HEAT TRANSFER OF A SPHERE IN A FIELD OF NONLINEAR OSCILLATION BURSTS

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The results are given from an experimental and theoretical study of the influence of nonlinear oscillations generated by a pulse chamber on the heat transfer of a sphere.

The action of a sound field affords a promising method for the intensification of heat- and mass-transfer processes [1-3]. However, in order to obtain a positive effect it is necessary to attain a definite threshold level of the intensity of the sound field, the value of which depends on the technological conditions and has to be at least 130 dB [4]. The generation of such powerful oscillations involves large expenditures of energy, particularly when the low acoustic output of existing radiators with efficiencies that scarcely reach 25% is taken into consideration [5]. Consequently, the use of oscillations for the improvement of technology on the basis of existing sound radiators is certainly not very realistic.

A promising outlook in this regard is offered by devices in which oscillations are generated by a combustion process, i.e., so-called vibratory combustion chambers [3, 6, 7]. It has been established [7] that the frequency of the oscillations in such devices can be varied over a wide range, from fractions of a hertz to several kilohertz, and the amplitude can be brought up to 180 dB or more.

Vibratory combustion chambers are divided into two types: resonant, where the oscillation frequency is determined by the acoustical properties of the chamber, and nonresonant or relaxation, where the oscillation frequency is set by means of a special control unit [7].

Since the frequency and amplitude of the oscillations are virtually unamenable to control in resonance vibratory combustion, the application of such chambers for the intensification of heat- and mass-transfer processes is rather limited. Preference must be given to pulse chambers, in which the relaxation combustion regime takes place [8, 9].

In the present article we give the results of investigations of a pulse chamber as a generator of nonlinear oscillations with the objective of ascertaining the hypothetical feasibility of using them for the intensification of heat- and mass-transfer processes.

The pulse chamber represents a duct that is closed at one end and is filled with a fuel—oxidant mixture. When the ignition source is fired, rapid combustion of the mixture occurs, accompanied by a sudden increase in the pressure, temperature, and flow velocity of the reaction products from the open end in the form of a jet and vortices; at the same time, strong shock-type oscillations of the pressure and velocity are generated both in the duct of the chamber and in the surrounding medium [10, 11]. This is followed by a transient process, in the course of which the pressure in the pulse chamber equalizes to the mean value. The nature of the pressure perturbations is shown in Fig. 1a, and an idealized version of the process for the velocity pulsations is shown in Fig. 1b. The analytical expression for the velocity oscillations in the time interval $\tau_2 - \tau_1$ has the form

$$U = U_0\left(1 + \frac{V_0}{U_0}\exp(-\delta\tau)\sin\omega\tau\right). \tag{1}$$

The damped behavior of the oscillations indicates that oscillatory energy losses exist in the investigated system, primarily on account of radiation from the open end of the pulse

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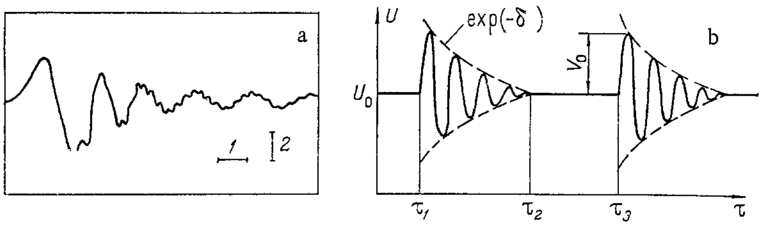

Fig. 1. Oscillogram of the pressure in the pulse chamber (a) and idealization of the process (b). Scale: 1) $5 \cdot 10^{-3}$ sec; 2) $1.4 \cdot 10^{4}$ Pa.

chamber. A calculation of the numerical value of this quantity, based on Gutin's impedance formula [12], in application to our conditions yields $\delta = 0.12$, whereas the value obtained experimentally was $\delta \geqslant 0.9$ and increased with the amplitude of the oscillations. Such a discrepancy between the calculated and experimental results indicates the inapplicability of the purely acoustical approach for describing the dynamic processes involved in relaxation combustion systems in general and in pulse chambers in particular, owing to the appreciable nonlinearity of the oscillatory processes. Thus, in the experiments the quantity P_0' was varied between the limits $(0.1\text{–}0.5) \cdot 10^5$ N/m², corresponding to an amplitude value of the velocity pulsations V_0 = 25–125 m/sec, which has been measured by the shadowgraph method [10, 11], and the sound pressure level in this case was 174–188 dB.

Consequently, in calculating the properties of the pulse chamber as a source of oscillations it is necessary to take into account nonlinear effects associated with, in particular, the nonexponential behavior of the oscillation amplitude as a function of the time. Thus, on the basis of integral conservation laws the rate of change of the oscillatory energy density in the pulse chamber is equal to the acoustic energy flux radiated from the open end of the chamber. The small contribution of viscous dissipation is neglected. The wave energy flux across unit area is

$$\Pi = \langle P'V' \rangle = \langle V'^2 \rangle \,\mathrm{Real}\, z.$$

The impedance is calculated according to Gutin's formula [12] for small amplitudes. In the investigated situation it is required to take into account the dependence of the impedance on the amplitude of the oscillations. We assume that [13, 14]

$$\mathrm{Real}\, z = x + \frac{1}{2}\rho_0 |V'|,$$

where, according to Gutin, $x = \rho_0 \omega^2 D^2 / 16c$. Then the time variation of the oscillatory energy $A = \rho_0 V^2 L$ is written

$$\frac{dA}{dt} = -\frac{\rho V^2}{2}\left(\frac{\omega^2 D^2}{8c} + V\right),$$

or

$$\frac{dV}{dt} = \frac{V}{4L}(k + V). \tag{2}$$

In the derivation of this relation it is borne in mind that the natural frequency of the pulse chamber, as a quarter-wave resonator, is $\omega = \pi c/2L$. It must also be explained where the factor L comes from in the expression for the energy density. Inasmuch as all considerations are referred to unit area, the energy density A in a pulse chamber of length L is determined as the energy density of unit volume formed on unit area, multiplied by the length L of the chamber.

The solution of Eq. (2) is

$$V = V_0 \frac{\exp(-\delta\tau)}{1 + \dfrac{V_0}{k}(1 + \exp(-\delta\tau))}. \tag{3}$$

Consequently, the shape of the envelope differs from exponential in the real process, the departure becoming more pronounced with increasing value of V_0/k, i.e., with increasing amplitude of the velocity oscillations, because a growth of the amplitude is accompanied by increased radiation losses. Accordingly, the Q of the pulse chamber as an acoustic resonator deteriorates rapidly.

If we introduce an effective damping factor, the value of which depends on the amplitude, then for the case $V_0/k = 312.5$, which corresponds to $V_0 = 125$ m/sec, $D = 0.05$ m, $L = 0.8$ m, $c = 330$ m/sec, we have $\delta_{ef}/\delta = 35.7$. The functional dependence for the 3% level is approximated with acceptable accuracy by the linear relation $\delta_{ef}/\delta = 1 + 0.111V_0/k$.

The dimensionless group $V_0/k = 2M_0(4L/\pi D)^2$ can be said to characterize the degree of influence of nonlinear effects on the structure of the oscillations generated by the pulse chamber, which differ significantly from acoustic oscillations insofar as they are nonlinear, exhibit a pulse-train ("burst") behavior, and are of the relaxation type, i.e., a "quiescent period" exists.

We consider the heat-transfer process around an isolated spherical particle of diameter d in the field of the above-described oscillations. The conventional approach based on the solution of the hydrodynamic and heat-transfer equations with appropriate boundary and initial conditions is perfectly natural for the theoretical investigation. However, since the equations are nonlinear and the behavior of the flow is complicated (by the presence of detached zones and the strong nonlinearity of the disturbances), it is practically impossible to obtain any kind of useful information with this approach.

Therefore, in the ensuing calculation of heat transfer in the field of nonlinear oscillations we invoke the quasi-steady state hypothesis, which yields a satisfactory qualitative, and often quantitative, description of the process. According to this hypothesis, the heat-transfer coefficient at every instant can be determined from the instantaneous values of the velocity by means of the corresponding steady-flow relation.

We use Eckert's formula [15]

$$\mathrm{Nu} = 2 + 0.37\,\mathrm{Re}^{0.6}\mathrm{Pr}^{1/3}.$$

We substitute the flow-velocity expression (1) in this formula with allowance for (3) and, averaging over the time interval $\tau_3 - \tau_1$ (see Fig. 1), we obtain

$$\mathrm{Nu} = 2 + 0.37\,\mathrm{Re}_0^{0.6}\mathrm{Pr}^{1/3}\frac{1}{\tau_3-\tau_1}\int\limits_0^{\tau_3-\tau_1}\left(\left|1 + \frac{B\exp(-\delta\tau)\sin\omega\tau}{1+\frac{V_0}{k}(1-\exp(-\delta\tau))}\right|\right)^{0.6}d\tau.$$

The absolute value in the integrand is dictated by the fact that heat transfer is indifferent to the direction of flow.

The measure of effect of the oscillations on the heat transfer is expressed by the relation

$$\Theta = \frac{\overline{\mathrm{Nu}}-2}{\mathrm{Nu}_0-2} = \frac{1}{\tau_3-\tau_1}\int\limits_{\tau_1}^{\tau_3}\left(\left|1 + \frac{B\exp(-\delta\tau)\sin\omega\tau}{1+\frac{V_0}{k}(1-\exp(-\delta\tau))}\right|\right)^{0.6}d\tau. \quad (4)$$

If the parameter $\Theta > 1$, the oscillations will intensify the heat transfer; otherwise they will suppress it. The integral in relation (4) is not expressed in terms of elementary functions. Consequently, to simplify the ensuing arguments we partition the domain of integration in accordance with Fig. 1b into two subdomains: one active in the interval between τ_1 and τ_2 ($\tau_a = \tau_2 - \tau_1$), where the influence of the oscillations is significant, and the other passive in the interval between τ_2 and τ_3, where disturbances are absent. We recall that $1/(\tau_3 - \tau_1)$ is nothing other than the frequency of relaxation oscillations of the pulse chamber L, and this frequency, in turn, depends on the rate of influx U_0 (m/sec) of fresh fuel mixture into the chamber, the length L of the chamber, and the degree of filling m ($f = U_0/mL$). The duration of the transient process $\tau_a = \tau_2 - \tau_1$, which we call the active time, is selected on the basis of the requirement that the amplitude of the oscillations is not more than 3% of the initial value, i.e.,

$$\tau_a = \frac{1}{\delta}\ln\left(\frac{1+0.03V_0/k}{0.03(1+V_0/k)}\right) \approx \frac{3.5}{\delta(1+0.111V_0/k)}.$$

Taking the foregoing into account, we rewrite relation (4) in the form

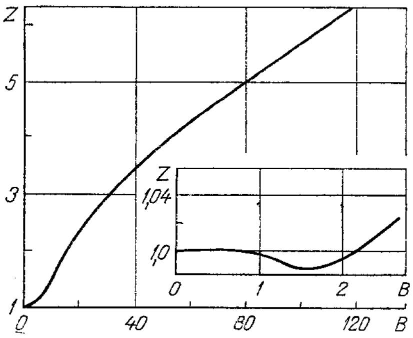

Fig. 2. Function Z vs relative oscillation amplitude B.

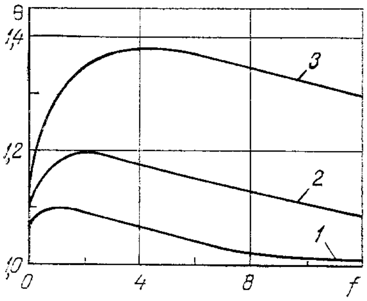

Fig. 3. Influence of the relaxation oscillation frequency f (Hz) on the intensification of heat transfer. 1) V_0 = 20 m/sec; 2) 40; 3) 80.

$$\Theta = 1 + \left(\frac{8}{\pi}\right)^2 M_0 \left(\frac{L}{D}\right)^2 \frac{7}{(1 + 0.111\, V_0/k)m} (Z - 1). \tag{5}$$

Here

$$Z = \frac{1}{\tau_a} \int_0^{\tau_a} \left(\left| 1 + \frac{B \exp(-\delta\tau) \sin \omega\tau}{1 + \frac{V_0}{k}(1 - \exp(-\delta\tau))} \right| \right)^{0,6} d\tau.$$

The nature of the dependence of Z on the relative amplitude B for small values of the parameter V_0/k is shown in Fig. 2. It is seen that for small amplitudes the presence of oscillations can even degrade the heat-transfer process, and only after they have attained a definite level is a positive effect observed. It follows from relation (5) that for a given influx rate (M_0 = const) the intensification of heat transfer will be higher for larger oscillation amplitudes. However, expression (5) is not altogether suitable for the final calculation. Therefore, making use of the fact that the pulse chamber is a quarter-wave resonator, i.e., $f_{ac} = c/4L$, we obtain

$$\Theta = 1 + \frac{112}{1 + 0.111\, V_0/k} \frac{f}{f_{ac}} \left(\frac{L}{\pi D}\right)^2 (Z - 1). \tag{6}$$

An analysis of relation (6) shows that for a specified frequency f of the relaxation oscillations the variations of the heat transfer depend not only on the initial amplitude factor B, but also on the acoustical properties of the chamber, f_{ac}, and its geometrical parameters L/D. In this case the positive effect increases with a decrease in the acoustic frequency or with an increase in the length of the chamber. This is because the active time increases in relation to the total period of the relaxation oscillations.

The final calculation of the intensification of heat transfer in the field of nonlinear oscillations generated by the pulse chamber was carried out as follows. The amplitude V_0

of the velocity oscillations and the geometrical parameters of the chamber (its length and diameter) were specified. The frequency of the relaxation oscillations (for m = 1) and the dimensionless amplitude B were calculated for various values of the rate of influx U_0 of fresh fuel mixture into the chamber. It was assumed here, in accordance with the data of [10], that the amplitude value $|V_0|$ of the velocity oscillations remains constant with a variation of U_0. Equation (6) was used to determine Θ once B and Z had been calculated.

Figure 3 shows the intensification of heat transfer as a function of the frequency of the relaxation oscillations of the pulse chamber for three values of the velocity pulsation amplitude. The process exhibits an extremal behavior, with the peak value of Θ increasing and shifting toward higher frequencies as the amplitude of the oscillations is increased.

Consequently, there is a definite frequency range in which optimal intensification is observed, the magnitude of which depends on the geometrical, dynamical, and acoustical properties of the pulse chamber.

We consider the case of a large relative amplitude $B \gg 1$. Then

$$\Theta = (\mathrm{Nu_p} - 2)/(\mathrm{Nu_0} - 2) \approx \mathrm{Nu_p}/\mathrm{Nu_0},$$

and, neglecting small quantities, we write relation (6) in the form

$$\Theta = fB^{0.6} \int\limits_0^{\tau_a} \frac{\exp(-\delta\tau)\, d\tau}{\left[1 + \frac{V_\theta}{k}(1 - \exp(-d\tau))\right]^{0.6}}.$$

Making the substitution

$$X = \exp(-\delta\tau),\ \beta = V_0/k,$$

$$\Theta = \frac{fB^{0.6}}{\delta(1+\beta)^{0.6}} \int\limits_0^1 X^{-0.4}(1 - \Phi X)^{0.6}\, dX,$$

after straightforward transformations [16] we obtain

$$\Theta = \frac{5}{3}\,\frac{fB^{0.6}}{\delta(1+\beta)^{0.6}} F(0.6;\ 0.6;\ 1,6;\ \Phi). \tag{7}$$

If the contribution of nonlinear terms is small ($\beta \approx 0$, $\Phi \approx 0$), then $F(\alpha_1, \alpha_2, \alpha_3) = 1$, and relation (7) acquires the form

$$\Theta = \frac{640}{3\pi^2} fB^{0.6} \frac{L}{c}\left(\frac{L}{D}\right)^2. \tag{8}$$

Consequently, for a given geometry of the pulse chamber the variations of the heat transfer will be proportional to the group ($fB^{0.6}$).

If, on the other hand, the contribution of nonlinear processes associated with radiation is appreciable ($B \gg 1, \Phi \approx 1$):

$$F(\alpha_1,\ \alpha_2,\ \alpha_3,\ 1) = \frac{\Gamma(\alpha_3)\Gamma(\alpha_3 - \alpha_2 - \alpha_1)}{\Gamma(\alpha_3 - \alpha_1)\Gamma(\alpha_3 - \alpha_2)}$$

(Γ is the gamma function), then relation (7) is written in the form

$$\Theta = 13.2 \frac{fL}{U_0^{0.6}}\left[\frac{32}{\pi^2 c}(L/D)^2\right]^{0.4}. \tag{9}$$

The distinctive feature of this case is the absence of any influence of the velocity oscillation amplitude on the heat transfer. We can therefore state that for large amplitudes there is a limiting multiplicity of the intensification of heat transfer of an isolated sphere and its value is determined by the mean flow velocity U_0 and the diameter of the duct, decreasing as these quantities are increased, and is also proportional to the length of the chamber and the frequency of the relaxation oscillations. This "saturation" is attributable to the restricting influence of the nonlinear oscillatory effects taking place in the pulse chamber, since the radiation losses from the open end of the chamber increase abruptly with the amplitude, thereby shortening the active time τ_a.

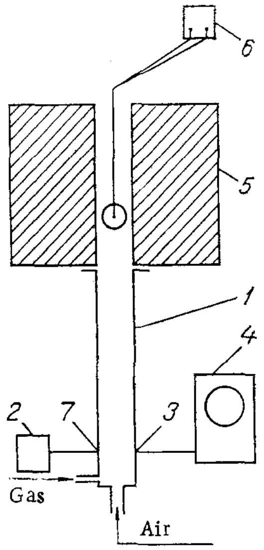

Fig. 4

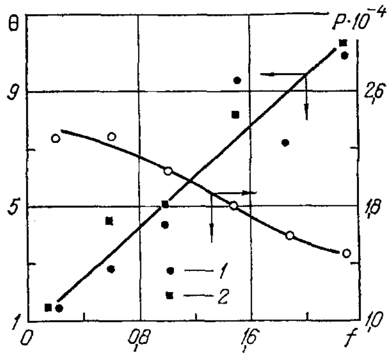

Fig. 5

Fig. 4. Schematic view of the experimental apparatus. 1) Pulse chamber; 2) ignition unit; 3) pressure sensor; 4) oscilloscope; 5) furnace; 6) recording instrument; 7) spark plug.

Fig. 5. Influence of the frequency of relaxation oscillations on the intensification of heat transfer and the pressure amplitude P (Pa) in the chamber. 1) d = $2\cdot10^{-2}$ m; 2) $2.9\cdot10^{-2}$ m.

The experimental study of heat transfer was carried out on the apparatus shown in Fig. 4, which includes the pulse chamber, an ignition unit, an LKh-600 pressure sensor, and an oscilloscope. The pulse chamber consists of a tube with an inside diameter D = $5\cdot10^{-2}$ m and a length L = 0.8 m; it is made of ST-3 titanium steel. The open end of the chamber goes into the working compartment of a type SUOL-0,44 furnace, which has the same inside diameter. The ignition unit generates periodic (with a 2.5% spread) high-voltage pulses at a frequency of 0.1-3 Hz. The spark plug is situated at the closed end of the pulse chamber. The propane fuel and air were fed into the chamber separately. The gas flow was recorded with a rheometer, and the air flow with an RS-5 rotameter, within 5% error limits. The pressure in the chamber was measured within 20% error limits by means of a piezoelectric transducer, whose output signal was recorded by a type S1-18 oscilloscope.

The object of investigation was a sphere of Kh13 chrome steel, which was attached to a holder; thermocouples were placed in a differential configuration both inside and outside the holder, and their signals were sent to an N-30 recording millivoltmeter. Two spheres having diameters of $2\cdot10^{-2}$ and $2.9\cdot10^{-2}$ m were used in the experiment. The thermophysical properties of the sphere material were determined in preliminary experiments. The deviation from sphericity did not exceed 3.4%.

The heat-transfer coefficient was measured by the regular heating method [17]. The steady-flow heat transfer was investigated first. Then the pulse chamber was activated; the rate of influx of the fuel mixture into the chamber was equal to the airflow velocity past the sphere in the steady process. To diminish the influence of the temperature fluctuations produced by the pulse chamber on the heat transfer the temperature in the furnace was maintained constant and equal to 180°C within 12% limits. The initial temperature of the sphere was 20°C in all the experiments.

The experimental investigations showed that the relative convective heat-transfer coefficient Nu_p/Nu_0 is a linear function of the frequency f of the relaxation oscillations, and better than tenfold intensification of the process is observed at the maximum frequency f = 2.3 Hz attained in the experiments (Fig. 5).

In this experiment the rate of influx of the fuel mixture into the chamber (U_0 = 0.67 m/sec), the concentration (C = 3.7%), and the geometrical parameters were held constant, while the frequency and amplitude of the oscillations were varied. In this case an increase in the oscillation frequency was accompanied by a decrease in the amplitude, owing to the decrease in volume of the combustible mixture. Thus, what appears at first glance to be an odd situation takes place, in that the heat-transfer process is intensified by a decrease in the amplitude of the oscillations.

All of this indicates that the amplitude of the oscillations does not affect the heat transfer. Additional investigations carried out at a fixed frequency supported this conjecture. The amplitude was regulated by varying the concentration of the mixture. These results are qualitatively consistent with the theoretical analysis. Thus, under the experimental conditions (V_0 = 25-120 m/sec, c = 410 m/sec, D = $5 \cdot 10^{-2}$ m, L = 0.8 m, U_0 = 0.67 m/sec) the numerical values of the amplitude factor and the nonlinearity parameter are B = 40-180 and β = 50-240, which are considerably greater than unity. In this case it is required to describe the heat transfer by relation (9), which indicates a linear dependence on the frequency of the relaxation oscillations and the absence of any influence by the amplitude. However, the calculations according to (9) predict a stronger intensification of heat transfer (Nu_p/Nu_0 = 40 for f = 2.3 Hz). This disparity is attributable to the approximate scheme of the computations, since the heat transfer was analyzed in an unbounded flow, whereas the experiments were carried out under confined-flow conditions.

The reported investigations lead to the conclusion that the pulse chamber as a generator of nonlinear oscillations is a highly promising device for the intensification of convective heat and mass transfer.

NOTATION

U_0, rate of influx of fresh fuel mixture into the chamber; V_0, amplitude of velocity pulsations; V',P', velocity and pressure pulsations; U, instantaneous value of velocity; V, instantaneous value of velocity pulsation amplitude; c, sound velocity; P_0', initial amplitude of pressure pulsations; Π, acoustic energy flux through open end of pulse chamber; A, volumetric acoustic energy density; z, impedance; x, linear part of Gutin impedance; L, D, length and diameter of pulse chamber; ρ, density; τ, time; ω, natural (angular) frequency of pulse chamber; m, degree of filling of pulse chamber; f, frequency of relaxation oscillations; d, diameter of sphere; τ_a, active time of oscillations; β, Z, X, Φ, Θ, dimensionless functions; $\Gamma(\alpha)$, gamma function; $F(\alpha_1, \alpha_2, \alpha_3, \Phi)$, hypergeometric function; $Re_0 = U_0 d/\nu$, Reynolds number; $Pr = \nu/a$, Prandtl number; $M_0 = U_0/c$, freestream Mach number; $B = V_0/U_0$, amplitude factor; Nu_0, Nu_p, dimensionless heat-transfer coefficient in the absence (B = 0) and in the presence of pulsations; $k = \pi^2 c(D/L)^2/32$, parameter; $\delta=\frac{\pi^2 c}{128L}(D/L)^2$, damping factor.

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STUDY OF PHYSICAL PROCESSES IN A SPARK DISCHARGE

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Temperature and energy balance are calculated for a breakdown channel in a solid dielectric.

Electrical breakdown of solid dielectrics is accompanied by liberation of heat in the discharge gap and scattering of energy into the surrounding medium. Scintillation of the breakdown channel, beginning at the moment of its formation and lasting until the end of the discharge, indicates that the matter within the channel is at a high temperature. Data on temperature and the components of energy balance in the stage of discharge formation in solid dielectrics are not available in the literature, while at the stage of discharge completion available data are scarce.

To measure the diameter of the discharge channel and the energy liberated therein, the apparatus described in [1] was used. Specimens were prepared from rock salt single-crystals. The interelectrode distance $d = 1$ cm. Breakdown was produced by square voltage pulses with an amplitude of 80 kV in a nonuniform field with positive polarity of the discharge point. The capacitor system used had $C = 2400$ pF, $L = 1.85$ μH, and braking resistance $R_r = 150\ \Omega$. The discharge was produced in the crystallographic direction (110), with a breakdown channel length $l = 1.4$, $d = 1.4$ cm.

Comparison of voltage u(t) and current i(t) oscillograms taken under identical conditions for breakdown of several tens of specimens showed good agreement. Typical u(t) and i(t) oscillograms are shown in Fig. 1.

The pulsed breakdown goes through two stages.

1. Discharge Formation. The time for this stage is shown in Fig. 1 by the segment t_f. It begins at the moment corresponding to the static breakdown voltage U_{st}, and ends with an abrupt drop of voltage across the specimen. In the beginning of breakdown development, electron avalanches develop and transform into a streamer which melts an incomplete breakdown spark channel into the specimen. The streamer propagates from one electrode to the other at a rate of the order of 10^6 cm/sec. By the end of the stage the current density passing through a channel of diameter 1 μm increases to 10^5 A/mm². The formation stage is completed by the full extension of the streamer across the gap.

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