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RESEARCH OF ENERGY PARAMETERS OF THE INSTALLATION FOR THE IMPLEMENTATION OF THE ELECTROHYDRAULIC EFFECT

The presented work considers in detail the issues of calculating the main parameters of the control voltage pulse as well as the discharge current that arises in the interelectrode space of the working chamber of a technical system operating on the basis of the electrohydraulic effect. This effect is characterized by the emergence of a local high-pressure region in the liquid medium, which fills the working chamber, when an intense spark discharge propagates through the fluid. The physical nature of the process lies in the almost instantaneous conversion of electrical energy, accumulated in the storage capacitor of the system, into the energy of the spark channel and further into the mechanical action on the surrounding liquid. Such a process makes it possible to use the electrohydraulic effect as an effective tool for generating short-term mechanical impulses of significant magnitude, which are widely applied in engineering technologies and special-purpose equipment.

In the framework of this research, a model of the electrical system of the device is presented, which allows analyzing the energy conversion stages from the storage capacitor to the interelectrode discharge. The model provides the possibility to evaluate the formation of transient processes, including the steep rise of voltage, the appearance of a spark channel, and the subsequent damped oscillations of the discharge current. Particular attention is paid to the calculation of these transient processes for two different values of the storage capacitor capacity, which makes it possible to determine the influence of the energy reserve on the duration and amplitude of the discharge. By comparing the obtained results, it is possible to trace how the system behaves under different energy-loading conditions, which, in turn, gives grounds for optimizing the parameters of the entire device in accordance with specific engineering requirements.

In addition, the article provides an analysis of the operation of a voltage multiplier circuit that is required to generate the necessary high-voltage potential in the interelectrode space of the working chamber. The multiplier ensures a gradual accumulation of voltage until the level required for spark breakdown is reached, which initiates the electrohydraulic effect. The features of multiplier operation, such as voltage rise time, efficiency, and losses in circuit elements, are considered in detail. The study also outlines possible limitations associated with dielectric strength of components and parasitic capacitances, which influence the stability of spark initiation. Thus, the presented research not only describes the physical essence of the electrohydraulic effect, but also develops a practical calculation and modeling base for designing systems where controlled spark discharges in liquids are the fundamental working mechanism.

Keywords: electrohydraulic effect, water hammer, transient process, spark discharge, electrodes, voltage multiplier, cavitation

INTRODUCTION

The essence of the electrohydraulic effect when an electric discharge pulse passes through a liquid, a large amount of thermal energy is released in a small interelectrode volume, as a result of which a certain volume of this liquid boils, resulting in the formation of a gas-liquid mixture. This leads to the occurrence of high hydraulic pressure. The magnitude of this pressure can reach tens and even hundreds of MPa [1].

The electrohydraulic effect (EHE) can be used in technological processes where there is a need to obtain high pressures, for example, in mechanical engineering for metal forming, the metallurgical industry, mining and geological exploration, oil and food industries for crushing various materials [2]. EHE is also used to create pumps for various purposes [1].

One of the main advantages of technical devices created on the basis of EHE is their environmental friendliness. The impact of hydraulic shock on an object does not introduce additional sources of pollution into the system.

In electrohydraulic systems, the conversion of electrical energy into mechanical energy occurs without an intermediate conversion of electrical energy into magnetic energy, as, for example, in electric motors. Such an energy conversion system has both its advantages and disadvantages [3].

The advantages include the ability to obtain a pressure gradient of hundreds of megapascals in small-sized devices, the ability to create high pressure both in a sealed and open volume of the working chamber, and the absence of additional sources of pollution during the technological process [4].

The disadvantages of the method are: the need to obtain high voltages between the working electrodes, the difficulty of describing the hydrodynamic processes that occur in the working chamber during discharge phenomena, the creation of interference in electronic equipment at the moment of discharge, the difficulty of monitoring the electrical parameters of the system due to the high level of interference.

As a result of the described problems arising in the creation of technical and technological systems based on the electrohydraulic effect, the development of such systems relies, to a greater extent, on experiment than theoretical calculation. This applies to both the hydraulic and electrical parts of the project [5].

When creating technical systems based on EHE, it is necessary to have reliable information about the processes occurring in the hydraulic system, which are formed due to the transition of electrical energy of the discharge into mechanical energy. Therefore, the system for forming a discharge pulse must be created based on calculations of transient processes occurring in the electrical circuit, both during energy storage and during discharge phenomena in a liquid medium [6].

This article is devoted to the technologies of calculating transient processes in the electrohydraulic system of generating EHE.

REVIEW OF SCIENTIFIC SOURCES

The electrohydraulic effect (EHE) describes the rapid release of energy within a liquid gap under the influence of a strong electric field. This intense energy density causes the breakdown and ionization of the insulating medium, forming an electrically conductive plasma channel [7,8]. The resulting thermal, chemical, and mechanical effects have been widely utilized across numerous industrial applications [9]. Despite considerable progress in understanding and applying electrohydraulic shock waves, experimental observations have revealed notable discrepancies in discharge behavior, reflecting the complex nature of the underlying processes.

Typically, EHE evolves through two stages: an initial pre-breakdown phase followed by a discharge phase, triggered when the applied electric field exceeds the dielectric strength of the liquid [7]. It has been demonstrated that the peak shock wave pressure (P_m) correlates proportionally with the capacitor energy at the instant of breakdown [10]. Acoustic efficiency - the fraction of electrical energy converted into mechanical energy - has been widely studied, suggesting a conversion efficiency of approximately 30% [11–13]. However, many models overlook mechanisms of energy dissipation, leading to overestimated predictions [14]. For instance, it has been found that, in low-voltage spark discharges, only around 2% of the deposited energy is emitted as acoustic radiation [15]. Efforts to enhance acoustic efficiency have included embedding metallic wires or energetic additives into the gap, achieving improvements up to 15% and 25% [16]. Extending the plasma channel length has also been shown to effectively amplify shock wave strength [17]. Nevertheless, a comprehensive understanding of EHE characteristics remains elusive, limiting its engineering application potential.

To address this, dynamic plasma expansion models using a time-dependent resistance based on the Braginskii framework have been proposed, providing improved fidelity in simulating discharge behavior [18]. Models of the fluid dynamics of the plasma-liquid interface during discharge events have also been developed, although much of the work has focused on low-current regimes [19].

Shock wave formation itself has been extensively modeled using piston-driven approaches. In some works, the shock wave is treated as generated by a rapidly accelerating piston obeying a power-law motion, enabling prediction of the shock front evolution [20–22]. Building on this, self-similar solutions for both cylindrical and spherical shock wave propagation have been derived, offering effective tools for modeling different geometries [21,23]. A cylindrical piston model tailored to the EHE has also been developed [24]. Plasma channel evolution models based on dimensionless parameters have provided additional insight into the dynamics of discharge and shock formation. Nevertheless, critical plasma properties such as conductivity and temperature during the discharge remain difficult to measure directly, introducing challenges in fully validating these models [12].

To characterize the behavior of the EHE and predict shock wave intensity, a computational model was developed based on experimental data from a shock wave generation platform. Plasma channel expansion was simulated using cylindrical and spherical approximations, showing good agreement with measurements. A piston-driven model was applied to analyze energy conversion during the rapid expansion phase. Complementary experiments using a point-plane electrode under impulse voltage and high-speed optical diagnostics revealed that localized heating and gas bubble formation are critical for discharge initiation. It was found that a minimum energy of 80 J is needed for bubble formation, and at energies above 200 J, full gap breakdown occurs, generating high-intensity shock waves, with peak pressures depending on residual energy and electrode gap length [25].

Despite advances in understanding the EHE, significant gaps remain in accurately characterizing energy transfer and optimizing system efficiency. Limited knowledge of plasma properties and energy dissipation mechanisms hampers the development of reliable predictive models. Therefore, focused research on the energy parameters of EHE installations - including breakdown thresholds, discharge energy, and pulse characteristics - is

essential for improving energy conversion efficiency and advancing practical applications of electrohydraulic technologies.

The operating principle of the system is based on the electrohydraulic effect

The electrohydraulic effect consists of creating alternately high and low pressure in the interelectrode space when a spark electric discharge passes through a liquid. Since its initial development in the first half of the twentieth century, the basic scheme of an electrohydraulic installation has undergone virtually no changes.

The block diagram of the device for creating the EHE is shown in Fig. 1.

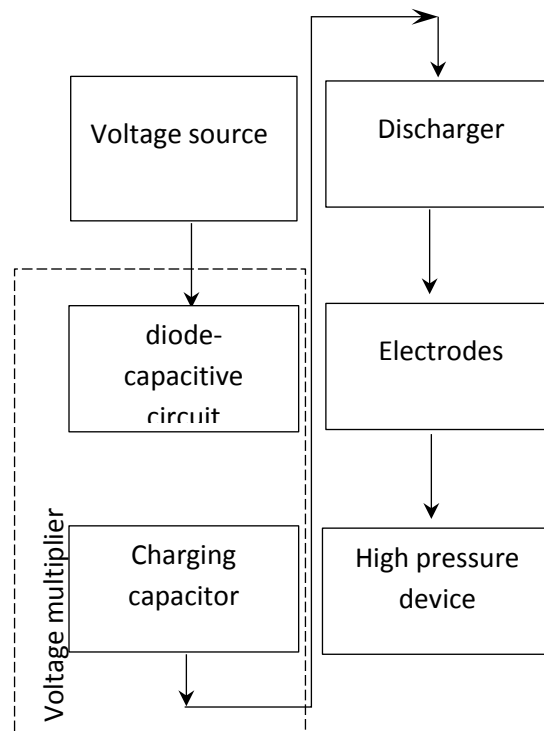


Figure 1 -Block diagram of the installation for obtaining an electrohydraulic effect

In systems designed for neutralizing mines and unexploded ordnance using the electrohydraulic effect, the power source is typically a standard industrial AC supply (~220 V, 50 Hz). To generate a high-energy hydraulic impulse capable of forming a high-velocity liquid jet, a sufficiently long spark discharge must be created within the fluid medium. The length of the discharge channel directly influences the peak pressure achieved in the electrohydraulic system. While shorter discharges of a few millimeters are adequate for fluid pumping applications, significantly longer discharge channels - often tens or even hundreds of times greater — are required to produce the extreme pressures necessary for jet formation capable of penetrating or disrupting explosive devices [26].

To initiate a spark discharge in a working chamber filled with a liquid medium, it is necessary to apply a constant voltage across the electrodes that exceeds the breakdown voltage of the liquid. This threshold voltage is determined by the electrical resistivity of the liquid, which can vary significantly depending on its composition. For instance, the specific electrical resistivity (ρ) of transformer oil and gasoline is approximately $\rho \approx 10^{11}$ Ohm m, for distilled water around $\rho \approx 10^4$ Ohm m, for groundwater approximately $\rho \approx 20$ Ohm m, and for seawater it decreases further to about $\rho \approx 0.3$ Ohm m [11].

Thus, to initiate a spark discharge in a liquid medium, it is essential to determine appropriate values for the interelectrode distance and the applied voltage, which are directly proportional to one another. In a medium such as antifreeze, achieving the conditions necessary for breakdown requires the application of a sufficiently high voltage across a relatively short gap. At the moment of electrical breakdown, a significant current begins to flow through the interelectrode space, resulting in a high-power discharge. This power release leads to the rapid conversion of electrical energy into thermal and mechanical energy. The duration of the discharge is typically very short, not exceeding several milliseconds, during which the energy Q is released in an intense, localized manner

$$Q = \int_0^{\Delta t} I(t) \cdot U(t) dt \quad (1)$$

$I(t)$ - discharge current; $U(t)$ - discharge voltage.

To generate a voltage sufficient to cause a discharge in the working fluid, it is necessary to convert the alternating voltage of the industrial network ~ 220 V, 50 Hz into a direct voltage of tens of kilovolts. This can be done, for example, using a diode-capacitive voltage multiplier (Fig. 2) [27].

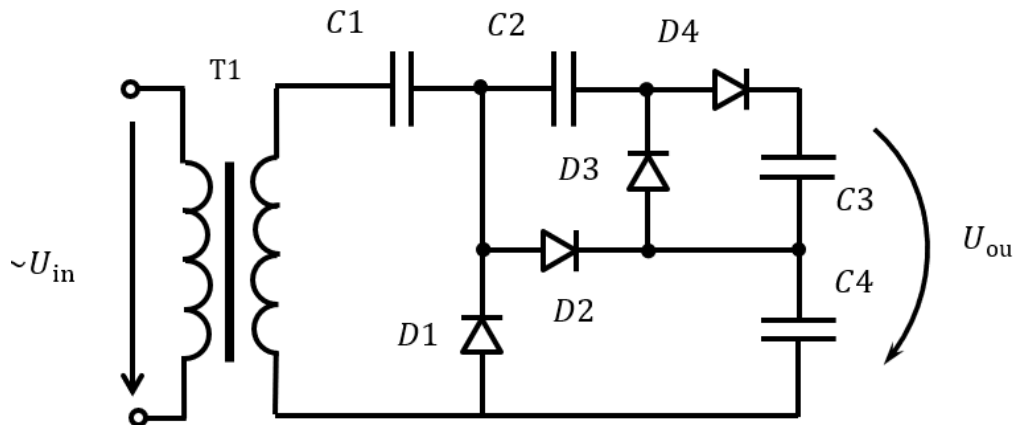


Figure 2 -Електрична Схема diode-capacitive voltage multiplier

In the circuit shown in Fig. 2, the alternating voltage from the secondary winding of the transformer is applied to a diode-capacitor network. During the first quarter of the input voltage period T , diodes $D1$ and $D3$ remain in the reverse-biased (non-conducting) state, while diodes $D2$ and $D4$ are forward-biased (conducting). As a result, capacitors $C1$ and $C4$ are charged to approximately half of the input voltage amplitude $U_{in}/2$. The voltages across capacitors $C2$ and $C3$, as well as across diode $D4$, remain close to zero during this interval, as these elements are effectively short-circuited by the low impedance of the conducting diode $D2$.

On the time interval $t = T/4 \dots T/2$ the input voltage begins to decrease, the voltage on the diodes $D2$ and $D4$ become negative, the diodes close, the voltage on the capacitors remains unchanged (a slow discharge of the capacitors occurs due to leakage currents and reverse currents of the diodes).

At the moment of arrival of the third quarter-period of the input signal ($t = T/2 \dots 3T/4$) diodes open $D1$ and $D3$, and the capacitor begins to recharge $C1$ and charge $C2$. Voltage on $C3$ and $C4$ remain practically unchanged: $U_{C3} = 0$; $U_{C4} = U_{in}/2$.

On the interval $t = 3T/4 \dots T$ diodes $D1$ and $D2$ close, and the diodes $D3$ and $D4$ open. Voltages on capacitors $C1$ and $C2$ begin to decrease (in absolute value), and on $C3$ and $C4$ grow. As a result, after one period of input action, the voltage on $C3$ becomes equal $U_{C3} = U_{in}/4$, $U_{C4} = U_{in}/4$.

The next cycle of capacitor recharging does not start from zero, so at the end of the next period, the voltages grow. And in the steady state, the voltages become: $U_{C3} = U_{in}$; $U_{C4} = U_{in}$. Therefore, the output voltage will be equal to the doubled amplitude value of the input voltage. Output voltage consists of voltages on the capacitor plates $C3$ and $C4$: $U_{ou} = U_{C3} + U_{C4}$.

To set the numerical value of the voltage, we will use Matlab/Simulink Online, in particular its Simscape block, which allows you to quickly create models of physical systems in the Simulink environment.

The output voltage graph has the form shown in Fig. 3. The voltage increases rapidly at first, exhibiting high-frequency oscillations. As time progresses, the voltage continues to rise but at a slower rate, and the oscillations gradually diminish in amplitude. Eventually, the output voltage stabilizes at approximately 24,000 V, indicating that the system reaches a steady-state condition. The duration of the transient process (i.e., the onset of the quasi-steady-state mode) is influenced by the capacitance of the capacitors and the characteristics of the diodes. In the first quarter-cycle, the circuit's time constant during capacitor charging is very short-on the order of microseconds. In contrast, during the discharge phase due to leakage currents in the second quarter-cycle, the time constant becomes significantly longer-ranging from tenths of a second to several seconds, depending on the capacitor capacity. For the output voltage waveform shown in Fig. 4, the formation time of the required high voltage can be considered approximately equal to 20 cycles of the input signal. For a standard 220 V, 50 Hz industrial power supply, this corresponds to about 0.45 seconds.

Upon contactor closure, the resistance within the discharge chamber undergoes significant variation, ranging from several megaohms to a few ohms. Nevertheless, the majority of the discharge, in terms of both duration and energy dissipation, occurs at low resistance values, typically not exceeding 10 Ohm. During the simulation of the circuit closing process (Fig 3), a rapid decrease in voltage and current is observed (Fig. 5), accompanied by substantial thermal energy release.

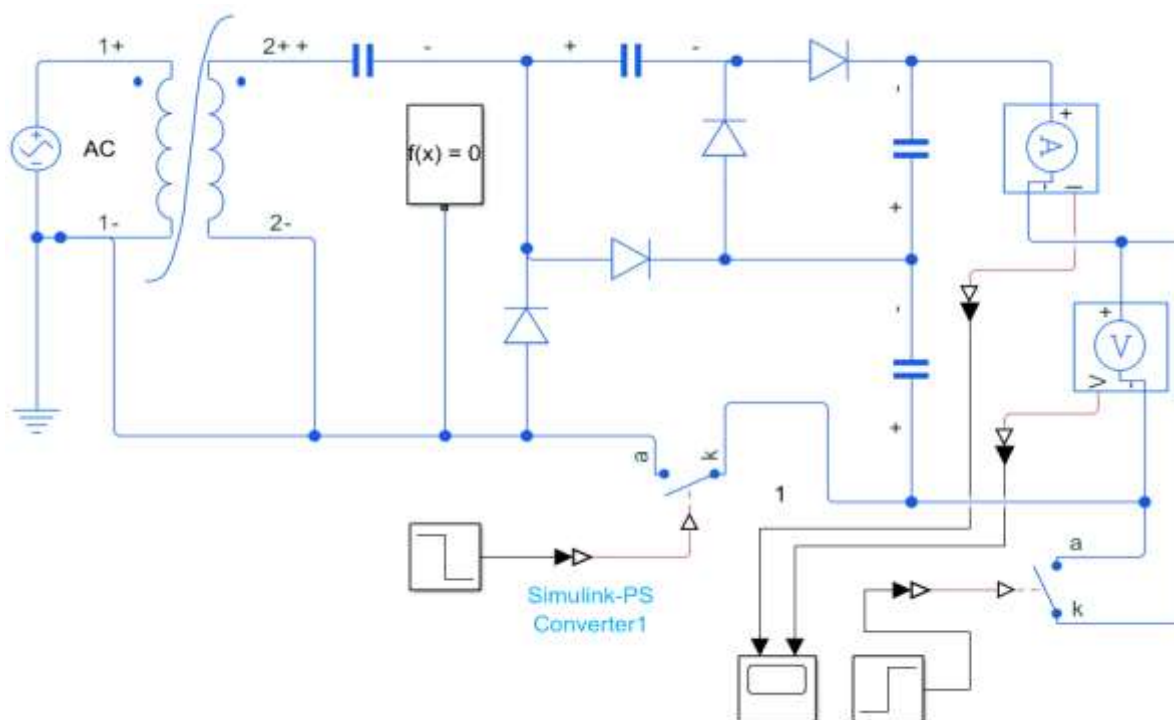


Figure 3 - Block diagram in an interactive environment for EHE effect modeling

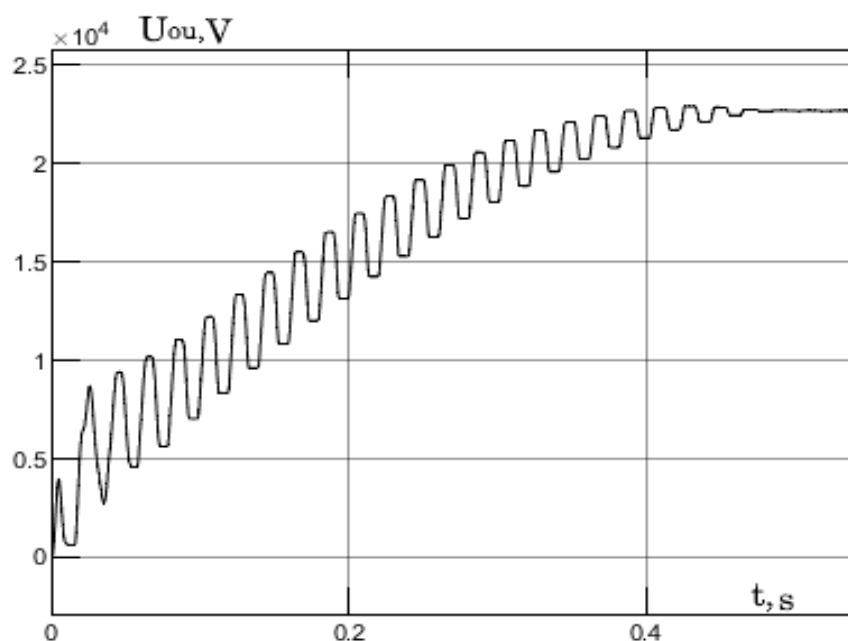


Figure 4 - Transient response of output voltage over time

Establishing the patterns of current and voltage variation enables the determination of the energy released during the electrohydraulic effect. In the considered case (Fig. 5), the discharge energy amounts to 40 μJ . The released amount of energy is sufficiently high to support the execution of a wide range of technological processes associated with material forming and fracture.

Given that the peak pressure of a shock wave is a major parameter for evaluating impact-related damage, it is used as an equivalent criterion in this study. The peak pressure resulting from the electrohydraulic effect can be represented, by analogy, as the peak pressure generated by a TNT explosion under similar conditions - in the same

medium and at the same distance. To achieve this, the law governing underwater explosive shock waves [28] is employed. The corresponding equation is as follows:

$$p = \frac{9000}{R} Q^{\theta} \quad (2)$$

where p denotes the peak pressure produced by the high-voltage pulse discharge, measured in bar; R represents the distance from the center of the discharge gap, in mm; Q is the discharge energy at the moment of breakdown, expressed in kJs; and θ is the energy attenuation exponent, with a value of 0.35.

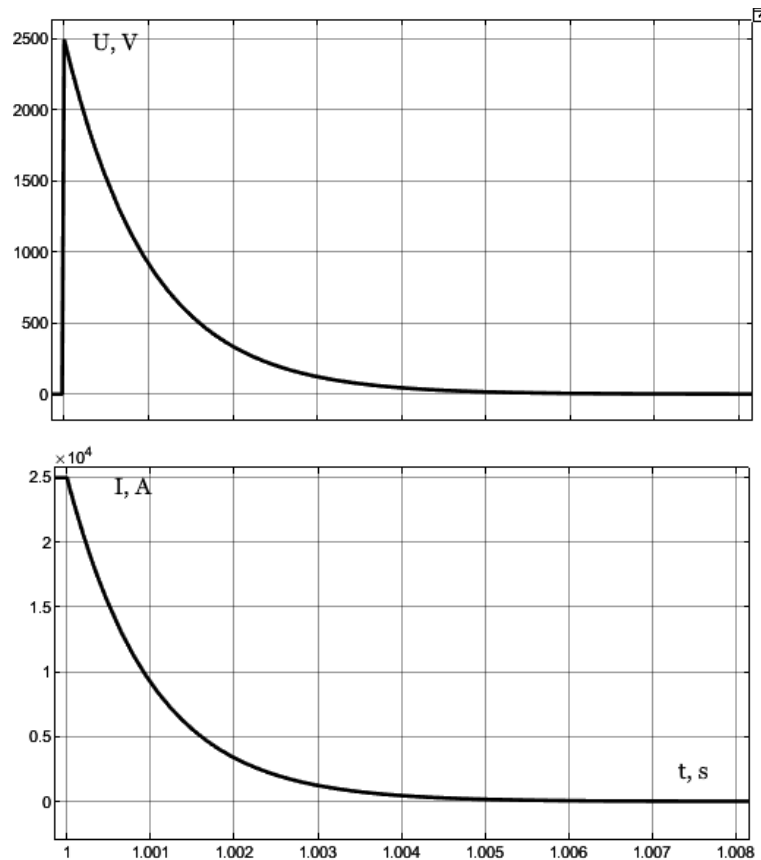


Figure 5 - Simulation of voltage and current behavior during the circuit closing process

The application of an empirical relationship (2) enables the calculation of the resulting pressure as a function of the geometric and energetic parameters characterizing the electrohydraulic effect. This approach provides a practical means of linking the physical configuration of the system with the dynamics of fluid motion induced by the discharge.

As part of the simulation of electrohydraulic effect conditions using SOLIDWORKS FloXpress, a qualitative assessment of water flow through the Jet.SLDPART model was carried out, with an inlet pressure of 7.00×10^8 Pa and an outlet pressure of 1.00×10^5 Pa at a temperature of 293.20 K. The analysis showed that the maximum flow velocity reached 1186.624 m/s, confirming the presence of high-intensity fluid ejection characteristic of electrohydraulic discharge processes.

The development of such water flow velocities enables the use of the electrohydraulic effect as a means of acting on various targets that require the impact of a high-energy flow similar to that produced by shaped charges [29, 30].

CONCLUSION

This study demonstrated the feasibility and effectiveness of using the EHE to generate high-energy hydraulic impulses capable of neutralizing hazardous objects. It was shown that the peak pressure and intensity of the generated shock waves strongly depend on the discharge channel length and the energy released during the breakdown process.

A diode-capacitive voltage multiplier was effectively used to transform industrial AC voltage into the high DC voltages necessary for initiating discharges in liquid media. Simulation and experimental results confirmed the possibility of achieving discharge energies of up to 40 kJ, resulting in peak water flow velocities exceeding 1180 m/s.

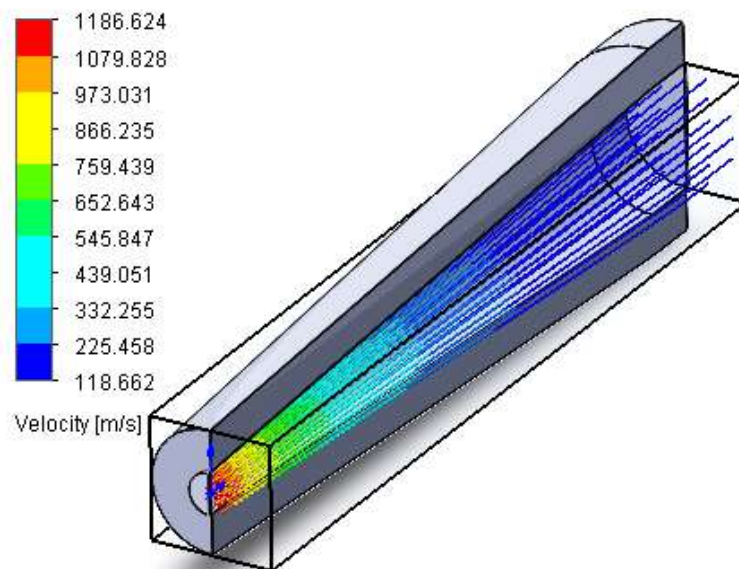


Figure 6 -Simulation of high-intensity water jet flow under electrohydraulic effect conditions

This high-speed jet formation validates the use of EHE-based systems for tasks requiring strong mechanical impact, similar to the effects achieved by shaped charges. The developed models and experimental data provide a solid foundation for optimizing EHE systems and adapting them to various technological and engineering applications.

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ДОСЛІДЖЕННЯ ЕНЕРГЕТИЧНИХ ПАРАМЕТРІВ УСТАНОВКИ ДЛЯ РЕАЛІЗАЦІЇ ЕЛЕКТРОГІДРАВЛІЧНОГО ЕФЕКТУ

У представленій роботі детально розглянуто питання розрахунку основних параметрів керуючого імпульсу напруги, а також струму розряду, що виникає в міжелектродному проміжку робочої камери технічної системи, яка функціонує на основі електрогідралічного ефекту. Цей ефект характеризується виникненням локальної області високого тиску в рідкому середовищі, що заповнює робочу камеру, коли через рідину проходить інтенсивний іскровий розряд. Фізична природа процесу полягає у майже миттєвому перетворенні електричної енергії, накопиченої у накопичувальному конденсаторі системи, в енергію іскрового каналу та далі — у механічну дію на навколишню рідину. Такий процес дозволяє використовувати електрогідралічний ефект як ефективний інструмент для генерації короткочасних механічних імпульсів значної величини, що знаходять широке застосування в інженерних технологіях та спеціальній техніці.

У межах цього дослідження представлено модель електричної системи пристрою, яка дає змогу аналізувати етапи перетворення енергії від накопичувального конденсатора до міжелектродного розряду. Модель дозволяє оцінити формування перехідних процесів, включаючи крутий фронт наростання напруги, виникнення іскрового каналу та подальші загасаючі коливання струму розряду. Особливу увагу приділено розрахунку цих перехідних процесів для двох різних значень ємності накопичувального конденсатора, що дозволяє визначити вплив енергетичного запасу на тривалість і амплітуду розряду. Порівняння отриманих результатів дає змогу простежити, як система поводить себе за різних енергетичних навантажень, що, у свою чергу, створює підґрунтя для оптимізації параметрів усього пристрою відповідно до конкретних інженерних вимог.

Крім того, у статті наведено аналіз роботи схеми множника напруги, яка необхідна для формування потрібного високовольтного потенціалу в міжелектродному проміжку робочої камери. Множник забезпечує поступове накопичення напруги до рівня, достатнього для іскрового пробою, який ініціює електрогідралічний ефект. Особливості роботи множника, такі як час наростання напруги, ефективність і втрати в елементах схеми, розглянуто детально. Також у дослідженні окреслено можливі обмеження, пов'язані з діелектричною міцністю компонентів і паразитними ємностями, що впливають на стабільність ініціювання іскрового розряду. Таким чином, представлена робота не лише описує фізичну сутність електрогідралічного ефекту, але й формує практичну базу для розрахунку та моделювання при проектуванні систем, де контрольовані іскрові розряди в рідинах є основним робочим механізмом.

Ключові слова: електрогідралічний ефект, гідралічний удар, перехідний процес, іскровий розряд, електроди, множник напруги, кавітація

Надійшла: 25.08.2025
Received: 25.08.2025