Mathematical model of the distribution of electrical and thermal energy in the working element of an information and measurement system designed to study the process of initiating industrial explosives

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Abstract. The use of sensitive explosives to detonate the main charge during perforation of solid rock layers, demolition of high-rise and strong structures, etc. is an inconvenient and dangerous method of initiation. This makes it urgent to develop and implement alternative methods for detonating explosives. One of these methods is to transmit a thermal pulse of the required power using thermal conductivity from a metal rod to an explosive. The determination of the thermal power of the pulse required for the occurrence of detonation is carried out by indirect measurements. The rating allocated by standard heat rod method is pretty rude, does not account for losses at the points of contact and spatial distribution of heat in the core, depending on the electric pulse parameters. In this paper, mathematical models of the formation of a thermal field in the rod, taking into account these factors, are constructed. Based on the results of the obtained models, numerical calculations are made for rods of different sizes and signals of different shapes and power. The results of the work allow us to determine the necessary initial and boundary conditions for a further description of fast-flowing thermal processes.

1. Introduction
Every year blasting explosives (explosives) are increasingly used in industry to solve a variety of problems. Such tasks include perforation of rock hard layers in the mining, oil, and gas industries [1-3], dismantling of high-rise and durable structures [4-6], welding of dissimilar metals [7-9], etc. Carrying out these types of work is associated with high risk, primarily due to the use of initiating explosives, characterized by low stability to external influences. Therefore, the task of developing and implementing alternative methods of detonation of blasting explosives used in production is very urgent.

One of the methods for detonating explosives is a method based on the transfer of a heat pulse to a substance of the required power from a metal rod, which is heated due to the flow of a high-power electric pulse through it. Each explosive must transmit its power for its detonation, the knowledge of which is basic when creating the initiation system.

The power of an electric pulse is determined by the values of voltage, current, and duration of the transmitted pulse, which may be unstable during the process and depend on some parameters (power stability, initial temperature of the operating elements of the installation, non-ideal contacts). An
electric pulse forms a detonation wave, which initiates an explosive. It is important to know the minimum energy that must be transferred to a substance for a fixed time for its detonation since it is this value that is a threshold parameter in the design and commissioning of detonators used in various practical problems.

2. Statement of the problem

The determination of the minimum amount of energy necessary for the detonation of a certain explosive is carried out using an information-measuring system, the functional diagram of which is shown in Figure 1 [10]. The pulse generator (PG) supplies a signal to a transformer block, consisting of a primary \((n_1)\) and secondary windings \((n_2, n_3, ..., n_i)\) and to the ADC input. The ADC is connected to a personal computer (PC), which captures the initial pulse signal from the GI and compares it with the measured signals in the system. From the secondary windings of the transformer, an electrical impulse enters a working element consisting of a strong metal housing 1, explosives 2, and a conductive metal rod 3 made of nichrome. Active resistance elements \(R_1\) and \(R_2\) serve as voltage dividers to convert the electrical signal from the working element to the ADC. Resistance \(R_{sh}\) acts as a shunt.

The thermal energy transferred by the heating element to the explosive for its detonation can be determined only indirectly by measuring the voltage and current of the electric signal passing through the metal rod of the working element. Having measured with sufficient accuracy the parameters of the electric signal, using the Joyle-Lenz law, it is possible to determine the thermal energy released by a metal conductor in the working element of the system. The data obtained will allow an estimate of the detonation conditions for the explosives used in the industry. However, as follows from the sources [11–13], the distribution of the electric flux in the conductor when the short pulse signal is passed through it is uneven, and, therefore, an uneven distribution of heat in the rod occurs.

Also, there is a loss of power of the electrical signal at the contact points of the rod and the conductor supplying the electrical signal, caused by the imperfect contact [14-16]. These losses are expressed in the occurrence of additional resistance at the contact points and the release of thermal energy in them that is not involved in the formation of the detonation wave.
The above factors should be taken into account in the algorithm for processing information signals when determining the minimum energy and thermal power for the detonation of industrial explosives.

3. Modeling

3.1. Estimation of signal energy loss at contact points

At the point of contact "conductor-nichrome rod" losses occur due to imperfect contact pads (Figure 2) and the presence of an oxide film on the metal. Due to the formation of films on the end surfaces of metal bodies and because when compressing two conductors facing each other with flat sides, contact is not carried out over the entire area, but only over individual sites, the current does not flow over the entire cross-section of the conductor. In this case, the real resistance at the point of contact \( R_{\omega} \) is written as shown in equation (1):

\[
R_{\omega} = \rho \frac{l}{S_{\omega}},
\]

where \( \rho \) is the resistivity of the rod material; \( l \) is the length of the rod; \( S_{\omega} \) is the real contact area.

From formula (1) it is obvious that to reduce the loss of electrical energy of the signal to heat at the contact point, it is necessary to increase the real contact area. This can be done by pre-treating the surface of the contact area to remove the oxide film and reduce surface roughness.

An effective way to increase the area of \( S_{\omega} \) is to apply contact force to the contact. An expression is known for evaluating the resistance at the contact point \( (R_k) \) under the influence of the contact pressing force. This dependence is reflected by equation (2):

\[
R_k = \frac{\rho \sqrt{\sigma}}{(0.102 F_k)^m}.
\]

Here \( \sigma \) is the temporary resistance to collapse, \( F_k \) is the compression force, \( m \) is an exponent depending on the shape of the contact. In the case under consideration, \( m = 1 \).

The dependence of the normalized resistance \( (R_{nk}) \) at the point of contact on the pressing force for the surface contact of a nichrome rod with a diameter of 0.3 mm, a length of 10 mm, and a tensile shear resistance of 675 N/mm² is shown in Figure 3.

The influence of the pressure force on the formation of resistance at the contact points is nonlinear. The temperature at the contact point \( (T_k) \) when an electric signal flows through it, nonlinearly depends on the voltage drop \( (U_k) \) on it [17]. Taking into account expression (2), the temperature change at the contact point \( (\Delta T_k) \) can be represented in the form of equality (3):

\[
\Delta T_k = \frac{I_k^2 \rho \sigma}{8 \lambda (0.102 F_k)^2},
\]

where \( I_k \) is the current flowing at the point of contact; \( \lambda \) is the coefficient of thermal conductivity.

3.2. The formation of the thermal field in the rod

The process of heat transfer from the nichrome rod of the explosive in the working element of the information-measuring system is described by the heat equation in cylindrical coordinates (expression (4)), with initial (equation 5) and boundary conditions of the fourth kind (equation (6)) [11,18]:

\[
\frac{dT}{dt} = \alpha \left( \frac{dT}{dr^2} + \frac{1}{r} \frac{dT}{dr} \right);
\]

\[
T(r,0) = T_0(r);
\]

\[
T_{\omega} = T_0; \quad q_{\omega} = q_{\omega}.
\]

Here \( t \) is the time parameter; \( \alpha \) is the coefficient of thermal diffusivity; \( r \) is the radial coordinate of the nichrome rod; \( T_0(r) \) is the initial temperature of the rod, which in this problem is formed by an electric
pulse flowing through it; $T_s$ and $T_v$ are the temperatures at the boundary of the rod and explosive, respectively; $q_s$ and $q_v$ are the heat flux densities at the boundary of the rod and explosive, respectively.

- Figure 2. Non-ideal contact pad “conductor-nichrome rod”.
- Figure 3. The graph of the normalized resistance at the point of contact on the pressure.

Equations (6) are provided by the experimental conditions, which consist of the requirement that the explosive is pressed tightly against the rod with a metal casing. The initial conditions depend on the parameters of the electric pulse and the characteristics of its flow along the nichrome rod.

The signal in the conductor is distributed unevenly. This is explained by the presence of the skin effect, according to which the current density is higher at the boundary of the conductor, the higher the frequency of the electrical signal [10,19,20].

For a nichrome rod used in the information-measuring system under consideration, the distribution of current density at different depths from the surface was determined when a signal with a frequency of 1 MHz was transmitted. The results showed that at a radius of 0.01 mm the current density over the entire cross-section is the same, and with an increase in the radius of the rod to 0.6 mm, the current density in the center is 60% lower than the same parameter at the boundary.

The signal passing through the rod is pulsed and has a wide frequency range uneven in amplitude. The amplitude spectrum of the signal ($A(f)$) is determined by the pulse duration ($\tau_o$) the maximum value of the amplitude ($A$), which can be changed to specify a specific energy, by the leading and trailing edges of the pulse:

$$A(f) = \frac{2A\tau_o}{\pi} \sin c(\pi f \tau_o / n) \sin c(2\pi f \tau_o / n) ,$$

where $n$ is a coefficient depending on the ratio of the duration of the pulse fronts and its duration.

In mathematical modeling of the process of formation of a thermal field in a nichrome rod, symmetrical trapezoidal pulses with a duration of the leading and trailing edges of 1/4, 1/8, and 1/10 of the duration of the entire pulse of 10 $\mu$s were selected. The signal amplitudes were selected from the condition that the energy supplied to the input of the working element of the pulse is equal to 10 W·s. Also, taking into account the presence of the skin effect during the flow of a short electric pulse in a nichrome conductor with a diameter of 0.3 mm, the mathematical record of the amplitude spectrum takes the form:

$$A_s(f) = A(f) e^{-\tau_s/\tau_o} .$$

As a result of the simulation, graphs were constructed (Figure 4) of the envelopes of the amplitude spectrum of the effective signal frequency width at the outer boundary of the rod, and in its center, taking into account the skin effect. Figure 4a) shows the envelopes of the spectrum at the boundary of the rod and in its center at a pulse edge duration of 1/4 of the pulse duration at a maximum current in
the rod of 133.3 A. Figures 4b) and 4c) show similar dependencies for the duration of the edges 1/8 of the pulse duration at the maximum current value of 114.3 A and the edge duration 1/10 of the pulse duration at the maximum current value of 111.1 A, respectively.

Figure 4. Graphs of the envelopes of the amplitude spectra at the boundary of the rod (1) and in the center (2).

As a result of the analysis of the obtained dependencies, using the expression of the energy spectrum [21], the heat difference was determined at the boundary of the rod and in its center, taking into account the heat loss at the point of contact between the rod and the conductor from the obtained dependence:

\[
\Delta Q = \int_{0}^{f_{\text{max}}} \left[ A_{\text{x}}(f) - A_{\text{c}}(f) \right] df - a \frac{dT}{dr},
\]

where \( f_{\text{max}} \) is the upper frequency of the effective spectrum width; \( A_{\text{x}}(f) \) and \( A_{\text{c}}(f) \) are the spectral densities of the signal at the rod boundary and in its center, respectively. The second term in the right-hand side of equation (9) reflects the heat loss at the contact points between the conductor and the nichrome rod with a compression load of 500 N. For the case shown in Figure 4, a) the heat difference was 0.744 W·s, for b) 0.367 W·s, for c) 0.309 W·s.

4. Conclusion
In the course of the studies, a dependence was obtained that takes into account the temperature change at the point of contact of the "conductor-nichrome rod", reflecting the energy loss of the electrical signal before its useful work in the working element of the information-measuring system. Mathematical models were also obtained and graphs of the envelopes of the amplitude spectra of electrical symmetric trapezoidal pulses flowing at the boundary and in the center of the conductor were taken into account, taking into account the skin effect. The difference in heat obtained at the boundary and inside the nichrome rod obtained by simulation when passing non-ideal electric pulses of the same energy and duration of 10 μs with fronts from 10% to 25% of the pulse duration is from
3.1% to 7.4% of the total signal energy. This means that the heat flux at the interface between the nichrome rod and the explosive is greater than under the assumption that the entire power of the electric signal supplied to the working element of the system is uniformly distributed over the entire volume of the rod.

The results obtained during the simulation can serve as the basis both for adjusting the calculations when determining the sensitivity of the explosive to thermal effects and for creating a control system for the parameters of the explosive initiation unit when solving problems in various industries.

5. References
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