Фізика аеродисперсних систем. – 2024. – № 62. – С.72-85

ФІЗИКА ГОРІННЯ

UDC 536.46

Poletaev N. I.

Odessa National Maritime University, Odessa, Ukraine, E-mail: poletaev@ukr.net

Correlation method for measuring the combustion time of micro-sized metal particles in a dust flame

The paper considers the possibilities of experimental determination of the combustion time of metal particles using the correlation analysis of flame luminosity. Experiments were carried out for dust flames of micro-sized spherical particles (d_{10}< 5 μm) of Fe, Zr and Al in an axisymmetric laminar diffusion dust flame. The number density of particles in the gas suspension (in nitrogen) was about 10^{12} m^{-3}. The width of the combustion zone at temperature T = (2000÷3000) K in the flame was 1÷2 mm. Under these conditions, the combustion zone is optically thin. This ensures the additive contribution of each particle to the combustion zone radiation. It was shown experimentally, as well as by simulation modelling methods, that the accuracy of combustion time measurements is affected by the stationarity of the object of study, the shape of the radiation trace from the burning particles, and the polydispersity of the initial fuel particles.It was found that the main cause of flame nonstationarity is low-frequency oscillations of different nature, which arise in the reacting two-phase flow at the moment of radiation registration.Studies have shown that processing of flame intensity time series by a high-pass filter (HPF) with a cut-off frequency of about 20 Hz significantly improves the appearance of the autocorrelation function (AF) and allows a more accurate determination of the effective correlation time (particle burning time). Limitations of the application of the HPF, which may lead to distortion of the AF and correlation time, are discussed.The interpretation of AF and correlation times is significantly complicated for polydisperse particle gas suspensions due to the dependence of the particle burning time and their radiative characteristics on the particle size. Simulation modelling methods show that in practice the range of monodispersity of fuel particles can be extended to values of the coefficient of variation of 20-25 %.

Keywords: *correlation analysis, autocorrelation function, particle burning times, metal dust flames, polydispersity.*

Introduction. The combustion time of dispersed propellant particles is an important characteristic that determines the possibility of using a particular propellant for energy or technological applications. This time can be most reliably determined experimentally by direct measurements (usually single fuel particles with a diameter greater than 50 μm) [1-3] and indirect measurements, in which information on combustion times is obtained by studying the combustion of gas suspensions of fuel particles under well-controlled conditions (flame interferometry, methods of photometry of the combustion zone of a dust flame, experiments to determine the normal flame velocity to determine the law of combustion of particles in a gas suspension $t_b \sim d^n$) [4-5].

Small (diameters less than 20 μm) combustible particles are best suited for practical application. In this case, the combustion time of particles is significantly reduced,

DOI: 10.18524/0367-1631.2024.62.318556

the flame propagation speed through their gas suspensions increases, there is no sedimentation and lagging of particles from the carrier gas, radiation heat losses are reduced, etc. At the same time, micro-sized fuel powders are usually rarely monodispersed. For polydisperse powders the problem of interpretation of combustion times measured by non-direct methods arises.

The classical measurement methods developed for single particles and large-particle gas suspensions, based on registration and processing of burning particle tracks, are practically inapplicable for them. The situation is complicated by the fact that particles in gas suspensions can burn in heterogeneous or gas-phase modes. In the first case, the combustion zone of a dust flame is discrete, while in the second case it looks homogeneous, since light fluxes are emitted mainly not by burning particles, but by submicron combustion products formed in the process of condensation. As a result, methods suitable for measuring the combustion times of heterogeneously reacting particles may not be applicable to vapour-phase (or gas-phase) burning combustible particles. Therefore, the development of methods for measuring the combustion times of dispersed fuel particles in two-phase flames remains relevant.

In [6], the autocorrelation function method was proposed for measuring the burning times of metal particles and determining the law of their combustion. The necessary condition for the application of the method is the optical transparency of the flame and stationarity of the radiation source (during the time of radiation registration). The essence of the method is that the integral intensity of radiation emitted by the flame is the sum of intensities from each burning particle and is therefore proportional to their number: that is $I(t) \sim n(t)$. The statistical independence of the ignition time of a particle and the optical transparency of the flame, allows us to construct the autocorrelation function for the flame intensity as the sum of AF for all burning particles.

This method was first applied to measure the combustion times of micro-sized Al, Zr and Fe particles in a dust flame in [7, 8]. The obtained values of the combustion times of Zr and Fe particles agreed well with the results of photometric processing of radial cross sections of the flame front luminosity [8]. For aluminums particles, it was not possible to explain the behavior of the obtained AF. The questions about the influence of the polydispersity of the fuel particles on the type of AF and the interpretation of the obtained effective correlation times remained unclear. Therefore, the aim of the present work is to develop methodological aspects of the application of the AF method for determining the combustion time of dispersed fuel particles.

1. **Application of autocorrelation functions to determine the law and time of particle combustion.** Let us briefly summarize the main ideas that were put in the basis of the correlation technique for measuring the combustion time of particles in gas suspensions. In [6], a method for determining the law of combustion of a combustible particle in a dust flame$t_b \sim d^n$ was proposed. The method is based on the registration of the intensity of radiation emitted by an optically thin layer (for which the absorption of radiation can be neglected) of burning particles of dispersed fuel and consists in the construction of a function of radiation intensity for a set of particles on the basis of some modelling ideas about the combustion patterns of individual fuel

particles. For example, the combustion time of a particle with initial diameter d_{0v} is given by the law $\vartheta_v = kd_{0v}^{\gamma}$. The index v shows the moment of ignition t_v of the particle, k is the rate constant of combustion, γ is the index of degree in the law of combustion of the particle ($\gamma = 1$ – kinetic mode, $\gamma = 2$ – diffusion mode and others). The extinguishing of the particle occurs at time $t = t_v + \vartheta_v$.

The radiation intensity of a burning particle taking into account its dependence on the particle size can be written in the form: $I_v(t) = \alpha d_{0v}^{\delta} F((t - t_v)/\vartheta_v)$ [6], where α is a constant in the law of radiation of a burning particle, δ is an exponent of degree in the dependence of the intensity of radiation of a particle on its size. The function F describes the shape of the radiation trace of the burning particle and is different from zero only during combustion. The values of ϑ_v and $I_v(t)$ depend on d_{0v}. Therefore, a direct relationship between these values can be established. Substituting $d_{0v} = \vartheta_v^{1/\gamma} / k^{1/\gamma}$ into the expression for $I_v(t)$ gives the radiative trace written in terms of burning time. The summation of all ignition times provides the radiation intensity of a dust flame as a function of time [6], i.e.

$$I(t) = \frac{\alpha}{k^m} \sum_{v} \vartheta_v^m F\left(\frac{t - t_v}{\vartheta_v} \right), \tag{1}$$

where $m = \delta / \gamma$.

In the general case, the AF($\psi(\tau) = \overline{I(t) I(t+\tau)}$, where τ is the delay time) of the random process (1) has a complex form (see formula 3 in [6]). However, if we assume that the radiation trace of the burning particle is rectangular-shaped signal $F\left(\frac{t - t_v}{\vartheta_v} \right) = 1$ at $0 \le \left(\frac{t - t_v}{\vartheta_v} \right) \le 1$, it can be shown that for small values of delays τ, the AF decreases linearly with time, and this initial decline describes the effective correlation time τ_c, defined as [6]:

$$\tau_c = -\frac{\breve{\psi}(0)}{\left.\frac{d\breve{\psi}(\tau)}{d\tau}\right|_{\tau=0}}, \tag{2}$$

where $\tilde{\psi}(\tau) = \psi(\tau)/\psi(0)$ is the normalized AF.

Thus, if the radiation trace of a burning particle is step-shaped signal, then from the experimentally recorded flame radiation intensity we can use correlation analysis to calculate the normalizedautocorrelation function $\breve{\psi}(\tau)$ and determine the effective particle burning time by the relation (2) $t_b = \tau_c$. In doing so, we do not explicitly use any additional information about the flame under study. All system parameters - particle and oxygen concentrations, particle size, combustion and radiation laws are implicitly included in the signal $I(t)$. The researcher only needs to interpret the obtained values.

If the parameters k, δ and γ in (1) are known, the effective correlation time (burning time) can be calculated from the relation [6]:

$$\tau_c = k\frac{\left\langle d_0^{2\delta+\gamma}\right\rangle}{\left\langle d_0^{2\delta}\right\rangle}, \tag{3}$$

where $\left\langle d_0^n\right\rangle = \int\limits_0^\infty d_0^n \rho(d_0) d(d_0)$, n is the moment of the particle size distribution function, $\rho(d_0)$ is the density of the particle size distribution function. If some parameter in (1) is unknown, then having determined experimentally the effective correlation time (1) it is possible to estimate the corresponding parameter using (2). Finally, if the condition $F\left(\frac{t-t_v}{\vartheta_v}\right) = 1$ is not fulfilled [8], then there are no simple analytical relations for the AF and correlation time, and a numerical solution of the problem will be required.

2. **Methodology of experimental research.** The correlation analysis of flame luminosity was applied by us to determine the combustion time of gas suspensions of spherical particles of Zr, Fe, Al with number particlesdensity about 10^{12} m^{-3} in a laminar diffusion dust flame (LDDF) [7, 8]. The table summarizes some of the distribution characteristics of the metal powders. The particle size distributions obey the logarithmic-normal law.

In the table: d_{10} - average metal particle size, $s = \sqrt{d_{20}^2 - d_{10}^2}$ - standard deviation, σ and μ - parameters of lognormal size distribution of initial metal particles $\varphi(d) = \frac{1}{\sqrt{2\pi} d\sigma}\exp\left(-\frac{(\ln d-\mu)^2}{2\sigma^2}\right)$, $CV = \frac{s}{d_{10}}\cdot 100\%$ is coefficient of variation, which characterizes the dispersibility of powders. It is assumed that the powder is monodisperse when $CV < 10$ %.The scheme of the experimental setup is shown in Fig. 1.

The dust flame was stabilized at the burner slice and at the volume flow rate of carrier nitrogen W=70-100 sm^3/s had the shape of a cone with a height of about 10 cm. Combustion of metal particles occurs in a narrow (l_f = 1÷ 2 mm) combustion zone at temperature T = (2000÷ 3000) K. Radiation of the flame surface with the help of a collecting lens was focused to the input of a photomultiplier (PMT). The depth of field in the probed volume was about 0.5 cm and was controlled by aperturing the light flux. The signal of the photomultiplier (Fig. 2a) was recorded by an analogue-to-digital converter (ADC) with a sampling frequency of 200 kHz. Registration of the combustion zone radiation was carried out for 3 or more seconds. Simultaneously with the digitization of flame intensity, the dust flame was recorded in cine-photo to determine the burning time of particles by photometry of radial light fluxes [8]. These

Table. Dispersion characteristics of metal powders

Metal	d_{10}, µm	s, µm	Σ	µ	CV, %
Al	4.8	2.8	0.54	1.42	58
Fe	4.7	1.7	0.35	1.49	36
Zr	4.8	2.3	0.45	1.47	48

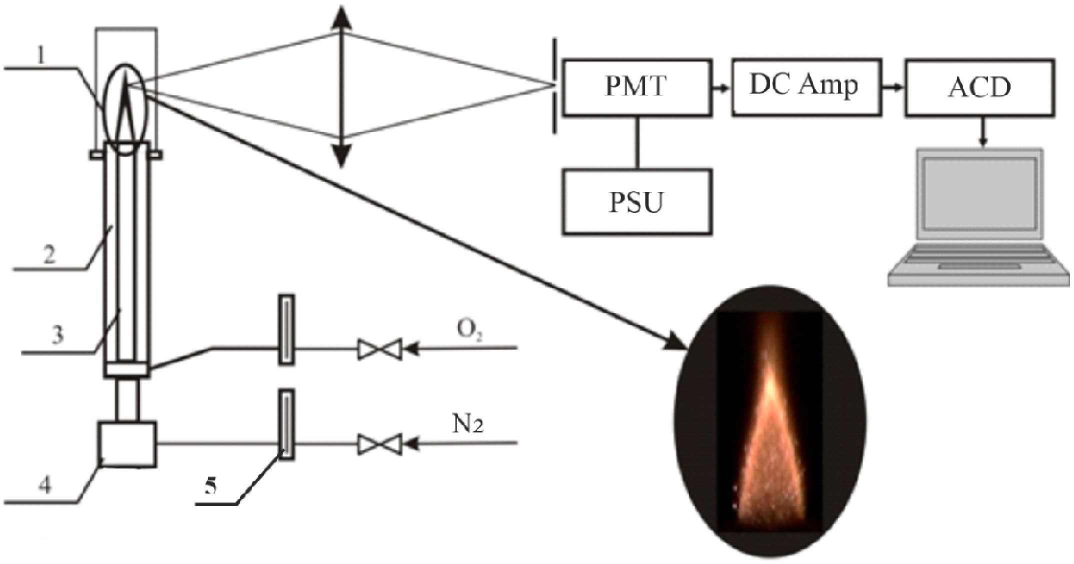
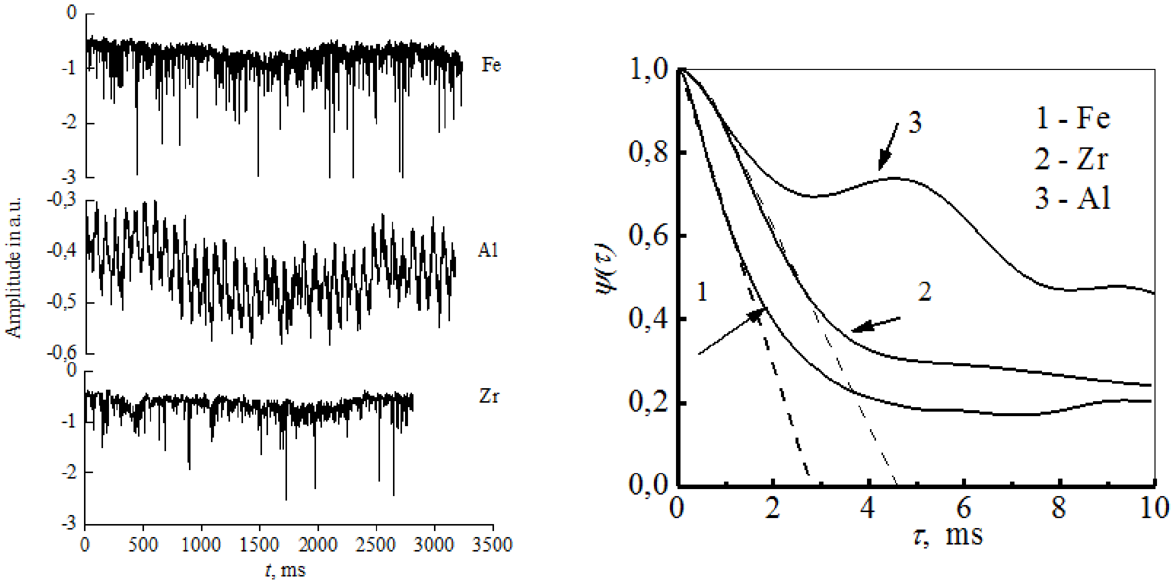


Fig. 1. Schematic diagram of the experimental setup for studying dust flames
1 –dust flame; 2 - blowing tube; 3 - inner tube of the coaxial burner; 4 - powder feeding unit; 5 - flow meter.



a) b)

Fig 2. Determination of burning time by AF method [7, 8]:
(a) radiation intensity of the burning zone of the dust flame Fe, Al, Zr particles;
b) autocorrelation function and correlation times of investigated metals

data were compared with the particle combustion time obtained by the correlation technique.

After separating the constant component from the digitized signal, the normalizedAF $\tilde{\psi}(\tau)$ was calculated (Fig.2b):

$$\tilde{\psi}(\tau)=\frac{\sum_{t=1}^{N-\tau} I(t)I(t+\tau)}{\sum_{t=1}^{N} I(t)^{2}}$$

Using formula (2), the effective correlation time τ_c was calculated, which was taken as the burning time of metal particles t_b. The obtained burning times of Fe ($t_b \approx$ 3 ms), Zr ($t_b \approx$ 4.5 ms) particles are in good agreement with the times calculated from photographs of the dust flames by the method of photometry of the combustion zone [8].

For Al (Fig. 2b, curve 3), it was not possible to interpret the AF and obtain particle burning times that at least in order of magnitude coincided with the burning times of Al particles (according to the results of photometry of the LDDF burning zone [8] $t_b \approx$ 4 ms). The authors [7,8] concluded that the autocorrelation function method is not applicable for metals whose particles burn in the vapour-phase or gas-phase regime. For aluminum, the main contribution to the emission is made by submicron particles Al_2O_3, which do not carry explicit information about the burning time of the aluminum droplet. As will be shown below this hypothesis is most likely erroneous.

It is known that the AF tends to zero if the immersion depthτ is much greater than the correlation timeτ_c. The burning times of the studied metal particles are $t_b \approx$ 4 ms, so it is sufficient to record the signal for a few tens or hundreds of milliseconds to determine the burning time. If the random signal is stationary, the combustion time determined over the whole sample should be close to the times obtained from shorter time series. This assumption was tested for the zirconia particles (see Fig. 2a). The time series was divided into 9 parts and the burning time was determined for each sample. After averaging, t_b =3.9± 0.8 ms or an error of 21% was obtained. This is a very large scatter of times, which, in our opinion, is a consequence of nonstationarity of the general time series.

The curves shown in Fig. 2b are characterized by a weak dependence of the AF in the region of large values of the delay timeτ. Moreover, the location of curves 1-3 in Fig. 2b is higher for powders with a large *CV* (i.e., more polydisperse). In addition, the AF appearance can be influenced by the difference in the shape of the light trace from the burning particle from the rectangular-shaped signal, gas dynamic and/or thermal instability of the dust flame. Below, by simulation modelling methods, we will try to identify the influence of some factors on the shape of the AF and on the results of determining the combustion times.

3. Simulation modelling of dust combustion. For simulation of gas-suspension combustion a sample of n =1000÷10000 particles distributed according to the lognormal law was generated (in this range of n the number of particles in the sample practically does not affect the simulation results). The mean particle size did not vary in all calculations (d_{10} = const). The *CV* varied in the range 5÷60 %. The distribution parameters for different AFwere calculated from the known d_{10} and standard deviation $s = \dfrac{d_{10} CV}{100\%}$ as $\mu = \ln\left(d_{10}^2 \Big/ \sqrt{s^2 + d_{10}^2} \right)$ and $\sigma = \sqrt{\ln\left(s^2 / d_{10}^2 + 1 \right)}$. Statistical independence of the ignition time of each particle was ensured using a random number generator. The duration of each pulse was determined by the particle combustion law $\vartheta_v = k d_{0v}^{\gamma}$, and the amplitude $I_v(t) = \alpha d_{0v}^{\delta} F((t - t_v)/\vartheta_v)$ (see Section 1). The function

$F(t)$ was modelled by rectangular-shaped signal, the parameter γ was chosen equal to 2 (diffusion mode of particle combustion) and δ=1. Calculations were carried out with the reaction rate constant $k = 0.05$.

The integral flame emission intensity was calculated as the sum of the emission intensities of all particles. The average value of the signal intensity was used to exclude the constant component from the model signal. The time τ_c was determined using relation (2).

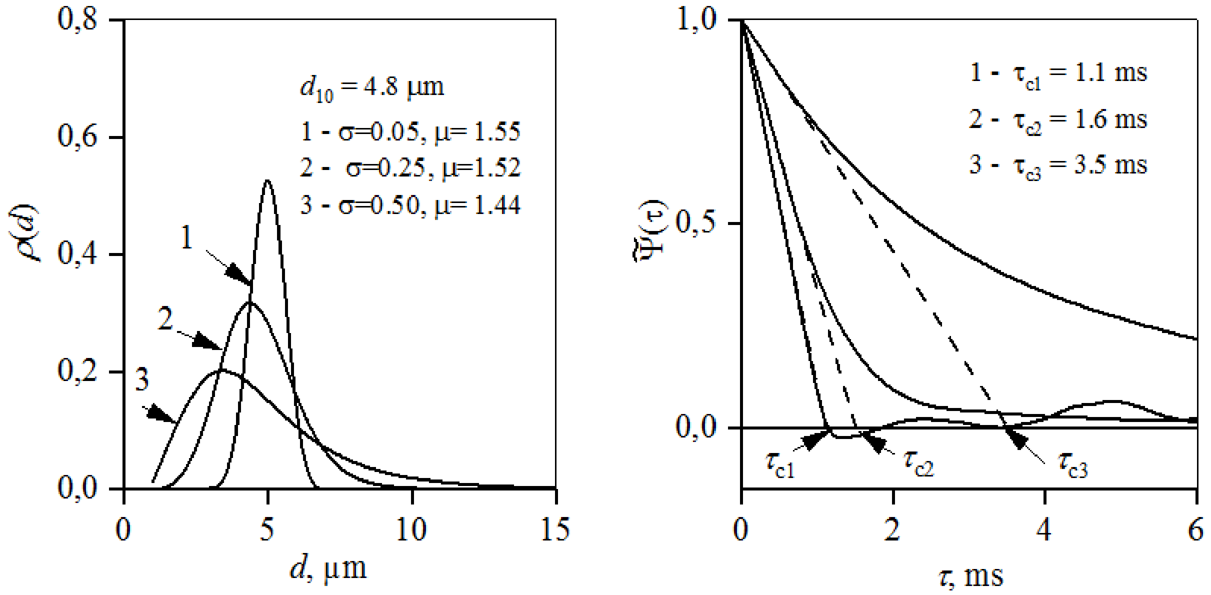
The simulation results of the behavior of the AF are shown in Fig.3 for three values of the coefficient of variation *CV* =5% (curve 1), *CV* =25% (curve 2) and *CV* =50% (curve 3). The effect of *CV* on the parameters of the particle size distribution function is shown in Fig.3a. The AF corresponding to these distributions and the effective correlation times τ_c are shown in Fig. 3b. For monodisperse particles (*CV* = 5%) the AF is linear and coincides with the straight line $\breve{\psi}(\tau) = \frac{d\breve{\psi}(\tau)}{d\tau} \cdot \tau + \breve{\psi}(0)$. With increasing variation coefficient, the deviation of the AF from the tangent to it at the point $\tau = 0$ noticeably increases. Thus, for the same average fuel particle size, the effective correlation time increases with increasing *CV*. This corresponds to the behavior of the experimental AF for the studied metals (see Fig. 2b).

The modelling carried out showed that the effective correlation times τ_c practically coincide with the times (τ_c^*) obtained using expression (3). For example, for the conditions considered above: τ_c = (1.1, 1.5, 3.5) ms (see Fig. 3b) and τ_c^*=(1.1, 1.5, 3.4) ms. Therefore, there are reasons to believe that the correlation technique determines some effective combustion time of metal particles in the gas suspension ($t_b = \tau_c$), which can be expressed through the ratio of the moments of distribution of combustible particles by combustion time [6] or by size (3). The order of the particle size distribution moments is determined by the parameters of the combustion and radiation processes δ and γ.

For correct interpretation of the results of measurements of the burning time of dispersed fuel particles using the flame luminosity AF, it is important to know about the influence of the shape of the signal of a given duration on the type of the autocorrelation function and on the value of the correlation time (particle burning time).

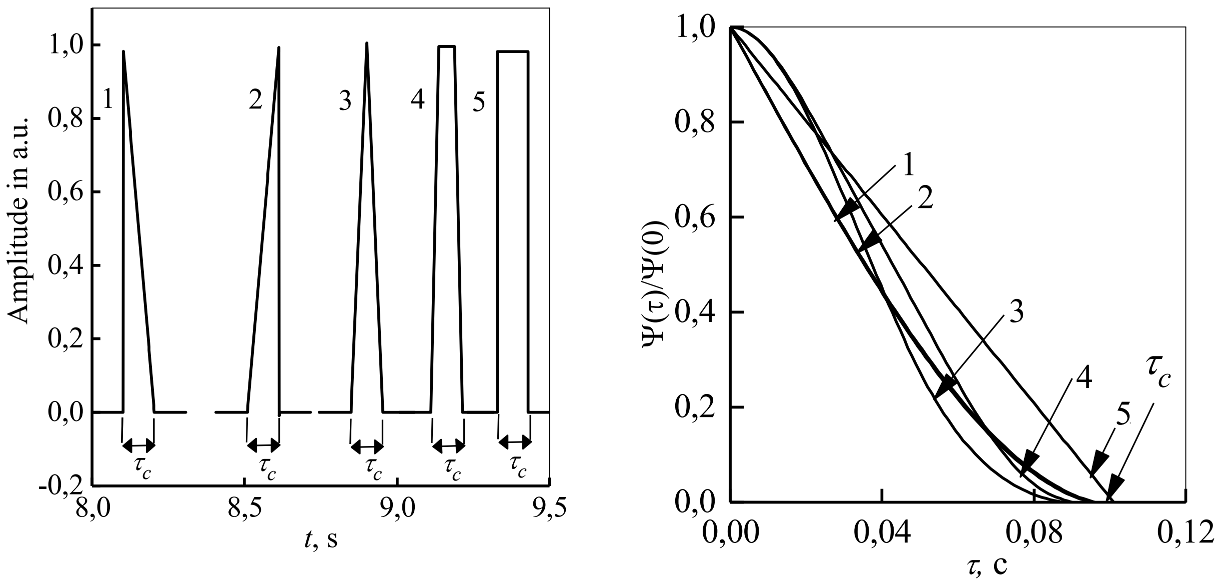
In practice, the light pulse from a burning particle may differ from the rectangular one. This may be due to finite rates of rising (particle ignition) or falling (particle extinguishing) signals. Therefore, the pulse may have a trapezoidal, triangular or other shape. To find out the influence of the pulse shape on its duration τ_c, obtained from correlation measurements, a series of calculations were performed, the results of which are shown in Fig. 4.

The main result of these calculations is the conclusion that the correlation time of pulses of different shapes but the same duration is a constant value and is determined by the point of intersection of the AF with the time axis. At the same time, the shape of the AF for different pulse shapes is different and relation (2) may become inapplicable for determining the effective correlation time.



a) b)

Fig. 3. Effect of propellant dispersity on effective correlation times:
a) the size distribution density of particles of different dispersity;
b) AF and effective correlation times (τ_c) for numerical experimental conditions;
solid line - autocorrelation function;dotted line is the tangent line to the AF at $\tau = 0$.

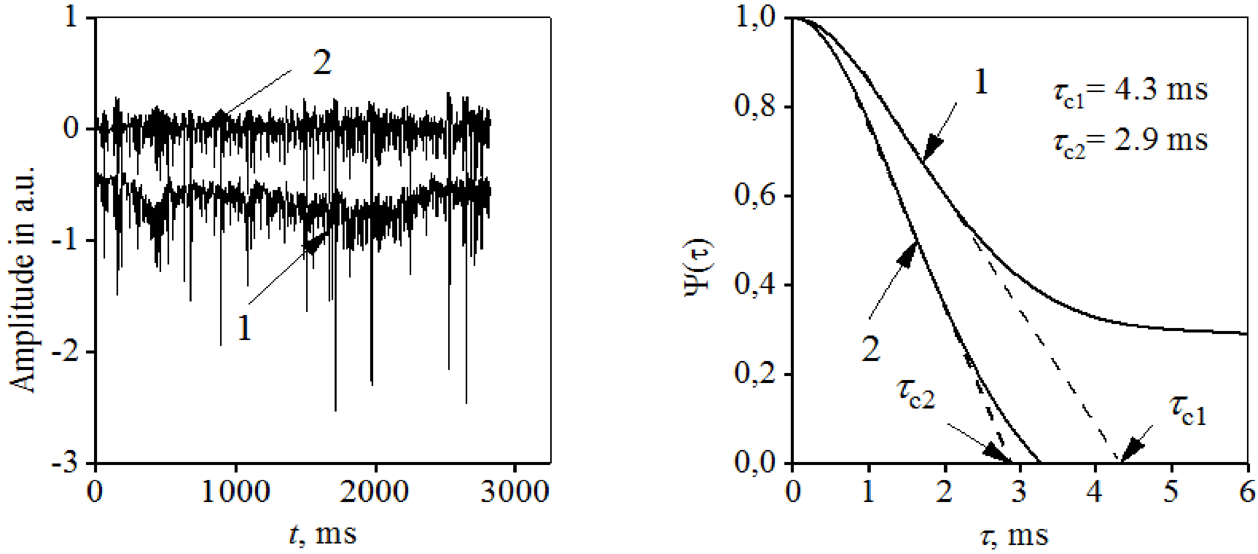


a) b)

Fig 4. Dependence of the autocorrelation function of a single pulse on its shape
a) pulse shape. b) autocorrelation function of a single pulse.
1,2 - sawtooth pulse; 3- triangular; 4 - trapezoidal; 5 - rectangular.

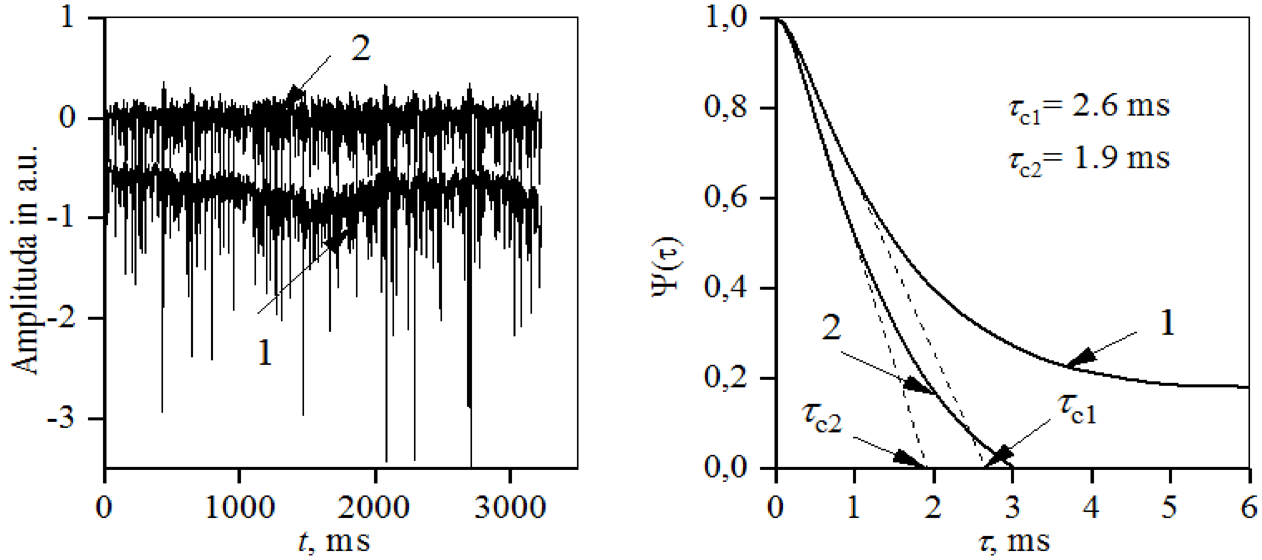
To determine the combustion time of the particle gas suspension in this case, a numerical analysis of the flame luminosity (1), in which the function *F(t)* has a complex form, will be required. The AF of such a process does not have a simple analytical solution and will require numerical analysis.

4. **Results and discussion.** Analysis of the results of experimental measurements of effective correlation times in dust flames of micro-sized Fe, Zr and Al particles



a) b)

Fig. 5 Radiation intensity of the combustion zone of the Zr particle plume (a) and its AF (b). 1. Radiation intensity of the combustion zone of Zr particle flame. 2. HPF filtered (f_{cf} = 20 Hz) radiation intensity of the combustion zone of Zr particles plume



a) b)

Fig. 6 Radiation intensity of the combustion zone of the plume of iron particles (a) and its AF (b). 1. Radiation intensity of the combustion zone of the particle plume. 2. HPF filtered (f_{cf} = 20 Hz) radiation intensity of the combustion zone of the particle plume

revealed several features of the AFbehavior, which were not paid attention to in [7,8]. Fig. 2b shows that at large delay times τ the CF remains almost constant. According to the properties of autocorrelation functions, it contains a constant component when the analyzed function $I(t)$ also has a constant component. However, when processing the initial intensity dataset, we excluded the mean value $\overline{I(t)}$ from the signal and built the covariance function $\Psi(\tau)$ for the time series $I(t) - \overline{I(t)}$ so the target function $\Psi(\tau)$ should not contain a constant component. The correlation function of polydisperse powders is monotonically decreasing (Fig. 3b).

Another feature of the obtained experimental results is a significant scatter of correlation times obtained for different parts of the time series of radiation intensities (t_b =3.9±0.8 ms, see Fig. 7). The significant scatter of correlation times can be explained by the fact that the mathematical expectation of the random process differs for a sequence of shorter time series of different samples. This is possible when the random process is not quite stationary. As is known, the statistical characteristics of a stationary random process do not depend on time. For a quasi-stationary process, the covariance function and, respectively, the correlation times can differ markedly for different moments of time.

There may be many reasons for violation of the stationarity of the process. For example, these are pulsations of concentrations of dispersed fuel and oxygen in a dust flame during signal digitization, convective instability of a free flame (heat-diffusion, aerodynamic, etc.), flame oscillations as a result of external influences (e.g. draughts), leading to defocusing of the optical scheme. Most often these disturbances are low-frequency (10-20 Hz).

To test the hypothesis about the influence of low-frequency perturbations on the fluctuations of the combustion zone radiation intensity, the method of constructing the covariance function was changed. The initial intensity function $I(t)$ was processed by a high-pass filter (HPF) with a cutoff frequency of 20 Hz. To take into account the peculiarities of the system under study, it is desirable to carry out test calculations to determine the cutoff frequency of the HPF. Obviously, the zero cutoff frequency of the HPF will allow filtering the constant component of the signal without changing the useful signal. Higher cutoff frequencies may distort the useful signal, thus affecting the type of the AF and the effective correlation times.

The results of the improved technique for measuring the combustion times of Zr and Fe particles are shown in Fig. 5. and 6.In Fig. 5a (curve 1) shows the digitized signal of the emission intensity of the flame front of zirconium particles (it is the same in Fig. 2a). The correlation function of such a signal is shown in Fig. 5b and, as discussed above, has an almost horizontal section in the region of large τ. The effective correlation time in this case is $\tau_{c1}\approx$ 4.3 ms. Curve 2 in Fig. 5b is obtained from curve 1 using a HPF with cutoff frequency f_{cf} = 20 Hz, and its corresponding AF is shown in Fig. 5b (curve 2). As a result of the filter cutting off signal components not related to the combustion time of the combustible particles, a different correlation time (combustion time) $\tau_{c2}\approx$ 2.9 ms was obtained. Similar results were obtained for iron (Fig. 6).

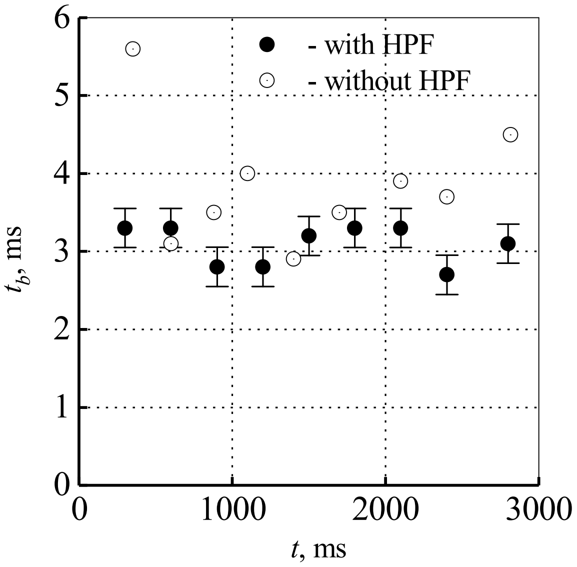
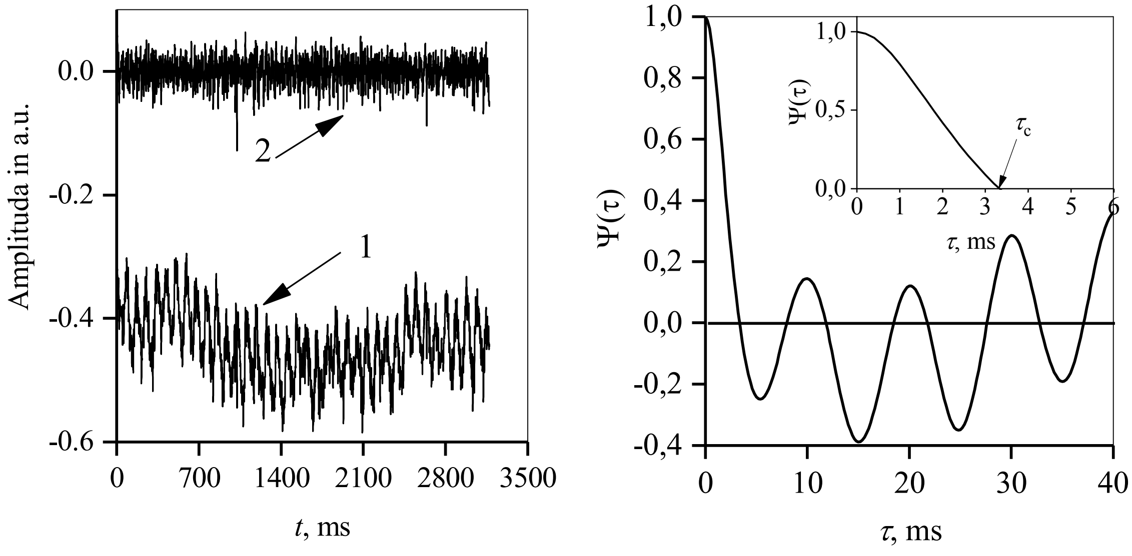


Fig. 7. Dependence of burning time of zirconium particles for different fragments of the time series

For zirconium particles, the scatter of effective correlation times at individual



a) b)

Fig. 8. Radiation intensity of the combustion zone of the plume of iron particles (a) and its AF (b). 1. Radiation intensity of the combustion zone of the particle plume; 2. HPF filtered (f_{cf} = 20 Hz) radiation intensity of the combustion zone of the particle plume

time intervals was calculated for the filtered signal. As for the original time series (see Section 2), the 3 second filtered signal was divided into 9 parts and the burning time was determined for each sample (Fig. 6, black circles). After averaging t_b =3.1± 0.3 ms was obtained, while without HPF above, t_b =3.9± 0.8 ms was obtained (white circles in Fig.6). That is, the scatter of the data was significantly reduced.

The application of the HPF allowed us to interpret the correlation function of the emission intensity for LDDP Al (curve 3 in Fig. 2). In [7], the authors concluded that the AF method is not applicable for metals burning in the vapour-phase or gas-phase regime. This was explained by the fact that the main source of radiation is aluminum oxide nanoparticles, which do not carry information about the burning time of metal particles. However, micro-sized Al particles burn in microflames, forming a high-temperature brightly luminous zone. The time of existence of this zone can be interpreted as the burning time of the Al particle.

Fig. 8a shows the original (curve 1) and HPF filtered (f_{cp} = 20 Hz) signal (curve2) of the radiation intensity of the combustion zone of the Al particle plume. The corresponding AF in Fig. 2b (curve 3) and Fig. 8b are very different. The AF of the filtered signal clearly contains a periodic component with frequency f =100 Hz. This means that the same frequency is present in the original signal. It is most likely that during the measurements in the measuring circuit there appeared parasitic inductions with the frequency of the 2nd harmonic of the network voltage, which were not noticed by the experimenters. As shown in the inset in Fig. 8b, the CF crosses the time axis at the point τ_b =3.3 ms. Considering the complexity of the object of study, it can be considered that this time agrees quite satisfactorily with the time τ_b =4.0 ms obtained by photometry of the radial profile of the aluminum LDPF in [8].

When applying filters for signal processing it is necessary to make sure that the condition $f_{cf} << 1/t_b$, where t_b is the burning time of large particles in the "tail" of the distribution, is fulfilled. For large particles the ratio $1/t_b$ increases and can become comparable to the cut-off frequency of the HPF. This will not only remove parasitic low frequencies from the signal, but also distort or remove information about large combustor particles. As a result, the measured effective correlation times will correspond to some fictitious particle size distributions. In such cases, it may be a better solution not to use a HPF.

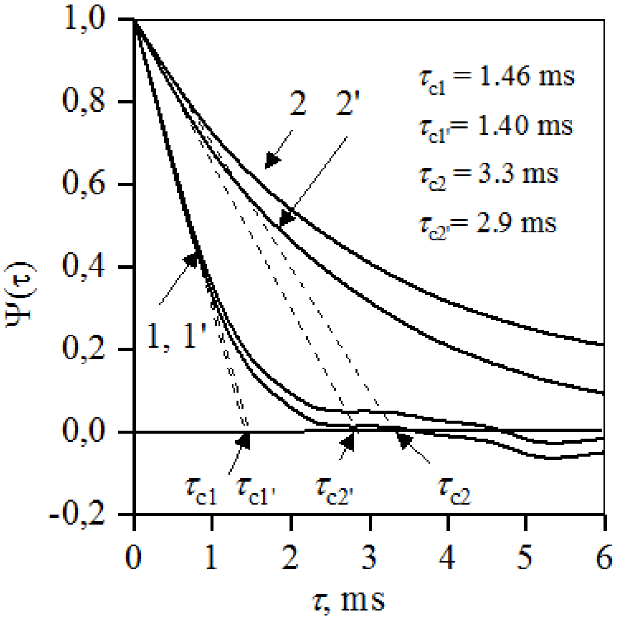


Fig. 9. Effect of HPF on AF and effective correlation time for powders of different dispersity. Curves 1 and 2 are obtained without HPF, curves 1’ and 2’ with application of HPF with cut-off frequency $f_{\mathrm{cf}} = 20$ Hz.

The above is illustrated by modelling calculations of the effect of HPF on the AF and effective correlation time τ_c (Fig. 9) for the conditions given in Section 3 and Fig. 3. For a monodisperse gas suspension (*CV=5%*), no differences in AF and τ_c were found. For *CV=25%*, the AF of the original (curve 1) and filtered (curve 1') signal begin to differ slightly in the region of large delays τ, and the effective correlation times (τ_{c1} and $\tau_{c1'}$ are almost equal. For *CV=50* % (curves 2 and 2') the influence of the HPF becomes significant. The filter leads to a noticeable decrease of the effective correlation time $\tau_{c2'}$ compared to τ_{c2}. In relative units the difference is about 14%.

Conclusion. The considered correlation method of determining the combustion time of dispersed fuel particles has a number of advantages over other methods (track methods, photometry of radiating objects, etc.). The advantage of the method is the possibility to measure the combustion time of dispersed fuel particles practically in real time. In this case, little information is required about the parameters of the carrier particle of the medium, the mechanism of combustion of particles in gas suspensions, and temperature. The conditions of applicability of the method are optical transparency of the flame, stationarity of the object of research, absence of strong external perturbations of the reacting two-phase flow. For the interpretation of the obtained results, the knowledge of the size distribution function of the initial fuel particles and the shape of the radiation trace from the burning particles is important.

The AF method is the most reliable for measuring the combustion times of monodisperse particles, since in this case the interpretation of the AF is the simplest. There are also analytical approximations that relate the correlation time to the parameters of combustion and light emission of particles in a two-phase flame. This allows one to determine the law of particle combustion on the basis of experimentally measured effective correlation times. In practice, the monodispersity range of gas suspensions can be extended to values of the coefficient of variation of 20-25 %.

To exclude the influence of low-frequency flame perturbations, as well as aerodynamic or heat-diffusion instability of the flame on the results of particle combustion time measurement, it may help to apply the HPF. In this case, it is necessary to evaluate the possibility of distortion of the useful signal if its frequencies are close to the cut-off frequency of the filter.

References:

1. *Gill R J, Mohan S and Dreizin E L* Sizing and burn time measurements of micron-sized metal powders // Rev. Sci. Instrum. – 2009. –Vol. 80. – P. 064101
2. *Ning D, Shoshin Y, van Oijen J A, Finotello G and de Goey L P H* Burn time and combustion regime of laser-ignited single iron particle // *Combust. Flame.* – 2021. – Vol.230. – P. 111424
3. *Corcoran A L, Hoffmann V K and Dreizin E L* Aluminum particle combustion in turbulent flames // *Combust. Flame.* – 2013.– Vol. 160. – P. 718–24
4. *Fan Peng, Hecong Liu and Weiwei Cai.* Combustion diagnostics of metal particles: a review // Meas. Sci. Technol. – 2023. – Vol. 34. – P. 042002 (21pp) https://doi.org/10.1088/1361-6501/acb076
5. *Tao Li, Christopher Geschwindner, Andreas Dreizle, and Benjamin Böhm.* Particle-resolved optical diagnostics of solid fuel combustion for clean power generation: a review // Meas. Sci. Technol. – 2023. –Vol. 34. – P. 122001 (36pp). https://doi.org/10.1088/1361-6501/acef49 .
6. *Kornilov V. N.,KorobkoA. V., Kondratyev E. N.* A correlation function method of recovering the combustion law parameters for particles burning in optically thin dust flames // Combustion and flame. – 2006. – V.146. – P. 530-540.
7. *Florko I. V.,FlorkoA. V. , DoroshenkoY. A., Poletaev N. I.* About determination of particle combustion time in dusty flame // European Aerosol Conference. –Greece, 2008. – T08A018P.
8. *N. I. Poletaev* “Determining the Burning Time of Fuel Particles in an Axially Symmetric Laminar Flame, in *Chemical and Radiation Physics*, Ed. by A. A. Berlin, G. B. Manelis, A. G. Merzhanov, and I. G. Assovskii (Torus Press, Moscow, 2011). – Vol. 4. – pp. 281–285.

Полєтаєв М. І.

Кореляційний метод для вимірювання часу згоряння мікророзмірнихчастинок металу в полум'ї пилу

АНОТАЦІЯ

У статті розглянуто можливості експериментального визначення часу горіння частинок металу за допомогою кореляційного аналізу світності полум'я. Експерименти проводилися для полум'я пилу мікророзмірних сферичних частинок (d_{10}< 5 мкм) Fe, Zr та Al в осесиметричному ламінарному дифузійному полум'ї пилу. Щільність частинок у газовій суспензії (в азоті) становила близько 10^{12} м$^{-3}$. Ширина зони горіння при температурі T = (2000÷3000) К у полум'ї становила 1÷2 мм. За цих умов зона горіння оп-

тично тонка. Це забезпечує додатковий внесок кожної частинки у випромінювання зони горіння. Експериментально, а також методами імітаційного моделювання показано, що на точність вимірювання часу горіння впливає стаціонарність об'єкта дослідження, форма радіаційного сліду від горючих частинок і полідисперсність вихідних частинок палива. . Встановлено, що основною причиною нестаціонарності полум'я є низькочастотні коливання різної природи, які виникають у реагуючому двофазному потоці в момент реєстрації випромінювання. Дослідження показали, що обробка часових рядів інтенсивності полум'я фільтром високих частот (HPF) із частотою зрізу близько 20 Гц значно покращує вигляд автокореляційної функції (AF) і дозволяє точніше визначати ефективну кореляцію. час (час горіння частинок). Обговорено обмеження застосування ФВЧ, які можуть призвести до спотворення АФ та часу кореляції. Інтерпретація AF і часів кореляції значно ускладнюється для полідисперсних газових суспензій частинок через залежність часу горіння частинок і їх радіаційних характеристик від розміру частинок. Методи імітаційного моделювання показують, що на практиці діапазон монодисперсності паливних частинок можна розширити до значень коефіцієнта варіації 20-25 %.

Ключові слова: *кореляційний аналіз, автокореляційна функція, час горіння частинок, полум'я металевого пилу, полідисперсність.*