Influence of the initial turbulence of the air suspension flow on the speed and limits of flame propagation

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Abstract. The paper presents experimental data on the effect of the initial turbulence of the air suspension flow of aluminum particles on the speed and limits of flame propagation. It was found that when installing the grate, depending on the diameter of the chamber and the size of the aluminum particles, the flame propagation speed can either increase or decrease. In the flow of air suspension of aluminum particles ASD-1, a simultaneous increase in the intensity and scale of turbulence leads to an increase in the flame velocity and expansion of the flame propagation limits.

1. Introduction
The aerodynamics of two-phase turbulent jets and flows has a number of features due to the effect of a condensed impurity on the averaged and pulsating motion. The characteristics of two-phase flows depend on the concentration of particles, their mass, aerodynamic properties, as well as on other factors that take into account the conditions for the outflow of a gas suspension. Initial conditions have a significant effect on the structure of two-phase turbulent flows, in particular, the conditions for the motion of a gas suspension in nozzles and supply pipelines [1].

In turbulent gas flows with solid particles one can observe both the effect of the turbulence of the carrier flow on the movement of solid particles is observed and the effect of the particles themselves on the turbulence parameters of the gas flow carrying them. Under certain conditions, particles suspended in the flow can dampen its turbulence. An increase in the volume concentration of particles leads to the fact that the effects of their influence on the turbulence of the carrying gas flow begin to play a noticeable role.

The behavior of solid particles in turbulent flows is a complex physical process, the implementation mechanism of which depends on both the concentration of particles in the flow and their size [2]. Researchers do not have a consensus on the effect of suspended particles on the turbulent characteristics of the flow [3].

In the general case, the motion of the carrier medium and solid particles cannot be considered independently of each other. The placement of a grating in front of the stabilizer to intensify the combustion process of the air suspension further complicates the problem of studying the turbulent structure of the flow.

The turbulence parameters generated by the cascades depend not only on the cascade geometry, but also on the oncoming flow turbulence and the channel diameter. And depending on the ratio of the characteristic dimensions of the channel and the lattice, the turbulence of the incoming flow will increase or, conversely, be extinguished.
In the combustion of dispersed metals in an active gas flow, it is necessary to know the effect of gas-dynamic factors (velocity, turbulence, etc.) on the flame propagation speed. For example, when the air suspension of aluminum particles moves in the channels, high velocities of flame front propagation (up to 1600 m/s) are rapidly achieved, as evidenced by experiments in laboratory and industrial conditions [4].

The concepts of the combustion process of suspensions of aluminum particles in an active gas flow, which have developed by now on many issues, cannot be considered completely complete. This, in particular, can be attributed to the determination of the speed of propagation of the flame front at various initial parameters of the turbulence of the air suspension flow.

The aim of this work is to determine the effect of the initial turbulence of the air suspension flow of aluminum particles on the speed and limits of flame propagation in a wide range of variation of the excess air coefficient $\alpha$.

2. Experimental equipment

The layout of the experimental stand (figure 1) which was used in the research is described in detail in [5].

![Figure 1. The scheme of the experimental setup: 1 - ejector nozzle; 2 - powder intake tube; 3 - bunker; 4 - receiving chamber of the ejector; 5 - ejector mixing chamber; 6 - combustion chamber; 7 - turbulizing grid; 8 - spark plug; 9, 10 - cranes with electric drive.](image)

In this setup, an ejector supply of powdered aluminum was used. Under the action of a vacuum created by an active air stream flowing out of the ejector nozzle (1), aluminum powder from the hopper (3) through the intake tube (2) is fed into the ejector receiving chamber (4). From the receiving chamber, aluminum powder enters the mixing chamber of the ejector (5), where it is mixed with an active air stream, forming an air suspension, which then enters the combustion chamber (6).

The ignition source was an electric plug (8), which was installed behind the plane of sudden expansion. The flow rates of air and aluminum powder were controlled using electric valves (9, 10).

Depending on the tasks set and the purpose of the experiment, heated or cold air through the nozzle entered the mixing chamber of the ejector.

In the air suspension as a dispersed material, we used aluminum powders of grades ASD-4, ASD-1, produced by industry and technical specifications for their dispersed composition.

To measure the flow rate of aluminum powder, a special system was developed, which consisted of a power supply, a force-measuring sensor, an electric stopwatch, a printing device and a converter. This system made it possible to measure the consumption of aluminum powder with an error of $\sim 5\%$.

The consumption of aluminum powder was calculated by fixing the values of the initial weight of the hopper with powder and the weight of the hopper after the measurement, and the measurement time was also recorded. Knowing the weight of the hopper at the beginning and end of the measurement, i.e.
the total consumption of powder and the time during which it was consumed, the second consumption of combustible aluminum powder was calculated by the formula:

\[ G_{Al} = \frac{G_{\theta}}{\tau} \]

where \( G_{\theta} \) is total powder weight consumed during the measurement; \( \tau \) is time, s.

The excess air coefficient \( \alpha \) was calculated by the formula:

\[ \alpha = \frac{G_B}{L_0 \cdot G_{Al}} \]

where \( G_B \) - air flow; \( L_0 \) - stoichiometric ratio, for the reaction of aluminum with air \( L_0 = 3.84 \); \( G_{Al} \) - aluminum powder consumption, g/s.

The initial level of turbulence of the air suspension flow at the inlet to the combustion chamber was varied using turbulizing grids (figure 2). The grids were perforated disks that were installed in the mixing chamber of the ejector at various distances from the plane of sudden expansion \( l \) (figure 1).

![Figure 2. Turbulent grilles. a - for the mixing chamber of the ejector with a diameter of 0.02 m; b - for the mixing chamber of the ejector with a diameter of 0.04 m.](image)

The velocity and turbulent characteristics of the "pure" (without aluminum particles) air flow were measured using a DISA-55M hot-wire anemometer set. Since it was impossible to measure the turbulence of the air suspension flow due to the lack of the necessary equipment, therefore, further in the text, the values of the initial levels of turbulence are given for a “pure” air flow.

To determine the speed of propagation of the flame front in the flow of aerosuspension of aluminum particles, a technique based on the flame stabilization mechanism was used. The principle of which is the equality of the values of the flow velocity of the air suspension at which the combustion breakdown occurs \( u_{off} \) and the velocity of the flame front \( u_f \). Having determined the boundaries of stable combustion in the flow of air suspension of aluminum particles at various values of the initial turbulence (without a grid and with the installation of a grid), the dependence \( u_f(\alpha) \) was constructed.

3. Research results
Using the previously obtained data on the boundaries of stable combustion, the dependences \( u_f(\alpha) \) were constructed and the influence of the initial turbulence \( \varepsilon_0 \) on the limits of flame propagation was established.

Figure 3 shows the limits of flame propagation in the flow of air suspension with ASD-1 particles, obtained in tests without installing a grating in the inlet channel, and when it is installed at \( l = 0.02m \).
For ASD-1 particles burning in a diffusion mode, the maximum values of the flame propagation velocity correspond to the values of the excess air coefficient $\alpha = 0.2\alpha$. It can also be seen from the figure that in the variant with a turbulizing lattice (decreasing $\varepsilon_0$), the value of the maximum flame velocity decreases and the flame propagation limits are narrowed.

Figure 4 shows the limits of flame propagation in the flow of air suspension containing powder of the ASD-4 grade, without a grate and with a grate at $l = 0.02\,m$, obtained in tests on a chamber also with a diameter of $0.07\,m$.

In this case, the combustion of ASD-4 aluminum particles is controlled by the kinetics of chemical reactions, and the maximum flame propagation speed is close to the stoichiometry $\alpha \approx 1.0$.

It can be seen from figure 4 that if the grating is installed (by decreasing $\varepsilon_0$) in the air suspension flow from ASD-4, the flame propagation speed increases and the flame propagation limits expand.

Thus, it was found that the presence of a grating in the inlet channel at $l = 0.02\,m$ (a decrease in $\varepsilon_0$) in the combustion chamber of $0.07\,m$ leads to a decrease in the speed and narrowing of the flame propagation limits in the ASD-1 air suspension with an average particle diameter $d_{32} = 17.4\,\mu m$. In air suspension ASD-4 with $d_{32} = 7.4\,\mu m$, on the contrary, to an increase in the speed and expansion of the flame propagation limits.
It is known [6] that one and the same grid in a large-diameter pipe acts as a damping grid with respect to large-scale free-flow turbulence and as a turbulizer in a small-diameter pipe. This fact is confirmed by the data presented in figure 5 when installing the same grate in a combustion chamber with a diameter of 0.05 m.

![Figure 5. Influence of initial turbulence on speed and the limits of flame spread in the flow of air suspension with aluminum particles ASD-1. Combustion chamber D = 0.05m, 1 - without lattice; 2 - with lattice (l = 0.02m).](image)

The figure shows that in this case, when installing the same grate in a combustion chamber with a diameter of 0.05 m (with an increase in $\varepsilon_0$), the flame propagation speed increases and the flame propagation limits expand.

To determine the effect of a simultaneous increase in the intensity and scale of turbulence on the speed and limits of flame propagation. For this, one and the same grating was installed at different distances from the plane of sudden expansion.

The results of experimental studies [7] on the determination of turbulent characteristics in a chamber with a sudden expansion showed that when the lattice is installed at $l = 0.02m$ and $l = 0.057m$, the scale of turbulence $l_0$ is 0.07 and 0.01 mm, respectively.

Figure 6 shows the effect of an increase in the intensity of turbulence $\varepsilon_0$ and the scale of turbulence $l_0$ on the speed and limits of flame propagation.

![Figure 6. Effect of increasing $\varepsilon_0$ and $l_0$ on speed and the limits of flame spread. Combustion chamber $D = 0.06m$; air suspension ASD-1, 1 – $l = 0.057m$ ($l_0 = 0.01mm$; $\varepsilon_0 = 12\%$); 2 – $l = 0.02m$ ($l_0 = 0.07mm$; $\varepsilon_0 = 22\%$).](image)
The figure shows that in the flow of air suspension with ASD-1 with an average particle diameter $d_{32} = 17.4 \mu m$, a simultaneous increase in the turbulence intensity $\varepsilon_0$ from 12 to 22% and the turbulence scale $l_0$ from 0.01 to 0.07 mm leads to an increase in speed and expansion of the flame spread.

From the point of view of the theory of flame stabilization based on the ratio of characteristic times. The influence of $\varepsilon_0$ on the combustion stability of powdered aluminum, on the one hand, is explained by a decrease in the size of the recirculation zone, and, consequently, by a decrease in the contact time $\tau_k$. On the other hand, turbulence intensifies heat and mass transfer processes between the main flow of air suspension and the recirculation zone. Thus, acting on the local ratio of components in the zone, on which, in turn, both the combustion temperature and the flame propagation speed depend [8].

4. Conclusions
Despite the fact that in the studies the initial turbulence of the air suspension flow was taken equal to the turbulence of the pure air flow (the effect of particles on the turbulence of the carrying air flow was not taken into account). Nevertheless, the data obtained in this work qualitatively reflect the nature of the influence of the initial turbulence of the air suspension flow on the velocity and limits of flame propagation for the investigated range of aluminum particle sizes.

Based on the research results obtained in this work, the following conclusion can be drawn. With an increase in the initial turbulence of the air suspension flow, for ASD-4 aluminum particles with $d_{32} = 7.4 \mu m$, reacting in the kinetic mode, the flame velocity decreases and the flame propagation limits are narrowed. For ASD-1 aluminum particles with $d_{32} = 17.4 \mu m$, combustion of which proceeds in a diffusion mode, the flame speed increases and the flame propagation limits expand.

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