

ESTIMATION OF THE SAFE ELECTRICAL LOAD ON SPIRAL BULBS HEATED BY CAPACITORS APPLIED TO MULTIPLE START-UPS OF OPEN GAS GENERATORS

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Abstract. A method was developed for the automated calculation of the safe electrical load on spiral bulbs warmed by capacitors for the multiple start-ups of open gas generators under water. An energy criterion was proposed that would, for spiral bulbs with known dimensions and thermal properties, allow the selection of the type of pulsed power supply providing wire heating required for dibasic solid fuel (DSF) ignition, and maintaining its operative state.

1 Introduction

For the enabling of multiple start-ups and stops of underwater open gas generators (OG) based on dibasic solid fuels (DSF) [1], a method [2] was proposed, according to which the block fuel 1 is located in an upright position (figure 1).

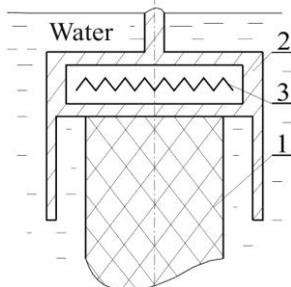


Fig. 1. Arrangement scheme of the block and the heat-resistance glass in the ignition.

Localization of the intended combustion zone at the upper end is achieved by using heat-resistant glass (HG) 2, at the bottom of which a CH 3 alloy with high electrical resistivity is placed (Table 1). The HG covers the sidewalls of the top part of the block with

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liquid that can completely fill the margin formed between the walls and the block.

Table 1. Thermal properties of alloys with high electrical resistance.

Alloy	ρ_p , kg/m ³	c_p , J/kg·K	$\rho_0 \cdot 10^8$, Ohm·m	T_{pl} , °K	$\gamma \cdot 10^4$, 1/K	$(\rho_p c_p / \rho_0) \cdot 10^{12}$
Constantan	8900	410.33	49	1533	0.10	7.45
Nickel	8900	468.84	7.24	1426	0.54	57.6
Nichrome	8400	460.57	110	1733	4.0	3.86

Burning is maintained due to the forced movement down of the HG, and the extinction of DSF occurs after the HG's retraction upward.

An experimental check confirmed [3] that the proposed method of DSF burning in an aquatic environment provides for stable ignition, stable combustion and reliable burning interruption.

2 The task

To ensure an emergency start-up of the OG, the energy of a charged capacitor may be used [4], for example, the capacitor included in the construction of the explosive device PC-2000m [5]. Its characteristics are shown in Table 2. The stored energy of the capacitor was estimated by the formula $E_0 = 0,5C_0U_0^2$.

Table 2. Parameters of pulsed power sources.

No.	Brand	Capacity C_0 , uF	Voltage U_0 , V	Energy E_0 , J	Mass, kg
3	CSM -3	4	1600	5	1.6
4	PC - 2000 m	50	1200	35	5.2

3 Approximate methods

The experience of condenser blasting machine design was used to calculate the heating portion of the ignition of DSF, located near the contact zone of CH with the bottom of the HG [5]. It was thought that the discharge of a capacitor with the size of C_0 at the initial voltage of U_0 , occurs to an external circuit having only active resistance. Then the force change of the current over the period of time t is described by the following expression [5]

$$I = (U_0 / R_h) \exp[-t / (R_h \cdot C_0)], \tag{1}$$

where R_h is the electrical resistance of the wire.

The heat flux density generated by CH is represented as a function exponentially decreasing with time [4]

$$q_h = q_{h0} \exp(-2t / R_h \cdot C_0), \tag{2}$$

where $q_{h0} = U_0^2 / (R_h \cdot S_h)$ is the maximum heat flux created by CH at the moment of the

circuit closing; S_h is a heating square, covered by CH.

The approximate method of calculating the characteristics of the ignition described below is based on a criterion - the achievement of the surface of the "temperature flashpoint" sample equal to $T_{bc} \approx 500$ K.

For the dependence of the surface temperature of the DSF sample on the time at the accident inert heating stage, an analytical solution with the following form was obtained [4]:

$$\Theta_{sp}(\tau) = \Theta_c + \frac{q}{n\sigma} \left[\frac{a_2 \Psi_2(a_2 \sqrt{\tau}) - a_1 \Psi_1(a_1 \sqrt{\tau})}{a_2 - a_1} - e^{(-\sigma\tau)} + \frac{(a_2 + a_1)}{\sqrt{\pi}} \int_0^\tau \frac{e^{[\sigma(z-\tau)]}}{\sqrt{z}} dz \right], \quad (3)$$

where similar complexes are marked in such a way for brevity

$$\Psi_i(a_i \sqrt{\tau}) = \exp(a_i \sqrt{\tau})^2 \operatorname{erfc}(a_i \sqrt{\tau}) . \quad (4)$$

Here $\operatorname{erfc}(z) = 1 - \operatorname{erf}(z)$ is an additional integral of probability.

The dimensionless parameters which are part of (3) are calculated in that way:

$$a_1 = n(1 - \delta_1)/2, \quad a_2 = n(1 + \delta_1)/2, \quad \delta_1 = \sqrt{1 - 4n \operatorname{Bi}_c}, \quad 1 - 4n \operatorname{Bi}_c > 0$$

$$\sigma = \frac{2t_r}{R_h C_0}; \quad \operatorname{Bi}_c = \frac{\alpha_{ef} l_m}{\lambda_k}, \quad q = \frac{q_h l_m}{\lambda_k T_m}, \quad n = \frac{c_h \cdot \rho_h \cdot d_h + c_s \cdot \rho_s \cdot d_s}{c_k \cdot \rho_k \cdot l_m} .$$

Here $t_r = 2.3R_{cl} \cdot C_0$ is the time of discharge of the capacitor [6]; physical properties of DSF, spiral bulbs and heat-resistant glass: ρ_k is density, kg/m^3 ; c_k is the specific heat capacity of the mass, $\text{J}/(\text{kg}\cdot\text{K})$; λ_k , a_k are thermal conductivity coefficients, $\text{V}/\text{m}\cdot\text{K}$ and thermal diffusivity, m^2/s ; c_h are the specific heat capacity of the mass, ρ_h is density and d_h is the diameter of the wire; c_s is the specific heat capacity of the mass, ρ_s is density and δ_s is the thickness of the HG's bottom; α_{ef} is the effective heat transfer coefficient.

The scale coordinates and density of the heat flux are:

$$l_m = \sqrt{a_k t_r}, \quad q_m = \lambda_k \cdot T_0 / l_m .$$

The calculation of the probability integral was carried out according to the interpolation formula [6] which has one coefficient

$$\operatorname{erf}(z) = \sqrt{1 - \exp(-1.26z^2)} .$$

The costs of heating the bottom part of the HG are calculated with the help of the n parameter in the DSF ignition scheme shown in figure 1.

$$q_{HC} = \frac{1}{t_r} \int_0^{t_r} q_H dt = \frac{U_0^2}{4.6R_h \cdot S_h} .$$

Let us note that q_{HC} indirectly depends on C_0 through t_r and affects the parameter σ , reducing it with the increasing of C_0 . Another option in data processing is the use of the initial value of the specific electrical energy equal to the ratio of $A_0 = E_0 / S_h$.

4 The results of the ignition time

An analysis was conducted for CH from nichrome wires of different diameters. Table 3 shows the calculated data of t_z depending on A_0 for the N type of DSF.

Table 3. Ignition time at varying the heat load on CH in the presence of the screen.

$A_0, \text{mJ/m}^2$		0.25	0.50	0.75	1.0	1.25
1)	t_z, ms	∞	0.2	0.14	0.10	0.065
2)		0.3	0.13	0.095	0.086	0.85
3)		0.3	0.075	0.03	0.02	0.018

The length of the wire was 140 mm and the diameter for variants 1 and 2 was 0.1 mm, and for variant 3 was 0.25 mm. For fixed $U_0 = 1600 \text{ V}$ capacitance the values ranged from 4 to 40 μF . The thermal load A_0 varied from 0.06 to 0.69 mJ/m^2 , and t_z decreased from 9.1 to 8.3 ms.

Installing HG onto the end part of the block leads to the appearance of a screen between the surface of DSF and CH of 1 mm thickness. The varying of U_0 from 950 to 2000 V increased E_0 from 22.6 to 100 J, the corresponding thermal load increased from 0.3 to 1.34 mJ/m^2 , and t_z decreased from 347 to 60 ms (variant 1). During the discharge the surface temperature of the block reached only 396 K when $C_0 = 5 \text{ uF}$ and $U_0 = 1600 \text{ V}$.

In the next series of calculations C_0 changed from 10 to 80 μF , and the voltage was $U_0 = 1600$. The results are shown in the form of the 2nd variant. From the structure of dependence (2) for the heat flux density generated by CH it follows that its amplitude is defined by the initial voltage U_0 . The capacitance value affects the development of the process of heating the sample in time - for large C_0 (σ parameter is less) the temperature rise is slower and the ignition time increases.

The change in d_p is affected through the n and q_{HC} parameters. A wire 2.5 times as thick was used in the 3rd variant and as a result, the n parameter value became 2.5 times larger. However, $R_h \sim 1/d_p^2$ and therefore q_{HC} increased to 6.25, which resulted in a decrease of t_z .

Thus, the analysis showed that in the presence of a thin steel screen between CH and the end surface of a block from DSF, sources that allow the production of an energy density of more than 30 mJ/m^2 in the section of DSF heating are necessary for the realization of this process. In particular, a PC – 2000 m explosive device can be used.

5 Estimation of the safe electrical load on spiral bulbs heated by capacitors

To ensure re-ignition of the block of the same CH it is necessary that its electrical resistance changes little and that contact with the connecting wires is maintained.

The conductor may break after its heating to a temperature comparable to the melting temperature T_{pl} of the corresponding metal with high resistivity shown in Table 1. The results of such an analysis for the variant of CH heating from an autonomous power supply of direct currents are shown in the work [7].

Within the thermo-technical approach of evaluating the load on the conductors of nichrome or another alloy, the maximum current strength is determined that can be passed through the wire heater surrounded by air, so that the maximum temperature does not exceed 1273 K [8].

In another source [9], it is necessary to calculate the strength of the current going through thin nichrome wire of 0.1 mm in diameter and 2 m in length, placed horizontally in the air, having a temperature of 293 K, at which its destruction will occur, if it is known that nichrome has $T_{pl} = 1733$ K.

There is such a task in [10]. An electric detonator in the form of a cylinder of 0.1 mm in diameter and 5 mm in length is in air whose temperature is $T_0=303$ K, the intensity of cooling heating wire is characterized by the heat transfer coefficient $\alpha = 10$ W/(m²·K). The thermal properties of the detonator are: thermal conductivity $\lambda_h = 20$ W/(m·K), $a_h = 5 \cdot 10^{-5}$ m²/s, the melting temperature of the detonator's metal is 1173 K, and the electrical resistance $R_h = 0.2$ Ohm. The task is to determine the time after which the detonator would explode when passing through it a constant current of 3 A, neglecting the radiation and escape of the heat to the attachment at the ends of the detonator. The value of $t = 7.62$ ms is given in the answer.

Let us add to the results of the DSF ignition analysis for spiral bulbs heated by capacitors an estimation of the time required to reach the temperature limit T_{pl} .

Let us sum up the formulations given in [7] due to the reducing current (1).

Let us write the heat balance of the area of wire based on the energy conservation equation.

When an electrical current passes through a conductor of cylindrical shape of d_p in diameter and l_p in length, heat is generated which can be calculated by the formula of Joule [9]:

$$Q = I^2 R_p = U_0^2 \cdot \exp(-2t / R_p C_0) \sigma_p / (\rho_{el} l_p), \quad (5)$$

where σ_p is the cross-sectional square of the conductor.

Cooling of the conductor is carried out by free convection and radiation, and c can be taken into account by an appropriate heat transfer coefficient [8]. Let us use the effective value of α equal to 2000 W/(m²·K) [11], which corresponds to the intensity of the heat exchange between wire of nickel alloy and chromium, heated when passing through an electrical current and DSF embedded in the surface layer. Estimation of the Bio number $Bi = \alpha d_p / 2\lambda$ shows that for thick wires in the task it is $Bi = \alpha d_p / 2\lambda = 2 \cdot 10^3 \cdot 0.5 \cdot 10^{-3} / 2 \cdot 11.6 = 0.043$. Consequently the thermally thin body model is applicable [9].

The heat balance equation for the wire has the following form

$$c_p \rho_p V_p dT_p / dt = Q - \alpha (T_p - T_w) S_p, \quad (6)$$

where c_p is the specific heat capacity of the mass of the conductor; ρ_p is its density; V_p S_p is the volume and the square of the surface of the conductor.

Having substituted into the differential equation (6) the expression for heat evolution (5), we obtain a linear inhomogeneous ordinary first-order differential equation:

$$dT_p / dt + A(T_p - T_w) = B \exp(-Dt), \quad (7)$$

where

$$A = \frac{\alpha S_p}{(c_p \cdot \rho_p \cdot V_p)}; \quad B = \frac{U_0^2}{(c_p \cdot \rho_p \cdot V_p \cdot R_{el})}; \quad D = \frac{2}{R_p \cdot C_0}.$$

The temperature of the wire is equal to the temperature of the wall of the heat-resistant glass at the initial moment of time: at $t = 0$ $T_p = T_w$.

Using the expression for the general integral (7) from [12] and determining the integration constant using initial conditions, we obtain

$$T_p = T_w + B[\exp(-Dt) - \exp(-At)] / (A - D). \quad (8)$$

The described algorithm for calculating the desired temperature was employed using a PC.

The following results were obtained in the course of the parametric analysis. The temperature of the nichrome wire $d_p = 0.2 \cdot 10^{-3}$ m, $l_p = 0.12$ m in length, reached a maximum value $T_p = 650$ K by the time moment $t = 0.08$ ms after using the capacitor subversive machine CSM-3 with $U_0 = 1600$ V and the capacity $C_0 = 4$ uF. A twofold reduction of d_p leaving the other parameters unchanged led to the wire after the heating time $t = 0.24$ ms reaching the maximum temperature of 1697 K, which exceeds the melting temperature of nichrome. Using a pulsed source of PC-2000m with higher energy ($E_0 = 50$ J) contributes to the intense increase in the temperature of the wire, which at the time $t = 0.06$ ms had already been exceeding T_{pl} .

Analysis of the obtained results showed that in cases when E_0 is less than the energy required to heat the wire to the melting temperature $E_p = c_p \rho_p V_p (T_{pl} - T_w)$, then the wire maintains a functional state.

For example, heating the wire of $d_p = 0.2$ mm and $l_p = 0.2$ m up to T_{pl} requires 34.3 J of energy. The PC-2000m pulsed source has 36.0 J of energy. By the time moment $t = 0.51$ ms the temperature of the wire reaches 1693 K. The choice of wire of $d_p = 0.5$ mm and the previous length requires 128.5 J of energy to heat it to the temperature T_{pl} . The use of a PC-2000m pulsed source allows heating of the wire to 694.6 K.

Another option for CH conservation in the functional state is to switch it off after its heating, for example, up to 1000 K. In practice, this can be realized with the aid of a technical solution [13], where the shunt resistor is set parallel to the heating wire and a fuse strip is placed successively with this juncture. When using an electro-initiator via a current impulse of an amplitude from 2 A and duration of 30 ms there occurs a fail-proof ignition of the working charge with a probability of not less than 0.999, and the subsequent fail-proof shutdown of the electro-initiator with the same probability.

6 Conclusion

A method was developed for the automated calculation of the safe electrical load on spiral bulbs heated by capacitors for multiple start-ups of an open underwater gas generator. An energy criterion has been proposed which allows the selection of a type of pulsed power supply that enables the heating of wire required for DSF ignition, and maintaining the functional state of spiral bulbs with known dimensions and thermal properties.

Acknowledgments

The reported study was funded by RFBR according to the research project No. 16-03-00630a.

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