We study a flame propagating in the gaseous combustible mixture with suspended inert solid micro particles. The gaseous mixture is assumed to be transparent for thermal radiation emitted by the hot combustion products, while particles absorb and re-emit the radiation. Thermal radiation heats the particles, which in turn transfer the heat to the surrounding unburned gaseous mixture by means of thermal heat transfer. Different scenarios are possible depending on the spatial distribution of the particles, their size and the number density. In the case of uniform spatial distribution the radiation absorption ahead of the flame causes a modest increase of the combustion wave velocity. On the contrary, in the case of non-uniform distribution of the particles, such that the particles number density increases far ahead of the flame, the preheating caused by the thermal radiation may trigger additional source of ignition. Far enough ahead of the flame, where number density of particles is higher, the temperature due to the radiative preheating can rise up to the value sufficient for ignition, and depending on the steepness of the temperature gradient formed in the unburned mixture, either deflagration or detonation can be initiated via the Zeldovich’s gradient mechanism. The ignition and the resulting combustion regimes depend on the number density profile and, correspondingly, on the temperature profile (temperature gradient), which is formed in effect of radiation absorption and gas-dynamic expansion.

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I. INTRODUCTION

It is known, that uncontrolled development of detonation poses significant threats to chemical storage and processing facilities, mining operations, etc., while controlled detonation initiation can be a potential application for propulsion and power devices. Studies of the premixed flames and detonations arising and propagating in the presence of suspended particulates may play an important role for the understanding of unconfined vapor cloud explosions, accidental explosions in the coal mines and in the chemical industry, dust explosion hazards, and for better performance of rocket engines using the solid particles fuels. In astrophysics, the detonation formation is an important, yet least understood aspect of the thermonuclear type Ia Supernovae explosion phenomenon, which was used as a standard distance indicators and led to the discovery of the accelerating expansion of the universe.

Usually, thermal radiation of the hot combustion products does not influence the flame propagation. For example, if the flame propagates out from the closed end of a tube, the radiation losses of the hot combustion products cause a relatively modest cooling of the burned products, which results in a modest decrease of pressure behind the flame front and, correspondingly, a minor decrease of the flame velocity. The radiation of hot combustion products has negligibly small effect ahead of the flame because the radiation absorption length (Rosseland length) in the unburned gaseous fuel is very large, so that the gaseous mixture can be considered as almost fully transparent for the radiation. The situation changes drastically in the presence of particulates suspended in the gaseous mixture, which is typical for e.g., coal mine, chemical industry, forest fire, etc. In such a case the absorption length of radiation can be estimated as $L = 1/N_p\sigma_p$, where $N_p$ is the particles number density, and $\sigma_p = \pi r_p^2$ is the cross section for the light absorption. The radiant energy is absorbed by the particles and transferred from the particles surface to the surrounding gas by means of thermal heat transfer. It should also be noted that even the presence of a relatively small concentration of particles increases the luminosity considerably, so that the radiant flux emitted by the hot combustion products may be well approximated by the black-body radiation. Particles preheated by the radiation can increase temperature of the surrounding gaseous mixture and in some instances may cause ignition of the unburned mixture.
A combustible mixture can be ignited by electrical sparks, or by thermal heating. The ignition capability of an electrical spark varies with fuel concentration, humidity, oxygen content of the atmosphere, temperature, and turbulence, requiring about \((0.01 \div 0.03)\) mJ depending on the mixture reactivity. In contrast, radiation-induced ignition typically requires much larger amounts of energy to be released in the mixture. Direct thermal ignition of gaseous combustible mixture by absorption of radiation causing a rapid increase in temperature at least up to 1000K is possible by focusing a high power laser radiation and has been demonstrated both theoretically and experimentally\(^9,10\). However, ignition at low power levels is unlikely because of a very large length of absorption of the combustible gases at normal conditions.

The flame propagating in the uniformly dispersed, quiescent, gravity-free, particle clouds and ignition of combustion by inert hot particles has been considered by different groups of authors assuming uniform dispersion of particulates with and without account of radiative heat transfer\(^11-16\). Coal combustion research\(^17,18\) is typically focused on two aspects of practical interest: production of volatiles due to thermal decomposition of coal dust and char combustion. The combustible volatiles may essentially contribute to the heat-up of the coal particles, enhance the combustion energy release due to energy feedback mechanism resulting in an explosion. Effect of radiation transfer on a spray combustion, which can be of interest for practical cases such as diesel engines, gas turbine combustors etc. was studied in\(^19\).

In practice, the plausibility of ignition ahead of the propagating flame is determined by the ignition conditions\(^20\) implying certain energy input with a certain rate. As the mechanism formulated above involves suspended particles as a carrier of radiation and since particles have to be heated up to relatively high temperature, their spatial distribution should be such, that the radiation to be absorbed mostly well ahead of the flame front in order to promote the ignition conditions before the flame arrival. Ignition occurs via the Zeldovich temperature gradient mechanism, with initiating of one or another combustion regime depending on the provided conditions\(^21,22\). The thermal energy accumulated by the particles and transferred to the gaseous mixture depends on the radiant energy absorbed by the particles, the energy transferred from the particle surface to surrounding gaseous mixture and the radiant losses from the particles.

In the present paper we consider the effects of thermal radiative preheating for a flame
propagating in the suspension comprising two phases: hydrogen/oxygen gaseous mixture and inert solid micro particles. The hydrogen/oxygen gaseous mixture is assumed to be transparent for radiation, while the solid particles absorb and re-emit the radiation. It is shown that there are different scenarios depending on spatial distribution of the suspended particles ahead of the propagating flame. For a uniform spatial distribution of dispersed particles ahead of the flame the radiative preheating results in a modest increase of the flame velocity. On the contrary, a non-uniform spatial distribution of dispersed particles, such that the particles concentration is relatively small just ahead the flame and increases far ahead of the flame forming a denser cloud of particles suspended in the gaseous mixture, results in ignition of either deflagration or detonation via the Zeldovich gradient mechanism.

The paper is organized as follows. Section 2 is the formulation of the problem and short description of the numerical method. In Section 3 we perform 1D direct numerical simulations and consider the planar hydrogen/oxygen flame propagating through the mixture with uniform distribution of small suspended particles. Section 4 presents analysis of the ignition of different combustion regimes initiated by the radiative preheating in the case of non-uniform distribution of dispersed particles. We conclude in the last Section.

II. GOVERNING EQUATIONS

The governing equations for a planar flame in the gaseous phase are the one-dimensional, time-dependent, multispecies reactive Navier-Stokes equations including the effects of compressibility, molecular diffusion, thermal conduction, viscosity, chemical kinetics and the chemical energy release, momentum and heat transfer between the particles and the gas:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} = 0, \quad (1)
\]

\[
\frac{\partial Y_i}{\partial t} + u \frac{\partial Y_i}{\partial x} = \frac{1}{\rho} \frac{\partial}{\partial x} \left( \rho D_i \frac{\partial Y_i}{\partial x} \right) + \left( \frac{\partial Y_i}{\partial t} \right)_{ch}, \quad (2)
\]

\[
\rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} \right) = -\frac{\partial P}{\partial x} + \frac{\partial \sigma_{xx}}{\partial x} + \rho_p \frac{(u - u_p)}{\tau_{St}}, \quad (3)
\]
\[
\rho \left( \frac{\partial E}{\partial t} + u \frac{\partial E}{\partial x} \right) = \\
- \frac{\partial (P u)}{\partial x} + \frac{\partial}{\partial x} (\sigma_{xx} u) + \frac{\partial}{\partial x} \left( \kappa (T) \frac{\partial T}{\partial x} \right) + \sum_k \frac{h_k}{m_k} \left( \frac{\partial}{\partial x} (\rho D_k (T) \frac{\partial Y_k}{\partial x}) \right) \\
+ \rho \sum_k h_k \left( \frac{\partial Y_i}{\partial t} \right)_{ch} - \rho_p \frac{(u - u_p)^2}{\tau_{St}} \rho P c_{P,p} Q_{gp}, \tag{4}
\]

\[
P = R_B T n = \left( \sum_i R_B Y_i \right) \rho T = \rho T \sum_i R_i Y_i, \tag{5}
\]

\[
\varepsilon = c_v T + \sum_k \frac{h_k \rho_k}{\rho} = c_v T + \sum_k h_k Y_k, \tag{6}
\]

\[
\sigma_{xx} = \frac{4}{3} \mu \left( \frac{\partial u}{\partial x} \right) \tag{7}
\]

We use here the standard notations: \( P, \rho, u, \) - are pressure, mass density, and flow velocity of gaseous mixture, \( Y_i = \rho_i / \rho \) - the mass fractions of the species, \( E = \varepsilon + (u^2) / 2 \) - the total energy density, \( \varepsilon \) - the inner energy density, \( R_B \) - is the universal gas constant, \( m_i \) - the molar mass of i-species, \( R_i = R_B / m_i \), \( n \) - the gaseous molar density, \( \sigma_{ij} \) - the viscous stress tensor, \( c_v = \sum_i c_{v_i} Y_i \) - is the constant volume specific heat, \( c_{v_i} \) - the constant volume specific heat of i-species, \( h_i \) - the enthalpy of formation of i-species, \( \kappa(T) \) and \( \mu(T) \) are the coefficients of thermal conductivity and viscosity, \( D_i(T) \) - is the diffusion coefficients of i-species, \( \left( \frac{\partial Y_i}{\partial t} \right)_{ch} \) - is the variation of i-species concentration (mass fraction) in chemical reactions, \( \rho_p = m_p N_p \) - mass density of the suspended particles, \( N_p \) - particles number density, \( u_p \) - particles velocity, \( \tau_{St} = m_p / 6 \pi \mu r_p \) - the Stokes time for the spherical particles of the radius \( r_p \) and mass \( m_p \), \( Q_{gp} \) - interphase thermal exchange source, \( c_{P,p} \) - the constant pressure specific heat of the particles material.

The changes in concentrations of the mixture components \( Y_i \) due to the chemical reactions are defined by the solution of system of chemical kinetics

\[
\frac{dY_i}{dt} = F_i(Y_1, Y_2, ... Y_N, T), \quad i = 1, 2, ..., N \tag{8}
\]

The right hand parts of Eq.(8) contain the rates of chemical reactions for the reactive species \( H_2, O_2, H, O, OH, H_2O, H_2O_2, \) and \( HO_2 \) with subsequent chain branching, production of
radicals and energy release. We use in simulations the standard reduced chemical kinetic scheme for hydrogen/oxygen combustion with the elementary reactions of the Arrhenius type and with pre-exponential constants and activation energies presented in\textsuperscript{23}.

The equations of state for the fresh mixture and combustion products were taken with the temperature dependence of the specific heats, heat capacities and enthalpies of each species borrowed from the JANAF tables and interpolated by the fifth-order polynomials\textsuperscript{23,24}. The viscosity and thermal conductivity coefficients of the mixture were calculated from the gas kinetic theory using the Lennard-Jones potential\textsuperscript{25}. Coefficient of the heat conduction \(\kappa = \mu C_p / Pr\) for the mixture as a whole are expressed via the viscosity \(\mu\) and the Prandtl number \(Pr = 0.75\).

The equations for the phase of suspended particles read:

\[
\frac{\partial N_p}{\partial t} + \frac{\partial (N_p u_p)}{\partial x} = \frac{\partial}{\partial x} \left( D_m \frac{\partial N_p}{\partial x} \right) \tag{9}
\]

\[
\left( \frac{\partial u_p}{\partial t} + u_p \frac{\partial u_p}{\partial x} \right) = \frac{(u - u_p)}{\tau_{St}} \tag{10}
\]

\[
\left( \frac{\partial T_p}{\partial t} + u_p \frac{\partial T_p}{\partial x} \right) = Q_{gp} - 2\pi r_p^2 N_p \left( 4\sigma T_p^4 - q_{rad} \right) \tag{11}
\]

Where \(T_p\) - temperature of the particles, \(D_m = kT_g / 6\pi\rho\nu r_p\) is the coefficient of molecular diffusion. The term \(2\pi r_p^2 N_p \left( 4\sigma T_p^4 - q_{rad} \right)\) is the thermal radiation energy accumulated and re-emitted by the particles. The energy transferred from the particle surface to surrounding gaseous mixture is

\[
Q_{gp} = \frac{3\kappa Nu}{2r_p^2 c_{P,p} \rho_\infty} (T - T_p), \tag{12}
\]

where \(\tau_Q = 2r_p^2 c_{P,p} \rho_\infty / 3\kappa Nu\) is the characteristic time of the energy transfer from the particle surface to surrounding gaseous mixture, \(Nu\) is the Nusselt number (see e.g.\textsuperscript{26}).

For a planar problem the equation for the thermal radiation heat transfer in the diffusion approximation is\textsuperscript{27,28}:

\[
\frac{d}{dx} \left( \frac{1}{\chi} \frac{dq_{rad}}{dx} \right) = -3\chi \left( 4\sigma T_p^4 - q_{rad} \right), \tag{13}
\]

where the radiation absorption coefficient is \(\chi = 1/L = \pi r_p^2 N_p\), and \(L = 1/\pi r_p^2 N_p\) is the radiation absorption length. The radiant energy flux emitted by the hot combustion products from the flame front is assumed to be equal to the black-body radiative heat source, \(q_{rad}(x =\)

\( X_f = \sigma T_b^4 \), where \( \sigma = 5.670310^{-8} W/m^2 K^4 \) is the Stefan-Boltzmann constant, and \( T_b \approx 3000K \) is temperature of the hot combustion products.

The calculations were carried out for stoichiometric hydrogen/oxygen at initial pressure \( P_0 = 1\text{atm} \) using a standard reduced chemical kinetic scheme\(^{23}\). The mass density of a small spherical particles suspended in the hydrogen/oxygen is assumed to be much smaller than the gaseous density. The numerical method is based on splitting of the Eulerian and Lagrangian stages, known as coarse particle method (CPM)\(^{29}\). A detailed description of the modified CPM optimal approximation scheme, details of the equations and transport coefficients, the reaction kinetics scheme together with the reaction rates appear, as well as the convergence of the solutions and resolution tests appear in\(^{30,31}\). The equation (13) was calculated for every time step using the implicit scheme.

### III. FLAME ACCELERATION IN THE MIXTURE WITH UNIFORMLY DISPERSED PARTICLES

First, we consider the flame propagating through the uniformly suspended particles cloud. As it was mentioned above, the particles ahead of the flame front absorb the thermal radiation and transfer the heat to the fresh gaseous mixture. In case of the uniform particles distribution it causes the preheating of the gas on the scales of the thermal radiation absorption length \( L \) ahead the flame front (see Fig. 1).

The calculated gaseous temperature distribution ahead of the flame shown in Fig.2 corresponds to the radiation absorption lengths, \( L = 0.28, 1.11 \text{cm}, \) and \( L = 2.22 \text{cm} \). The corresponding values of radius and number density of the particles are: \( r_p = 6, 1.5, 0.75 \mu\text{m} \) and \( N_p = 3.18 \cdot 10^6, 1.27 \cdot 10^7, 2.55 \cdot 10^7 \text{cm}^{-3} \). In the simulations all the dynamical parame-
FIG. 2. Temperature distribution ahead of the flame front calculated for uniformly distributed suspended particles and for different radiation absorption lengths, \( L = 0.28, 1.11, 2.22 \text{cm} \).

Parameters of the two-phase reacting flow were taken the same, so that \( \tau_{St} = 40 \mu s \) and \( \tau_Q = 480 \mu s \) \((Nu \approx 2)\) in all three cases. A momentum coupling of the particles and the gaseous phase is essential if the mass loading parameter \( \varsigma = m_p N_p / \rho \) becomes of the order of unity. In order to distinguish the effects of the radiation preheating in all calculations the mass loading parameter was taken the same, \( \varsigma = 0.3 \). This is also convenient because for a constant value of \( \varsigma \) the initial flame velocities are the same independently on the particles sizes and number densities, which in such a case determine only the radiation absorption lengths. This choice of the parameters allows to distinguish the effects of the radiation preheating on the process, because in this case the initial temperatures and the initial flame velocities are the same.

Absorption of the radiation by the particles and a modest rise of temperature of the reacting gaseous mixture ahead of the flame front \((\Delta T \approx 150 \div 200 K)\) cause the corresponding increase of the flame velocity. As shorter the absorption length is as shorter the preheated zone ahead of the flame, and as faster the flame velocity increases up to some new constant value. The corresponding increase of the combustion wave velocities due to the temperature increase ahead of the flame front for the radiation absorption lengths \( L = 0.28, 1.11, 2.22 \text{cm} \) is shown in Fig. 3. The increase in the combustion velocity is modest, about 10\%, and it is maximal for the given parameters. Asymptotically, the combustion velocity goes to the normal flame velocity for \( L \to \infty \), which corresponds to the pure gaseous mixture, and for \( L \to 0 \), which determines the conditions when all the radiation energy is absorbed inside the exothermal reaction zone giving no effect to the reaction intensification.
FIG. 3. Burning velocity increase as the flame propagates through the gas-particles cloud with different thermal radiation absorption length ($L$)

IV. COMBUSTION REGIMES INITIATION DUE TO THE RADIATIVE PREHEATING OF NON-UNIFORMLY DISPERSED PARTICLES

Since the radiant energy flux emitted from the flame is not very intense, temperature of the reacting gaseous mixture ahead of the flame can not increase significantly for a uniform distribution of the particles. It results in a relatively small increase of the burning velocity and causes modest effect on the overall process evolution. The interesting opportunities appears in the case of non-uniform distribution of the particles, such that over a noticeably large distance ahead of the flame the mixture is almost transparent for the thermal radiation and the radiation is absorbed only far ahead of the flame front as it is shown schematically in Fig. 4. In this case time of the thermal radiation heating is much longer than in the case of a uniform particles distribution as the flame should overcome the ultimate distance separating it from the dense region. Particles in the dense cloud far ahead from the flame absorb much more of the thermal radiant energy, so that temperature of the particles and surrounding mixture can rise up to the value suitable for ignition long before the flame arrival.

In such conditions the ignition starts when the temperature exceeded the crossover value, which is for hydrogen/oxygen at 1atm is about $1050 \pm 50$K and determines the limit where the induction endothermic stage passes into the fast exothermic stage. Assuming that the radiation is absorbed on the length $L$ during the time interval $t$, we can roughly estimate the temperature increase due to radiative preheating. Neglecting by the gas expansion this gives $\Delta T \approx q_{\text{rad}}t/\rho c_p L \approx 10^5(t/L)K$. This means that to rise temperature of the mixture
FIG. 4. Scheme of the radiant preheating of the gaseous mixture inside the gas-particles cloud far ahead the flame front.

up to crossover temperature would require about $0.1 \div 0.2\text{ms}$ for absorption length inside the cloud $L \approx 1\text{cm}$ (time of the particle/gas heat exchange is not taken into account). Thus, the left boundary of the denser particles cloud, where radiation is absorbed, should be far ahead from the propagating flame as shown in Fig.4. Below we assume that the "gap" between the flame and the left boundary of the gas/particles cloud is transparent for the thermal radiation, so that in this area the radiation absorption length is much larger than the distance from the flame to the boundary of the cloud.

The temperature gradient established due to the radiative preheating of the mixture in the gas-particle cloud via radiation absorbed by the particles depends on the thermal radiation absorption length, which local non-uniformity is also influenced by the gas expansion during the heating. If the particle-gas cloud is far enough from the flame so that the combustible gas temperature rises up to crossover value due to the thermal radiation preheating, then, depending on the steepness of the formed temperature gradient, either a deflagration or a detonation can be ignited via the Zeldovich’s gradient mechanism\textsuperscript{20–22}.

Figure 5 shows the calculated temporal evolution of the gaseous temperature and mass density of the particles profiles during preheating for the distant cloud with the initial stepwise profile of particles number density. In the calculations the particle radius and the particles number density were taken: $r_p = 1\mu\text{m}$ and $N_p = 2.5 \cdot 10^7\text{cm}^{-3}$, correspondingly. The number density of particles between the left boundary of the cloud and the flame is assumed to be much less than it is inside the cloud, so that the radiation absorption length there is much larger than the distance to the flame and this area can be treated as almost transparent for the radiation. At the same time it should be noticed that even a relatively small concentration of the particles in the hot combustion products behind the flame front increases considerably the luminosity and the radiant energy flux, so that the radiation form
FIG. 5. Temporal evolution of the gaseous temperature (a) and the mass density of the suspended solid particles (b) profiles during radiative preheating inside the gas-particles cloud far ahead the propagating flame front. Profiles are shown with the time intervals of 50µs. For initial stepwise particles density profile, $N_p = 2.5 \cdot 10^7 cm^{-3}$, $r_p = 1\mu m$.

the flame can be approximated by the black-body radiation.

The steepness of the formed temperature gradient, $\Delta = (T* - T_0) / |dT/dx| \approx 1cm$, in Fig. 5 is in agreement with the value of the radiation absorption length, $L = 1/\pi r_p^2 N_p \approx 1.2$ cm. Such temperature gradient can ignite a deflagration according to classification of combustion regimes initiated via the Zeldovich’s gradient mechanism in the hydrogen/oxygen at 1atm\textsuperscript{21,22}. The calculated temporal evolution of the gaseous temperature and pressure profiles during the deflagration wave formation in the vicinity of the left boundary of the gas-particles cloud far ahead of the flame front are shown in Fig. 6. The solid line in the upper frame of Fig. 6 shows the formed density profile at the instant $t_0 = 900 \mu s$ prior to the ignition, when the corresponding temperature gradient with $T* = 1050$ K is formed (the first temperature profile in the middle frame).

For the case of a somewhat smaller initial number density of the particles in the cloud, the temperature gradient, formed at the moment, when maximal temperature $T*$ achieved crossover value, is shallower and the fast deflagration behind a weak shock wave can be formed\textsuperscript{21,22}. It should be noted that the principle factor which defines steepness of the
FIG. 6. Temporal evolution of the gaseous temperature profiles (middle frame) and pressure profiles (bottom frame) during the slow combustion wave formation in the vicinity of the boundary of the gas-particles cloud far ahead the propagating flame front, $t_0 = 900 \mu s$, $\Delta \tau = 50 \mu s$. The upper frame shows the distribution of particles mass density: dashed line - the initial density profile, solid line - density profile at time instant $t_0$ prior to the ignition. Initial stepwise particles density.

temperature gradient caused by the radiative preheating is the radiation absorption length, $L = 1/\sigma_p N_p$. A more gentle temperature gradient can be formed either in the cloud with smaller concentration of the particles, or for smaller particles of the same concentration, or for the cloud with a properly diffuse interface instead of the cloud with the stepwise particles number density spatial distribution. In the latter case the radiation absorption length varies along the diffusive cloud interface, which may result in the formation of a smooth temperature profile with a shallow temperature gradient capable to initiate a detonation. Examples of the particle clouds with diffuse interface and the corresponding temperature profiles caused by the radiative preheating are shown in Figs. 7 and 8.

We consider the cloud of particles with the same maximal number density of particles and with a smooth, diffuse left boundary. Figure 7 shows the formed diffuse boundary of the particles cloud (upper frame) and temporal evolution of the gaseous temperature and
FIG. 7. Temporal evolution of the gaseous temperature profiles (middle frame) and pressure profiles (bottom frame) during the fast combustion wave formation behind the outrunning shock in the vicinity of the margin of the gas-particles cloud far ahead the propagating flame front, \( t_0 = 1650\, \mu s \), \( \Delta \tau = 50\, \mu s \). The upper frame shows the distribution of particles mass density: dashed line - the initial density profile, solid line - density profile at time instant \( t_0 \) prior to the ignition. The initial linear diffuse boundary width 1.0 cm.

pressure profiles during the formation of the fast deflagration behind the outrunning shock in the vicinity of the gas-particles cloud boundary. The initial boundary diffusivity of the cloud is the linear decrease of the particles number density on the scale of 1 cm.

Initiation of a detonation wave via the Zeldovich’s gradient mechanism requires much more shallower temperature gradient. Calculations\(^{21,22}\) for hydrogen/oxygen, which used the initial linear temperature gradient at normal conditions and \( T^* = 1050\, K \) at the top of the gradient, have shown that the scale of the gradient needed for the detonation initiation was about 20cm. The results of the simulation for the cloud with initial diffuse boundary, where the particles number density drops linearly on the scale of 10cm, are presented in figure 8. Here the upper frame depicts the formed diffuse boundary of the particles cloud, which was smeared due to gas expansion during the thermal radiation heating up to 20cm. Temporal
FIG. 8. Temporal evolution of the gaseous temperature profiles (middle frame) and pressure profiles (bottom frame) during the detonation formation in the vicinity of the margin of the gas-particles cloud far ahead of the flame front, \( t_0 = 4980\mu s \), \( \Delta \tau = 4\mu s \). The upper frame shows the distribution of particles mass density: dashed line - the initial density profile, solid line - density profile at time instant \( t_0 \) prior to the ignition. Cloud with diffuse boundary: the particles number density drops linearly on the scale 10cm.

Evolution of the gaseous temperature and pressure profiles during the detonation formation in the vicinity of the diffusive cloud boundary are depicted in the two other frames. Dashed line in the upper frame shows the initial density profile, and the solid line shows density profile at the time instant \( t_0 = 4980\mu s \) prior to the ignition of a spontaneous combustion wave triggering the detonation.

V. CONCLUSIONS

The purpose of the present study was to demonstrate that the radiative preheating in the presence of a gas-particle heat exchange can considerably influence the overall picture of the flame propagation. Depending on spatial distribution of the particles, the radiative preheating can either result in a modest increase of the flame velocity, or can promote
formation of the temperature gradients, which can ignite either deflagration or detonation via the Zeldovich’s gradient mechanism far ahead of the main flame front inside the gas-particles clouds. In contrast to the previous studies, which mostly considered the decrease of a flame velocity due to the radiation losses, the present study is focused on the influence of the radiative preheating of the unburned gaseous mixture ahead of the flame front. The performed numerical simulations demonstrate the plausibility of radiation preheating as the principal effect of the combustion intensification and even detonation initiation in the gaseous fuel, where relatively low concentration of suspended solid micro particles or any other substance can absorb the radiative heat flux and rise temperature of the fuel ahead of the flame.

Different scenarios [4-8] were considered in attempt to explain the detonation formation in type Ia Supernovae explosion phenomenon. We want to draw attention to another possibility, related to the the huge, about $10^{43}$ erg/sec radiant energy flux produced by the beta decays of $Ni^{56} \rightarrow Co^{56} \rightarrow Fe^{56}$ during the SNIa burning. This radiant flux increases in course of the star incineration by the expanding deflagration and presumably the detonation at the late stage can be initiated due to the radiative preheating of the outer layers. Even absorption of a small fraction of the radiation may lead to the formation of a shallow temperature gradient and to the detonation ignition.

Finally, it should be emphasized that this study is a necessary prerequisite aiming to show principle physics and role of the radiative preheating in the case of a gas-particle heat exchange. The obtained results show that the thermal radiative preheating can play a significant role in determining the regimes of combustion in two-phase reacting flows. The conditions under which a reactive two-phase mixture can ignite and produce a heat release are also considered to be important in the area of fire safety.

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