Thermal explosion of aluminum particles suspended in airflow

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Abstract. Thermal explosion of aluminum powder ASD-4 suspended in an airflow was studied experimentally using the model of hotspot ignition. A critical hotspot radius and ignition condition have been determined, and the effect of turbulence intensity on the development of the hotspot has been established.

1. Introduction
It is known that there are many factors influencing initial ignition of aluminum particles suspended in an airflow and its further development: particle size distribution, particle surface shape and condition, calorific value and other physical and chemical properties, initial temperature, speed, turbulence, pressure etc.

Thus the study of initial hotspot development allows qualifying and quantifying the impact of each factor on the process of ignition in an airflow with suspended aluminum particles.

The study conducted in [1] determined the relationship between basic airflow parameters and the minimum specific enthalpy $I_{ign}$ required for ignition of aluminum powders ASD-1 (with average particle size $(d_{32} = 17.4 \mu m)$ and ASD-4 $(d_{32} = 7.4 \mu m)$). It has been discovered that aluminum powder particle size exercises decisive influence on its ignition in an airflow. It has also been established that the decisive process is heat transfer from one element of volume to another in case of ASD-4 and from finer to coarser particles in case of ASD-1. The findings also indicate that the enthalpy of ignition of ASD-4 powder suspended in the airflow cannot ensure simultaneous ignition of the whole suspension because the average temperature of suspension is lower than that of aluminum particles ignition. The authors assumed that ignition first occurs locally in a hotspot and then propagates across the entire airflow. Below are the results of the research that was conducted to validate this assumption.

In the present study of thermal explosion in an airflow with suspended aluminum particles, a critical hotspot radius was determined and the dynamics of its development before the formation of a steady-state flame front in the recirculation zone was examined. Formation of the initial hotspot in a turbulent airflow with suspended aluminum particles was studied similarly to [2] in view of the thermal model proposed by Zel’dovich [3].

2. Experimental setup
The setup used in the experiments, the direct-flow combustion chamber model, and the hydrodynamics of the flow in it are described in detail in [4, 5]. Combustion chambers with sudden expansion were modeled by axisymmetric channels of diameter $d_0 = 0.04 ... 0.09 m$ with an inlet orifice of diameter...
\( d_0 = 0.02m \). The relative length \( \frac{L_c}{d_0} \) varied in the range of 8.0–15.4, and the degree of expansion \( r^* = \frac{D_c}{d_0} \) in the range of 2.0 - 4.5. The characteristic size was taken to be \( H = R_c - r_0 \), which was varied from 0.01 to 0.035 m.

Tests without combustion were performed on models made of Plexiglas, and tests with combustion on models made of refractory Pyrex glass.

A turbulizing grid was used in studies of the effect of the air flow turbulence intensity on the development of the initial hotspot. Initial turbulence was varied by using a turbulizing grid, which was placed at various distances from the plane of sudden expansion \( l_P \). A change in parameter \( l_P \) led to a change in the distance between the grid and the spark plug. Under these conditions, the turbulence intensity varied from 5 to 12%.

The development of initial hotspot in the recirculation zone during spark ignition of a turbulent air flow with suspended aluminum particles was visualized by an optical method using SKS-1M camera with a shooting speed of up to 5000 frames/sec.

The setup involved ASD-4 aluminum powder made by a Russian manufacturer and fully compliant with the industry standard and specifications for the particle size. Air at 293 K temperature was used as a carrier gas.

The turbulent flow of aluminum particle-air mixture was ignited using an electrical plug with a discharge energy \( W = 0.05 J \).

3. Results of experimental study
The results of visualization of initial hotspot development in the recirculation zone obtained with a high speed camera are presented below. Figure 1 shows some frames demonstrating various patterns of initial hotspot development for ASD-4 aluminum powder suspended in the airflow: propagation and fading.

The shots demonstrate that during the initial phase after initiating the process with a spark the initial hotspot expands after which it either grows explosively (fire propagates, figure 1b) or disappears completely (flame dies, figure 1a).

![Figure 1. Development of initial hotspot in case of a dying (a) and propagating (b) flame (air flows left to right).](image-url)
In both scenarios formation of an initial hotspot takes place at \( \tau \approx 1,6 \cdot 10^{-3} \) s. Then in case of a fading flame (figure 1a) the hotspot practically does not change in size \( (R_0 \approx 1\text{mm}) \) over \( \tau \approx 3,2 \cdot 10^{-3}s \), after which the flame goes out completely. In case of a propagating flame (figure 1b) the initial hotspot expands rapidly and the flame spreads across the entire recirculation zone at \( \tau \approx 3,2 \cdot 10^{-3}s \). Then at \( \tau \approx 4,8 \cdot 10^{-3}s \) the flame expands from the recirculation zone into the main stream of aluminum-air mixture.

The initial hotspot in both scenarios does not change in size \( (R_0 \approx 1\text{mm}) \) over \( \tau \approx 0 \div 1,6 \cdot 10^{-3}s \), which means that the flame propagation rate equals zero while the temperature in the hotspot remains practically the same [6].

\[
U_0 = 50\text{m/s}; T_0 = 293K; D_k = 0,04\text{m}; \alpha = 1,1
\]

Thus the hotspot critical radius must be \( R_{cr} \geq 1 \) mm in order to ignite airborne ASD-4 particles in the recirculation zone with an electric spark. Assumedly, the nearest particles will ignite before the spark heated spot cools down. Given that for aluminum particles with diameter \( d_{32} = 7,4\mu\text{m} \) the flame front length \( b_f = 2 \cdot 10^{-3}m \) [7], Zel’dovich formula shall be presented as follows:

\[
R_{cr} \geq 0,5 \cdot b_f
\]

A high speed camera was also used to monitor the dynamics of airborne ASD-4 particles ignition in a sudden expansion channel. The initial hotspot near the spark plug develops and fills the recirculation zone in \( \tau \approx 3,2 \cdot 10^{-3}s \) if \( R_{cr} \geq 1\text{mm} \). After that the flame front is formed along the ‘defining’ cylindrical surface (the diameter of which is equal to the diameter of the channel inlet orifice \( d_0 \)) and ignites the main stream of the airborne particles.

Figure 2 shows graph \( R_0 = f(\tau) \) for a fading (curve 2) and propagating (curve 1) flame of ASD-4 aluminum powder. It can be seen that the induction period of thermal explosion is \( \tau \approx 2,0 \cdot 10^{-3}s \).

The duration of the thermal explosion induction period, that was registered using a high speed camera, agrees with the value obtained during ignition of ASD-4 airborne powder behind reflected shock waves in pure oxygen [8].

It is known [9] that dependence of the initial propagation rate on the diameter of the initial hotspot is most probably related to the no steady-state initiation of the process. Having obtained data on critical radius for ASD-4 powder, we can now calculate the initial flame propagation rate in the first approximation using formula [9].

\[
(dx/dt)_0 = (2 \div 3) \cdot 10^3 \cdot a/i_d .
\]
where $a$ – thermal diffusivity of air ($8 \cdot 10^{-5} \text{m}^2/\text{s}$); $d$ – hotspot diameter.

The initial flame propagation rate for airborne ASD-4 aluminum particles calculated using (1) is $80 \div 120 \text{ m/s}$. These flame propagation rate ranges agree with the values obtained in the study of nonsteady flame propagation in a gaseous suspension of aluminum particles [10].

The obtained value of hotspot critical radius can be used to calculate a minimal level of spark discharge energy $E_{\text{min}}$. According to Zel’dovich [3], a hotspot which can propagate in an air suspension of aluminum particles just like in gas-air mixtures can be created if its diameter is equal to the width of combustion zone $b_f$. Accordingly, $E_{\text{min}}$ must heat a certain volume of aluminum-air mixture with the radius $R_{cr}$ from initial temperature $T_0$ to combustion temperature $T$ proportionate to the flame front width [3].

$$E_{\text{min}} = b_f^3 \cdot c_p \cdot \rho \cdot (T - T_0)$$

where $c_p$ – heat capacity of aluminum-air mixture at constant pressure; $\rho$ – density of aluminum-air mixture $\approx 1782 \text{ kg/m}^3$.

Calculation of the minimum energy using formula (2) shows that a minimal level of spark discharge energy required to ignite ASD-4 aluminum particles suspended in the airflow should be $0,025 \text{ J}$, which agrees with the experimentally obtained value of ignition energy for an aluminum powder with particle size of ASD-4 [11].

The effects of turbulence intensity on the development of flame from the initial hotspot are different for a homogeneous mixture and a heterogeneous aluminum-air mixture. The behavior of solid particles in a turbulent airflow is a complex physical process, the mechanics of which depend on concentration and size of the particles.

Propagation of the initial hotspot depends on whether the combustion process will generate heat faster than it will be dissipated into the environment through radiation and turbulent diffusion. Since heat is dissipated from the initial hotspot by turbulent diffusion and intensity of dissipation depends on pulsating rate, it is necessary to establish how the initial turbulence influences the process of initial hotspot development in the recirculation zone.

![Figure 3. Initial turbulence influence on ignition process.](image-url)
The results of high-speed camera shooting, which enable us to make conclusion about the influence of initial turbulence of the airflow $\epsilon_0$ on the development of the initial hotspot, are presented in figure 3. Figure 3a shows that in case of tubular turbulence it takes 2 frames, i.e. $3,2 \times 10^{-3} \text{s}$, for the flame to propagate from the initial hotspot to the entire recirculation zone. With a higher turbulence (figure 3b, c), it takes $4,8 \times 10^{-3} \text{s}$. In both cases, the flame propagates from the recirculation zone into the mainstream of the aluminum-air mixture within one frame, i.e. in less than $1,6 \times 10^{-3} \text{s}$. It has also been established that fragmentation of the initial hotspot increases with the increase of its size even if turbulence intensity decreases when the turbulizing grid is moved farther away from the plane of sudden expansion (figure 3c).

$$D_{KC} = 0,4 \text{m}; \text{a - without grid ($\epsilon_0 = 5\%$); b - with grid at } l_p = 0,057 \text{m ($\epsilon_0 = 12\%$)}$$

The effect of turbulence on spherical flame increases because a larger hotspot is exposed to bigger pulsations and thus to a higher pulsation rate.

In case of a tubular turbulence, the flame first propagates across practically the entire recirculation zone and then ignites the mainstream of the aluminum-air mixture, whereas in case of higher turbulence hotspots are drawn into the mainstream before they propagate in the recirculation zone and then die out thus delaying the ignition of the mainstream of the aluminum-air mixture. Next frames illustrate how the flame fills the recirculation zone and propagates into the mainstream of the aluminum-air mixture.

The restraining effect of turbulence on flame development during the initial stage may have two causes: firstly, increased dissipation of heat from the hotspot which obstructs ignition and, secondly, expansion of the reaction zone in a turbulent flame which decreases the average temperature of gas in it and thus its expansion ratio.

The effect of initial turbulence on the dynamics of hotspot development for ASD-4 aluminum powder is presented in figure 4.

The figure demonstrates that ASD-4 aluminum-air mixture hotspot develops in two stages. During the first $\tau \approx 2,5 \times 10^{-3} \text{s}$ (the first stage) the hotspot develops faster in the airflow with 12% turbulence than in the airflow with 5% tubular turbulence due to a more intensive supply of oxidizer to the hotspot. Conversely, during the second stage ($\tau > 2,5 \times 10^{-3} \text{s}$) the hotspot develops faster in the airflow with 5% tubular turbulence than in the airflow with a higher turbulence due to poorer heat dissipation from the hotspot.

4. Conclusions
Thermal explosion of aluminum powder ASD-4 suspended in an air flow was studied experimentally using the model of hotspot ignition. A critical hotspot radius $R_{cr} \geq 1 \text{mm}$ for aluminum powder with average particles size $d_{32} = 7,4 \mu \text{m}$ and ignition condition $R_{cr} \geq 0,5h_f$ have been determined.
A hotspot in airborne ASD-4 aluminum powder develops in two stages, similarly to ASD-1 [2]. Higher initial turbulence of the airflow with suspended aluminum particles promotes hotspot development during the first stage and obstructs it during the second stage. Thus the obtained results prove the assumption that ignition of ASD-4 and ASD-1 aluminum powder particles suspended in the airflow develops from initial hotspot in recirculation area and propagates into the main flow of aluminum-air mixture.

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