Implementation and investigation of a pulsed aluminum-air flame

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Abstract. To implement a pulse combustion process in a flow of aerosolized particles, flow aerodynamics investigation and determination of the time of aluminum particle residence in a sudden expansion combustion chamber was conducted. The identified flow aerodynamics features and obtained values of the local residence time of aluminum particles made it possible to develop a combustion chamber for a pulse power plant. The temperature field of a pulsed aluminum-air flame was obtained and the type of temperature-time relationship along the flame axis was established in the course of plant tests. Integrated radiation flux density and distribution of radiant energy intensity of a pulsed aluminum-air flame was determined in the wavelength spectral range $\lambda = 1.0...4.5\mu m$. The investigation results obtained in this work can be applied to create pulse power plants fired with powdered metal combustible.

1. Introduction
The use of powdered metals in propulsion and technological installations [1-4] is due to their high energy characteristics. In installations pulsed combustion may be promising use of gas-dispersion jet streams containing high-powdered metals. Depending on the purpose of the power plant can obtain gas-dispersion pulse streams with preset parameters: speed, dimensions, temperature, frequency, etc.

At present, the technological capabilities of pulsed combustion are far from being fully disclosed. Studies in [5] demonstrated the ability to create rapid combustion based on aluminum powders in effective radiating plasma source with a volume of about 100 m$^3$ and the energy of the radiation is above 10 MJ.

The use of energy-consuming metals as a powdered metallic fuel (PMF) in pulsed power plants is associated with the organization of a stable combustion process in a non-stationary air suspension flow. Pulse combustion mode aerosuspension flow of the mixture may be arranged by turning on and off supply of fuel to the combustion chamber with a sudden expansion.

In this work, in order to solve the problem of organizing a pulsed combustion regime in an air suspension flow, the aerodynamics of the flow are investigated and the local residence time of aluminum (Al) particles in a chamber with a sudden expansion is determined. Based on the obtained data the installation and the radiating characteristics defined aluminum-air pulsed flame.

2. Experimental apparatuses
Investigation activities were being performed on a test bench built by the Research and Education Center “Energy-Rich Material Combustion Physics” at Togliatti State University. The test bench design and control systems are described in several monographs and our previous publications in periodicals.
The schematic of the experimental apparatus for implementation of pulse combustion in a flow of aerosolized aluminum particles is shown in Figure 1. The apparatus functions as follows: under the effect of vacuum created by an active air jet streaming out of ejector nozzle 1 powdered Al is fed from hopper 9 through intake tube 8 into ejector inlet chamber 2. From the inlet chamber Al powder passes to ejector mixing chamber 3, where it is mixed with the air streaming out of the ejector nozzle, to form an aerosolized flow which then is conveyed to combustor 6. A pulsed operating mode of the combustion chamber is implemented by turning on and off the feed of powdered aluminum into the combustor using valve. The valve is activated by electronic control unit 7 that allows varying the time of turning on and off the feed of Al powder into the combustor. The combustion process is initiated by ignition plug 5.

Figure 1. Schematic of the experimental apparatus for implementation of pulse combustion in a flow of aerosolized Al particles. 1 – air supplied from the system; 2 – ejector inlet chamber; 3 – ejector mixing chamber; 4 – perforated disk plate; 5 – ignition plug; 6 – combustor; 7 – electronic control unit; 8 – intake tube; 9 – hopper.

Commercial aluminum powder grades ASD-4, ASD-1, PA-4 and PA-1 were used as PMF. Air at a temperature of 293 K served as oxidizer. The in-flame temperature was measured using an AGA 782 thermographic system including a camera unit, thermal image display and highlighted-line display. The screen of the highlighted-line display was being photographed by an ANF camera with a frequency of 1 frame/s. The thermal image display visualized relative in-flame temperature distribution (a more intense background corresponded to a higher temperature). The highlighted-line display provided visualization of temperature distribution along the jet axis in real time with a frequency of 16 lines/sec. It is well known [6] that the most efficient methods of metal combustion mechanism’s investigation include high-speed micro & macro-cinematography and photographing. The high-speed cinematography method was therefore applied to study aerosol flow aerodynamics in the combustor and determine the local residence time of Al particles. It permits measuring the local residence time of Al particles with an accuracy of ~ 5%. Isothermal and short-term tests with combustion were performed in combustion chamber models made of Pyrex heat resistant glass.

In the above experiments, initial turbulence of the incident aerosol flow was taken to be equal to turbulence of the “pure” air flow, i.e. disregarding the presence of Al particles therein.

Pyroelectric sensors were employed to measure thermal radiation energy in different spectral ranges. The relationship between instantaneous power and time \( W(\tau) \) in a spectral range \( \lambda \) of 1.0…4.5 \( \mu m \) was determined by differentiating the time dependence of radiant energy \( E(\tau) = 4\pi L^2 \cdot F(\tau) \) where \( F \) is the energy density measured by the pyroelectric sensors at a distance \( L \) from the pulsating dispersed gas flame. Radiation power of the flame as a whole was determined by the relationship \( W_p = I \cdot S \) where \( I \) is the energy emitted by a unit of volume per unit of time into a solid angle and \( S \) is the lateral area of the flame.
3. Results and discussion
The time of combustible and oxidizer residence in the flow is determined by the structure of its aerodynamics. This parameter is of critical importance for molecular processes (molecular diffusion and chemical reaction) occurring during, or after, turbulent (convective) diffusion. For that reason, aluminum-air flow aerodynamics determines the local time of Al particle residence in the combustion chamber, on which in turn the work process parameters will depend.

To enable a pulse combustion chamber operation mode at a maximum frequency, the opening time of the combustible feed valve should be minimal, but sufficient to allow filling the recirculation zone with Al particles, their igniting and firing the mainstream flow of aluminum-air mixture. In such a case, a minimum time required for filling the recirculation zone with Al particles and their ignition, as well as firing the mainstream aerosolized flow can be calculated using the expression

$$\tau_{\text{min}} = \tau_{RZ} + \tau_{CC}.$$ 

The values of $\tau_{RZ}$ and $\tau_{CC}$ found for ASD-4 Al powder were $10 \times 10^{-3}$ and $4.2 \times 10^{-3}$ s. For ASD-1 those values were $15 \times 10^{-3}$ and $18.2 \times 10^{-3}$ s, respectively. Consequently, $\tau_{\text{min}}$ for aerosolized Al particles of $d_{32} = 7.4 \mu m$ will be equal to $14.2 \times 10^{-3}$ s, and $33.2 \times 10^{-3}$ s for particles of $d_{32} = 17.4 \mu m$. With the turning on and off times of PMF feed to the combustor taken as equal, the period duration (pulse + interval) will be $28.4 \times 10^{-3}$ s for ASD-4 and $66.4 \times 10^{-3}$ s for ASD-1 aerosolized particles. Based on the obtained values of the local time of Al particle residence in the combustor models, a combustion chamber for a pulse power plant has been developed.

Power plant operation in the pulse mode is shown in figure 2.

Figure 2. Power plant working in the pulse mode. $D_{CC} = 0.07 \ m$; a) pulse time: 0.2 s; b) interpulse time: 0.8 s; PMF: ASD-4 + PA-1 (in a ratio of 10 to 4).

According to figure 2a the flame assumes a near-cylindrical shape during the pulse time and a spherical shape during the interpulse time (see figure 2b). Temperature fields of the pulsed aluminum-air flame were recorded at the pulse and interpulse instant employing a thermographic system. Figure 3 shows that the area with a maximum temperature of 2274 K is localized on the flame axis. The temperature during the interpulse time is the same throughout the reacting volume, amounting to 1069 K.
Figure 3. Temperature field of a pulsed flame: a) pulse time: 0.2 s; b) interpulse time: 0.8 s; PMF: ASD-4 + PA-1 (in a ratio of 10 to 4).

Radiative fluxes in a dispersed gas flame are determined by flame macro-parameters (mass concentrations of oxidizer and combustible, metal particle fineness, geometric dimensions of the flame, etc) and optical characteristics of the initial combustible and condensed combustion products, such as absorption and dissipation efficiency, as well as complex refractive index. Also, the above parameters may depend heavily upon the temperature, wavelength and the radiating particle size [7]. Figure 4 shows temperature variation along the axis of a pulsed aluminum-air flame with the time.

The measured maximum temperature value is close to the boiling point of Al ($T_b = 2723K$) and is significantly lower than the dissociation temperature $Al_2O_3$ ($T_d \approx 4000K$), which corresponds to the temperature of the condensed phase in the flame front obtained by the poly-color method [8].

By controlling the operating modes of the apparatus and, respectively, PMF consumption it was established that the pattern of temperature distribution along the axis of the pulsed aluminum-air flame did not change. Such a relationship between the condensed-phase temperature in the combustion zone and the mass concentration of combustible was observed in a laminar aluminum-air flame [7].

Our experimental findings confirm the assumption of the authors of [7] that the condensed-phase temperature is "stabilized" not by phase transitions or $Al_2O_3$ dissociation, but by radiative heat losses that increase significantly with the rise of temperature due to a heavy dependence of radiative characteristics of $Al_2O_3$ particles on the temperature. It has been established that the type of the
dependence of \( T(\tau) \) prevailing during combustion of the aluminum-air flame and of aluminum-iron oxide thermite is the same. The maximum temperature is reached in both cases within the same time of \( \approx 0.2 \) s [9]. The dependence of \( T(\tau) \) for a pulsed aluminum-air flame is shown in figure 5.

![Figure 5](image_url)

**Figure 5.** Temperature change during an intense flash PMF: ASD-4 + PA-4 (in a ratio of 10:2).

Figure 6 shows a calculated curve of integrated radiation flux density prevailing during an intense aluminum-air flame flash. As can be seen, the shape of the dependence curve \( F(\tau) \) is in agreement with the dependence \( T(\tau) \) of the aluminum-air flame burning during an intense flash (see figure 5).

![Figure 6](image_url)

**Figure 6.** Integral radiation flux density during an intense flash. PMF: ASD-4 + PA-4 (in a ratio of 10:2).

The value of de-excitation time of the bulk of energy of a pulsed aluminum-air flame is consistent with the adjusted de-excitation time of the bulk of energy when burning stationary aerosolized Al particle clouds, which amounts to \( 0.2 - 0.3 \) s/kg\(^{1/3} \) [10]. It turned out that the dependence of integrated radiant energy flux density \( F \) on the temperature is of a linear type both for an aluminum-air flame in the range of 400..1723 K and a flame formed by heterogeneous products of aluminized combustible mixture firing [11].
In order to reveal the relationship between the radiant energy intensity of a pulsed aluminum-air flame and the wavelength, temperature measurements were performed during the pulse and interpulse time. Then the spectral distribution of radiant energy intensity $I_{\lambda}$ in the wavelength range $\lambda = 1.0...4.5 \ \mu m$ was calculated. The spectral distribution of radiant energy intensity for a pulsed aluminum-air flame is shown in figure 7. The nature of the change in spectral distribution of the intensity of radiation energy of a pulsed aluminum-air flame in the investigated wavelength range correlates with the nature of the change $I_{\lambda}$ of a stationary aluminum-air flame [7].

![Figure 7. Spectral distribution of radiant energy intensity for a pulsed aluminum-air flame $I_{\lambda}$ in the wavelength range $\lambda = 1.0...4.5 \ \mu m$: 1-pulse; 2-pause; PMF: ASD-4 + PA-4 (in a ratio of 10:2).](image1)

By varying the operating mode of the apparatus (changing the pulse and interpulse times) it has been established that the energy emitted by the flame in the investigated spectral range of $\lambda = 1.0...4.5 \ \mu m$ is proportional to powdered aluminum consumption per pulse. Figure 8 shows the dependence of radiated energy $\varepsilon$ on the consumption $G_{Al}$ of powdered Al per pulse.

![Figure 8. Dependence of the radiated flame energy $E$ on the consumption of aluminum powder per pulse $G_{Al}$ in the wavelength range $\lambda = 1.0...4.5 \ \mu m$: PMF: ASD-4 + PA-4 (in a ratio of 10:2).](image2)

The established linear relationship between the energy emitted by a pulsed aluminum-air flame and the powder quantity is in good agreement with the data obtained according to [7]. By varying the work
mode of the apparatus, two reacting volumes of aerosolized Al particles have been obtained simultaneously: one with a radiation power of 6 kW and the other with 2.5 kW.

4. Conclusion
The results of the above investigations allowed implementing a pulse-combustion mode in an aerosolized aluminum particle flow. Based on the obtained values of the local time of Al particles residence in a sudden-expansion combustion chamber model, a full-sized power plant combustor has been developed. The results of the tests performed confirmed a reliable power plant operation in the pulse mode. Plant work mode variation admits of controlling the energy, power and the dimensions of a pulsed aluminum-air flame.

It has been ascertained that the nature of the relationship between the integrated radiation flux density of a pulsed aluminum-air flame and the time corresponds to that of the temperature change. Spectral distribution of radiant energy intensity of a pulsed aluminum-air flame \( I_\lambda \) in the wavelength range \( \lambda = 1.0...4.5 \ \mu m \) was determined. The dependence of the emitted energy of flame \( E \) on the Al powder consumption per pulse \( G_{Al} \) in the wavelength range \( \lambda = 1.0...4.5 \ \mu m \) was established.

The investigation results of the present work can be applied to create pulse power plants fired with powdered metal combustible, and also simulate radiative and gasdynamics processes related to the entry into Earth’s atmosphere and ground impact of asteroids and meteorites.

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