса, повышающая точность расчета скорости обжатия в 1,2 раза для области основания КО.

5. Для оценки пробивного действия корпусных КЗ сложной конструкции (например, использующих торцовые поджимные гайки, облицовки с цилиндрическими “юбками” и др.) целесообразно использовать разработанную численную методику расчета скорости обжатия с последующей подстановкой полученных результатов в инженерные методики для оценки пробивного действия.

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NUMERICAL ANALYSIS OF LINER COLLAPSE VELOCITY

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Engineering methods of calculating shaped charge effect (see, for example, [1, 2]) are widely used in research and engineering practice. The main advantage of engineering methods is their rapid calculation capacity, while the main disadvantage consists in the use of quite a few allowances and approximations in constructing mathematical relationships underlying their basis. Such approximations adversely affect accuracy of the calculations, especially while analyzing shaped charges of a complex structure (e.g., those using gland nuts, shaped charge liners with cylindrical skirts, thick-walled casing parts, etc.).

Numerical calculations, based on the methods of finite differences and finite elements, allow us to conduct a thorough examination of the engineering methods, including their fundamental principles and allowances underlying their basis. This examination is especially important for creating algorithms and programs for evaluating the impact that technological errors have on the penetration performance of a shaped charge (SC), where the engineering methods and their elements are used as components of more complicated methods and are being used, for example, to calculate the liner collapse velocity w_c derivatives according to the parameters of a SC construction [3, 4]. In engineering methods by w_c we usually mean velocity of a liner after it being thrown by products of detonation of the explosive at the moment of jet formation.

The main goal of this work is to improve the accuracy of analyzing liner collapse velocity in the engineering methods [1]. In order to reach this goal we have developed a method of numerical analysis of liner collapse velocity, a thorough comparison of the results of analyzing liner collapse velocity has been carried out, a thorough comparison of the results of analyzing liner collapse velocity, achieved by both numerical and engineering methods, has been carried out, corrections for the delay in arrival of the expansive wave to the regarded liner section from the side face of the SC have been made and justified.

Numerical calculations of liner collapse velocity were conducted on a lab charge of 46 mm in diameter with copper liner structurally designed both without an outer casing (SC №1) and with a steel casing 3 mm thick (SC №2).

All calculations have been performed through the software ANSYS AUTODYN in the Eulerian frame in accordance with the work recommendations [5, 6]. The liner was made out of copper (COPPER) with constitutive equation Shock, explosive – octogene (HMX) with constitutive equation JWL, lens – plexiglas (PLEXIGLAS) with constitutive equation Shock. The casing was made out of plain carbon steel with 1% manganese content, as a constitutive equation we have chosen Shock impact adiabat.

The size of the cell used for this task was 0,2 mm x 0,2 mm. To study the dynamics of collapse velocity of different liner elements its outer and inner surfaces were equipped with moving detectors secured together with the liner material. The detectors were set in pairs on the shortest possible distance from one another – the dark dots on the liner surface marked by numbers 1 – 26 (fig. 1). The detectors were designed for reading off physical parameters at each given moment during the liner collapse process and further jet development.

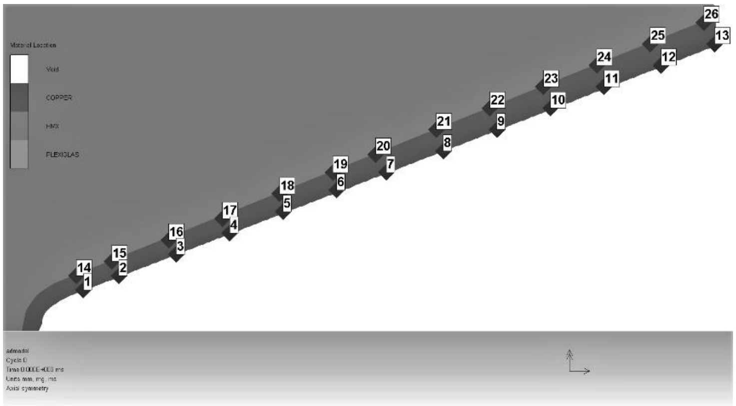
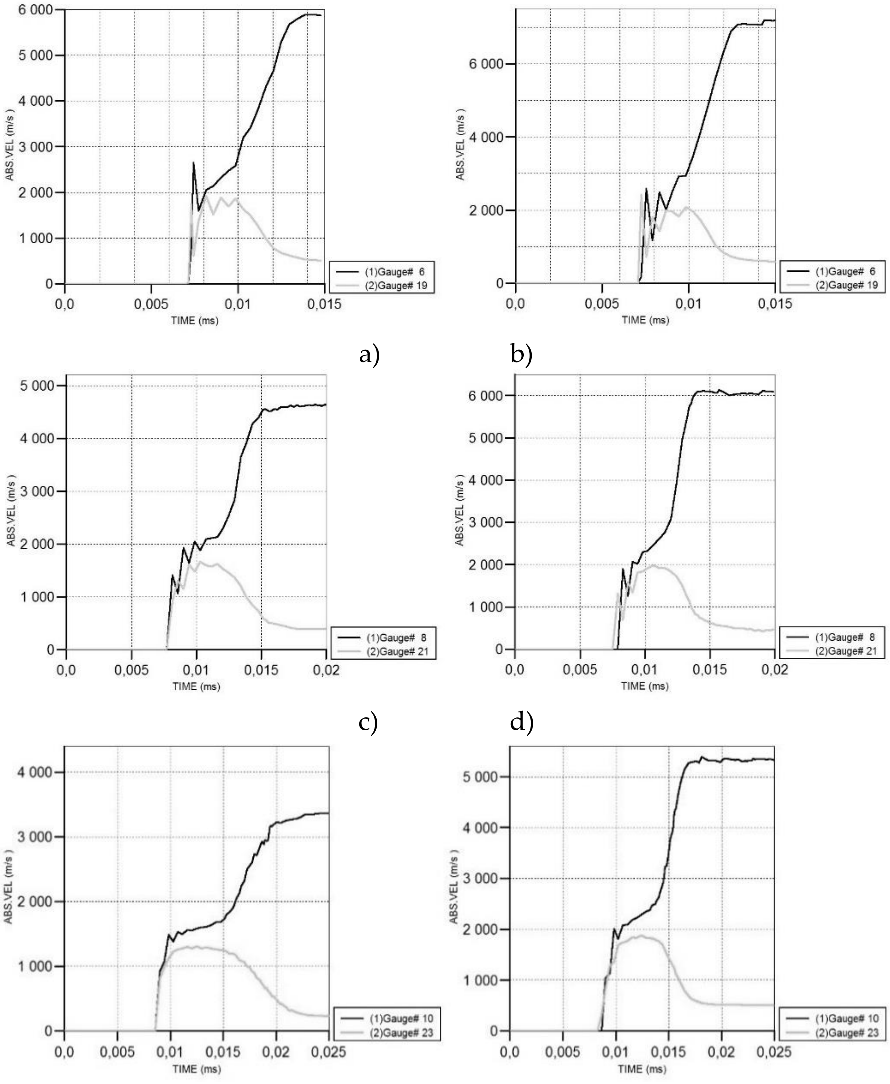


Figure 1. Initial position of the moving detectors on the liner surface

Calculations have shown that the detectors lying opposite to each other on the outer and inner surfaces change their velocity $w(t)$ the following way: the detectors on the inner surface (1 – 13) accelerate at first, after which their velocity reduces, followed by its abrupt increase, which results in the fact that by the time of slug formation velocity of the detectors goes to the asymptotic level. The detectors on the outer surface (14 – 26) accelerate at first, then, their velocity reduces, by the moment of slug formation velocity of the detectors goes to the asymptotic level. Such behavior of velocity $w(t)$ does not contradict the regular pattern of jet and slug formation. It has been established that for each pair of opposing detectors there is a characteristic time t^*, which corresponds to the extremum of velocity for an outer detector w_e and a kink of the curve of velocity for an inner detector w_k (fig. 2). This is characteristic of both SC №1 and SC №2.

It seems obvious that kinks w_k and points of extremum w_e on the graphs $w(t)$ correlate with the beginning of formation of the stream elements – its jet and slug. In order to level the differences between w_k and w_e for each liner element, said differences being caused by the influence of liner thickness, by collapse velocity w_c for each liner element we shall mean an averaged value:

$$w_c = (w_k + w_e)/2.$$



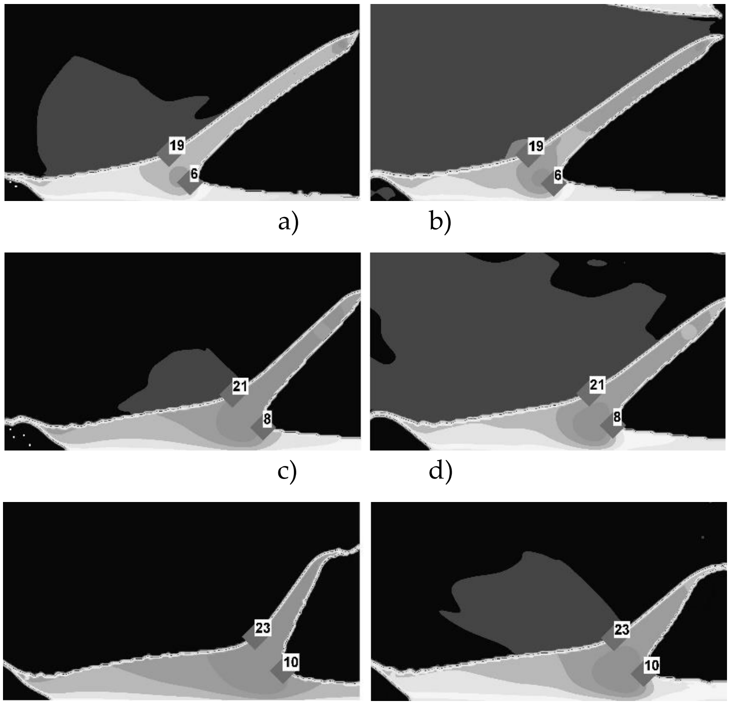
a) b)

c) d)

e) f)

Figure 2. Velocity w of liner elements for SC №1 and SC №2 in dependence to the time t of the process for different detectors: a), b) – detectors 6, 19; c), d) – detectors 8, 21; e), f) – detectors 10, 23; a), c), e) – SC №1; b), d), f) – SC №2

It has also been established that kinks w_k and points of extremum w_e on the graphs $w(t)$ (fig. 2) correlate with the time t^* when the detectors, lying at the initial moment on the outer and the inner liner surfaces, go to the according bisectors of the collapse angles (fig. 3).



a) b)

c) d)

e) f)

Figure 3. Location of the moving detectors on the liner (the dark dots) of SC №1 and SC №2 at the moment of going to the bisector of the inner and the outer angle: a), b) detectors 6, 19; c), d) detectors 8, 21; e), f) detectors 10, 23; a), c), e) SC №1; b), d), f) SC №2

To check the adequacy of the proposed method of analyzing liner collapse velocity w_c we have compared the results of numerical calculations with the calculation data according to the engineering methods for SC №1 (fig. 4 a). Numerical calculations adequately coincide with the engineering working method [1] which is widely used in designing and studying SC. This allows us to consider the proposed method of analyzing collapse velocity acceptable for practical evaluation. At the same time, for SC №2 numerical calculations coincide with the data of the engineering method only at the level of liner apex. It may be explained by the fact that the engineering working method [1] from the start does not take into account the way the casing influences collapse velocity.

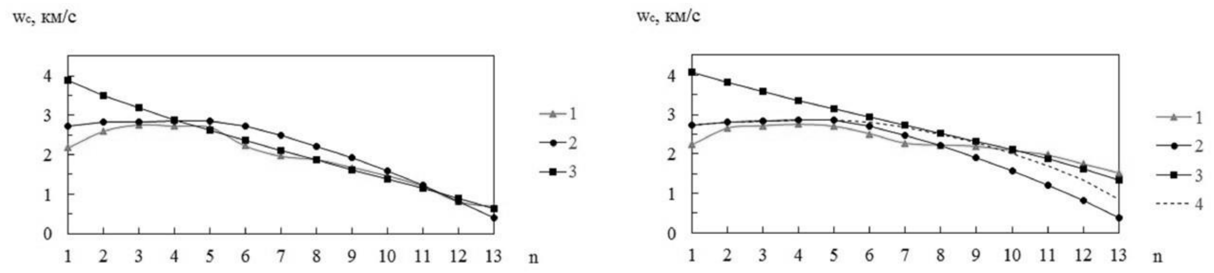
To take into account casing influence we shall complete the engineering working method [1] by adding a component, proportional to double the time of shock wave range along the casing, to the time of the lateral expansive wave arrival. It is worth mentioning, that the casing also has an impact on the intensity of pressure drop, which affects the liner at its basis and which was not taken into consideration in this paper.

We shall define the moment of lateral expansive wave t_6 arrival towards a correspondent liner element in the engineering method [1] with consideration of the casing by the following relation:

$$t_6 = t_0\left[1 + 1{,}43\frac{y}{Dt_0} + 0{,}43\left(\frac{y}{Dt_0}\right)^2\right] + k\frac{2\delta}{c_0} \qquad (1)$$

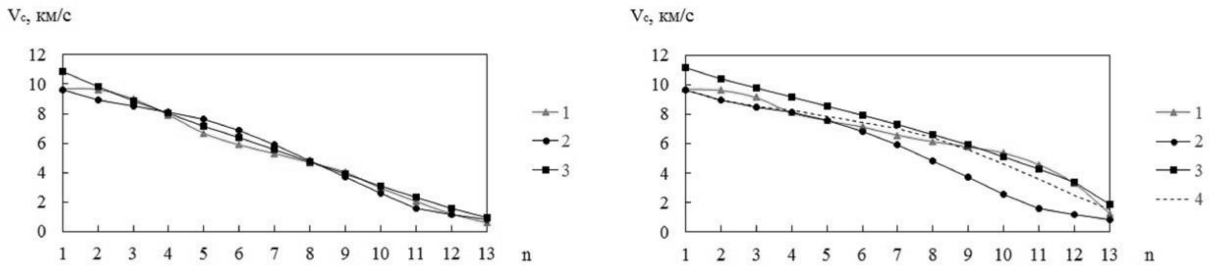
where t_0 indicates the time of shock wave arrival to a current liner element, y – is the distance covered by the expansive wave in the time t; D stands for the detonation speed of the shock wave, k – is the coefficient depending on the angle of the shock wave arrival to the casing of the SC (1...1,2); δ stands for SC casing thickness; c_0 – is sound velocity in the SC casing material. The second term of the proposed dependence is the delay which is caused by the influence of the casing.

The proposed method of accounting the delay for the expansive wave adequately coincides with the results of numerical calculations of liner collapse velocity w_c as well as jet velocity V_c for SC №2 (fig. 4, 5; n – the number of liner section).



a) b)

Figure 4. Dependency of liner collapse velocity w_c on the number n of the liner cross section: 1 – numerical calculations; 2 – calculations according to the engineering working method [1]; 3 – calculations according to the engineering working method [2]; 4 – calculations according to the engineering working method [1] considering *(1);* a) – SC №1; b) – SC №2



a) b)

Figure 5. Dependency of the collapse velocity V_c on the number n of the liner cross section: 1 – numerical calculations; 2 – calculations according to the engineering working method [1]; 3 – calculations according to the engineering working method [2]; 4 – calculations according to the engineering working method [1] considering *(1);* a) – SC №1; b) – SC №2

It is obvious, that the existence of the casing has a certain impact on the penetrating performance of the SC. Calculations according to the engineering working method [1] show that within the focal distance of $F = 2{,}5d_0$ the difference in penetrating performance of SC №2, in contrast with SC №1, is $0{,}5d_0$, while within the distance of $F = 4d_0$ the difference reaches the point of d_0 (fig. 6).

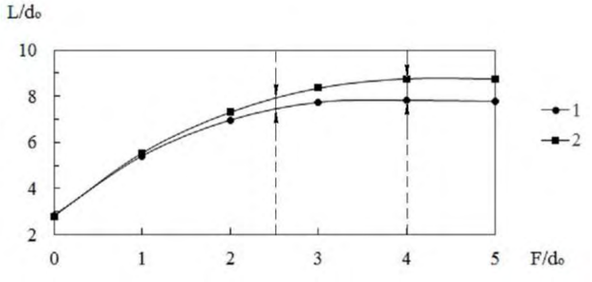


Figure 6. Dependency of relative penetration KC L/d_0 on the relative distance from SC to the steel barrierF/d_0: 1 – SC №1 (according to the engineering method [1]); 2 – SC №2 (according to the engineering method [1] considering *(1)*).

Conclusions

A method of calculating liner collapse velocity, based on analyzing the results of numerical calculations of liner velocity in the opposing areas of its inner and outer surfaces, has been developed.

1. It has been shown that collapse velocity w_c corresponds to the mean value of the velocity of kinks w_k (detectors on the inner liner surface) and points of extremum w_e (detectors on the outer liner surface).

2. It has been established that numerical calculations of collapse velocity adequately coincide with the data of the engineering working method [1] only for shaped charges with no casing. For shaped charges with a casing numerical evaluations and the data of the engineering method are substantially different from each other for the liner basis area.
3. It has been proposed to introduce a correction to the formula of calculating the time of the lateral expansive wave arrival for the engineering working method [1], proportional to twice the time of shock wave range along the thickness of the casing, which enhances the accuracy of evaluating collapse velocity by 1,2 times at the level of liner basis.
4. In order to evaluate penetrating performance of a shaped charge of a complex structure (e.g., those using gland nuts, cylindrical skirts, etc.) it would be only logical to apply the developed numerical method of calculating collapse velocity followed by inserting the results into the engineering methods for evaluating penetrating performance.

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ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ КУМУЛЯТИВНЫХ ЗАРЯДОВ С КОМБИНИРОВАННОЙ ОБЛИЦОВКОЙ ПОЛУСФЕРА-ЦИЛИНДР ДЕГРЕССИВНОЙ ТОЛЩИНЫ

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Одной из наиболее актуальных задач в настоящее время является проблема осуществления наземного моделирования высокоскоростного взаимодействия тел для проведения исследований поведения материалов и конструкций в условиях высокоинтенсивного воздействия различных частиц естественного и искусственного происхождения. Одним из методов получения высокоскоростных компактных элементов для последующего исследования является применение кумулятивных зарядов (КЗ) с облицовкой комбинированной формы полусфера-цилиндр (ПЦ-облицовкой) [1–3]. Преимуществами данного способа метания являются низкая трудоемкость и стоимость проводимого эксперимента, а также возможность получения необходимых массово-