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GAS-PHASE IGNITION OF A FILM OF LIQUID CONDENSED SUBSTANCE BY A METAL PARTICLE HEATED TO HIGH TEMPERATURES UNDER MIXED-CONVECTION CONDITIONS

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A numerical analysis of the scale of influence of the mixed convection of an oxidant and a fuel vapor on the characteristics of the gas-phase ignition of the film of a typical liquid condensed substance — kerosene — by a small-size metal particle heated to high temperatures has been made. The limiting values of the velocity of air-mass motion for which no ignition conditions are realized in the system "metal particle heated to high temperatures–kerosene films–air" have been established. The ranges of variation in the air temperature and the initial warmed-up-particle temperature in which the ignition conditions are realized have been determined. It has been shown that no ignition occurs even for a high heat content of the heating source when $Re > 1.3 \cdot 10^3$.

Keywords: *ignition, heat and mass transfer, heated particle, film of a liquid condensed substance, mixed convection.*

Introduction. The processes of ignition of solid and liquid condensed substances by heating sources with a finite energy content, in particular, by small-size metal and nonmetal particles, wires, and metal rods, have found application in various industries [1–3]. However, these processes are often responsible for uncontrolled spontaneous fires at factories [4].

The conditions of ignition of condensed substances are not clearly understood at present. Only the general theory of ignition of condensed substances with different methods of energy supply has been developed [5]. Based on the solid-phase, heterogeneous, and gas-phase ignition models proposed in [5], a number of models of ignition of solid [6, 7] and liquid [8–10] condensed substances by small-size single metal and nonmetal particles of various configurations, which are heated to high temperatures, have been proposed. Experimental investigations of the ignition processes in the heated particle–liquid fuel–air [11] and heated particle–mixture fuel–air [12] systems have been performed. However, the influence of mixed convection (convective motion of the fuel vapor in the oxidant medium and forced convection of the oxidant due to the air-mass motion) on the ignition characteristics was not investigated before [8–11], although this factor is of importance under actual conditions.

It is well known [6, 7] that forced convection intensifies ignition under the conditions of solid-phase ignition. However the characteristic scale of influence of the convection of the external medium on the ignition conditions has not been established for liquids.

The present work seeks to numerically investigate the regularities of the gas-phase ignition of a film of a typical liquid condensed substance by a metal particle warmed up to high temperatures under mixed-convection conditions.

Formulation of the Problem. The process of ignition of a film of a condensed substance by a singe particle has been investigated using the system in Fig. 1 as an example. It was assumed that the metal particle was immersed in the liquid film (Fig. 1a). The film thickness Z_{liq} was assumed to be smaller than the particle height Z_{p}. Under these conditions, we ensured the contact of the heating source with both the inflammable liquid and the formed mixture of the fuel vapor and air. The initial air velocity in the gas region above the film surface in the direction of the coordinate R was taken to be $U_0(R, Z, 0) \neq 0$. The velocity of air motion perpendicularly to the film surface was assumed to be equal to zero ($V_0(R, Z, 0) = 0$). We considered the following stages of ignition. The film of a liquid combustible is heated by the source energy. Evaporation of the fuel begins on attainment of the vaporization conditions. This produces a vapor gap

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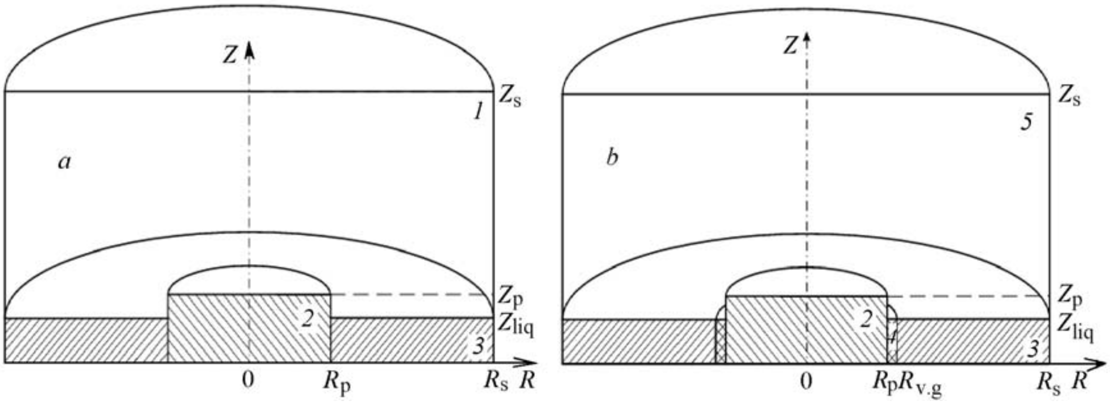

Fig. 1. Diagram of the solution domain of the problem at the initial ($\tau = 0$) instant of time (a) and at $0 < \tau < \tau_d$ (b): 1) air; 2) particle; 3) liquid; 4) fuel-vapor layer; 5) vapor-gas mixture.

between the particle and the liquid (Fig. 1b). The vapor-gas mixture is warmed up as a result of the cooling of the heating source. Once the critical temperatures and concentrations of the fuel vapor have been attained, the mixture ignites.

An analysis was made with the example of a kerosene film. A disk-shaped steel particle with characteristic dimensions R_p and Z_p and initial temperature Θ_p was selected as the ignition source. The problem was solved in the cylindrical coordinate system in the axisymmetric formulation (Fig. 1).

The system of equations corresponding to the physical formulation of the problem is written, in dimensionless variables ($R_p < R < R_{v.g}$ and $0 < Z < Z_{liq}$, $R_p < R < R_s$ and $Z_{liq} < Z < Z_p$, and $0 < R < R_s$ and $Z_p < Z < Z_s$, as follows:

the continuity equation is

$$\frac{\partial^2 \Psi}{\partial R^2} + \frac{1}{R}\frac{\partial \Psi}{\partial R} + \frac{\partial^2 \Psi}{\partial Z^2} = \Omega \, ; \tag{1}$$

the equation of motion of the vapor-gas mixture is

$$\frac{1}{\mathrm{Sh}}\frac{\partial \Omega}{\partial \tau} + U\frac{\partial \Omega}{\partial R} + V\frac{\partial \Omega}{\partial Z} = \frac{1}{\mathrm{Re}_5}\left[\frac{\partial^2 \Omega}{\partial R^2} + \frac{1}{R}\frac{\partial \Omega}{\partial R} + \frac{\partial^2 \Omega}{\partial Z^2}\right] + \frac{\mathrm{Gr}_5}{\mathrm{Re}_5^2}\frac{\partial \Theta_5}{\partial Z} \, ; \tag{2}$$

the energy equation is

$$\frac{1}{\mathrm{Sh}}\frac{\partial \Theta_5}{\partial \tau} + U\frac{\partial \Theta_5}{\partial R} + V\frac{\partial \Theta_5}{\partial Z} = \frac{1}{\mathrm{Re}_5\mathrm{Pr}_5}\left[\frac{\partial^2 \Theta_5}{\partial R^2} + \frac{1}{R}\frac{\partial \Theta_5}{\partial R} + \frac{\partial^2 \Theta_5}{\partial Z^2}\right] + \mathrm{Sr1} \, ; \tag{3}$$

the equation of diffusion of the fuel vapor is

$$\frac{1}{\mathrm{Sh}}\frac{\partial C_f}{\partial \tau} + U\frac{\partial C_f}{\partial R} + V\frac{\partial C_f}{\partial Z} = \frac{1}{\mathrm{Re}_4\mathrm{Sc}_4}\left[\frac{\partial^2 C_f}{\partial R^2} + \frac{1}{R}\frac{\partial C_f}{\partial R} + \frac{\partial^2 C_f}{\partial Z^2}\right] - \mathrm{Sr2} \, ; \tag{4}$$

the equation of diffusion of the steam is

$$\frac{1}{\mathrm{Sh}}\frac{\partial C_{wat}}{\partial \tau} + U\frac{\partial C_{wat}}{\partial R} + V\frac{\partial C_{wat}}{\partial R} = \frac{1}{\mathrm{Re}_6\mathrm{Sc}_6}\left[\frac{\partial^2 C_{wat}}{\partial R^2} + \frac{1}{R}\frac{\partial C_{wat}}{\partial R} + \frac{\partial^2 C_{wat}}{\partial Z^2}\right] ; \tag{5}$$

the balance equation is

$$C_f + C_o + C_{wat} = 1 ; \tag{6}$$

the heat-conduction equation for the metal particle ($0 < R < R_p$ and $0 < Z < Z_p$) is

$$\frac{1}{Fo_2}\frac{\partial \Theta_2}{\partial \tau} = \frac{\partial^2 \Theta_2}{\partial R^2} + \frac{1}{R}\frac{\partial \Theta_2}{\partial R} + \frac{\partial^2 \Theta_2}{\partial Z^2} + Sr3 ; \tag{7}$$

the heat-conduction equation for the liquid-fuel film ($R_{v.g} < R < R_s$ and $0 < Z < Z_{liq}$) is

$$\frac{1}{Fo_3}\frac{\partial \Theta_3}{\partial \tau} = \frac{\partial^2 \Theta_3}{\partial R^2} + \frac{1}{R}\frac{\partial \Theta_3}{\partial R} + \frac{\partial^2 \Theta_3}{\partial Z^2} . \tag{8}$$

Here Sr1, Sr2, and Sr3 are the dimensionless numbers (Sr1 = $Q_o W_o z_s/[\rho_5(T) C_5(T) \Delta T V_{sc}]$, Sr2 = $z_s W_o/[\rho_{12}(T) V_{sc}]$, and Sr3 = $Q_c W_c z_s/[z_p \Delta T \lambda_2(T)]$). Expressions for determining the dimensionless variables presented in the system of equations (1)–(8) and the velocities W_o, V_{sc}, and W_c have been given in [8–10]. The initial and boundary conditions are analogous to [8–10], except for $U_0(R, Z, 0) \neq 0$.

We used the traditional ignition conditions [5]: (1) the heat released as a result of the chemical reaction of oxidation of the fuel vapor in air is larger than the heat transferred from the particle to the liquid and the vapor-gas mixture; (2) the temperature of the vapor-gas mixture is higher than the initial temperature of the particle.

The method of solution of the system of equations describing the process of gas-phase ignition of a film of liquid fuel by a warmed-up particle in the system in question (Fig. 1) is analogous to that of [8–10]. To evaluate the reliability of the obtained results we checked the conservatism of the difference scheme whose algorithm has been presented in [9]. The problem was solved in dimensionless variables. To pass to them we used z_s = 0.02 m, u_{sc} = 1 m/sec, t_{sc} = 1 sec, and T_{sc} = 1000 K as the scale quantities.

Investigation Results and Discussion. The process of ignition in the system warmed-up steel particle–kerosene film–air (Fig. 1) was analyzed for the following values of the parameters [13–16]: initial kerosene temperature Θ_0 = 0.3, initial steel-particle temperature Θ_p=1.5, initial air temperature Θ_{air} = 0.308, initial mass concentration of the steam in air C_{wat0} = 0, thermal effect of oxidation of the kerosene vapor in air Q_0 = 43.8 MJ/kg, thermal effect of evaporation of kerosene Q_e = 26.1 kJ/kg, activation energy of the oxidation reaction for the kerosene vapor–air system E = 190 kJ/mole, pre-exponential factor for determining the mass velocity of oxidation of the fuel vapor $k_0 = 7 \cdot 10^7$ sec^{-1}, crystallization temperature of the steel-particle materials Θ_c = 1.5, thermal effect of crystallization Q_c = 205 kJ/kg, dimensions of the particle $R_p = Z_p = 0.1$, kerosene-film thickness Z_{liq} = 0. 05, and dimensions of the solution domain R_s = 0.5 and Z_s = 1. The thermophysical characteristics of the interacting substances as functions of the temperature were taken according to [14–16].

In investigating numerically a combination of interrelated physicochemical processes occurring in ignition of flammable liquids by single metal and nonmetal particles, we revealed earlier [8–10] the scale of influence of different factors on the conditions and characteristics of ignition. In particular, we determined the role of diffusion-convective heat and mass transfer in the gas phase in the small vicinity of the heating source and the evaporating liquid. It was established that the convection of the fuel vapor in the oxidant medium substantially slows down the processes of warming up of the mixture and formation of a level of fuel concentration sufficient for ignition in it compared to diffusion heat and mass transfer. Convective transfer due to the nonuniform temperature field in the gas phase near the zone of contact of the heating source and the liquid substance and to the evaporation of the flammable liquid was allowed for.

The ignition process becomes even more complicated under the conditions of forced oxidant convection (e.g., for nonzero air velocity in the small vicinity of the zone of contact of the heating source and the inflammable liquid). To analyze this factor we varied the initial air velocity $U_0(R, Z, 0)$ in the system "warmed-up steel particle–kerosene film–air" (Fig. 1). The most typical parameter of ignition — the ignition-delay time τ_d characterizing the inertia of the process under study — was selected as the investigated characteristic. The results of investigation of the scale of influence of $U_0(R, Z, 0)$ on τ_d are presented in Fig. 2.

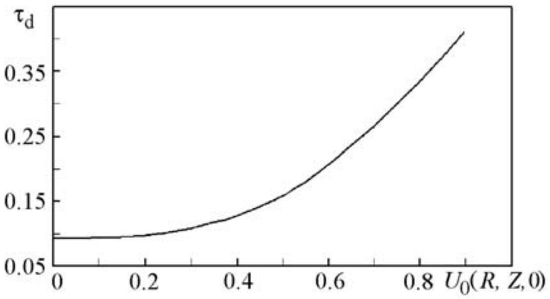

Fig. 2. Ignition-delay time τ_d vs. $U_0(R, Z, 0)$ at $\Theta_p = 1.5$ and $R_p = Z_p = 0.1$.

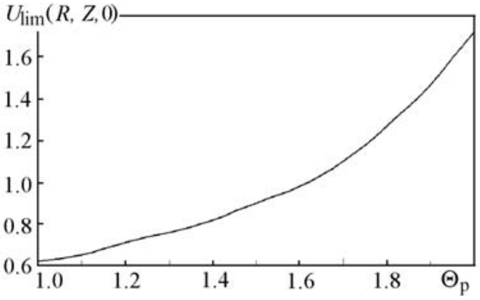

Fig. 3. Limiting velocity $U_{lim}(R, Z, 0)$ vs. Θ_p for $R_p = Z_p = 0.1$.

It is seen that the influence of this parameter on the inertia of ignition is insignificant when $U_0(R, Z, 0) < 0.2$ (the deviations of τ_d for $U_0(R, Z, 0) = 0$ and $U_0(R, Z, 0) = 0.2$ amount to less than 5%). However, as the air velocity increases to 0.9, the deviation of τ_d increases to 80% compared to the regime of the absence of forced oxidant convection. When $U_0(R, Z, 0) > 0.9$ no ignition conditions are realized at all (Fig. 2). In this case the particle is slowly cooled down by heat exchange with the liquid and the moving components of the vapor-gas mixture, which in turn have no time to warm up to a temperature sufficient for ignition because of the high velocity of their motion. The total area of the zone of the heated vapor-gas mixture increases with distance between the heated vapor-gas flows and the heating source. However, regions with a temperature sufficient to accelerate the chemical reaction of oxidation of the fuel vapor followed by ignition have no time to be formed in this mixture. Clearly, in the system in question, such regions can be formed only in the small vicinity of the heating source and the fuel-evaporation boundary.

It has been established [8–10] that the inertia of ignition of flammable liquids by warmed-up particles of different physical nature is mainly influenced by the energy content of the heating sources. This parameter in turn is determined by the initial temperature, the dimensions, and the thermophysical characteristics of the ignition sources. To analyze the scale of influence of the heat content of the particles on the characteristics of ignition in the system in question we varied the initial temperature Θ_p. Thus, e.g., the dependence of the limiting air velocities $U_{lim}(R, Z, 0)$ for which the ignition conditions are still realized on the initial temperature Θ_p was established (Fig. 3).

It is clear from Fig. 3 that the limiting velocity $U_{lim}(R, Z, 0)$ increases from 0.62 to 1.73, as Θ_p changes from 1 to 2. The obtained result allows the conclusion that at high particle temperatures ($\Theta_p > 2$), the probability of ignition is high even when $U_0 > 1.5$. In such cases the "retarding" action of forced oxidant convection is compensated for by the high energy content of the particle and hence the "accelerating" influence of the convective transfer of the fuel vapor. At the same time, when the temperatures are relatively low ($\Theta_p < 1$) the probability that ignition conditions will be realized is small (the vapor-gas mixture is not warmed up to a temperature sufficient for its ignition).

Figure 4 plots the ignition-delay time τ_d as a function of $U_0(R, Z, 0)$ and Θ_p in the form of a surface separating the ranges of variation in these parameters for which ignition conditions are realized (below the surface) and are not realized (above it). It is seen that the surface has a concave profile. This is due to the nonlinear dependence of τ_d on both the velocity $U_0(R, Z, 0)$ and the initial temperature Θ_p. At the same time, it should be noted that the increase in τ_d with $U_0(R, Z, 0)$ is of a larger scale than that with Θ_p.

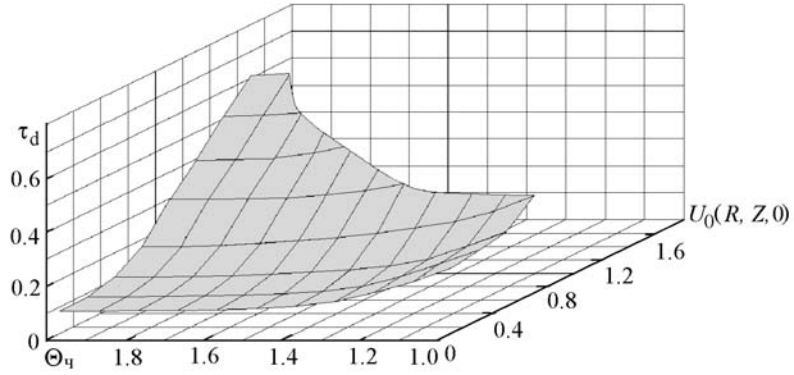

Fig. 4. Ignition-delay time τ_d vs. Θ_p and $U_0(R, Z, 0)$ for $R_p = Z_p = 0.1$.

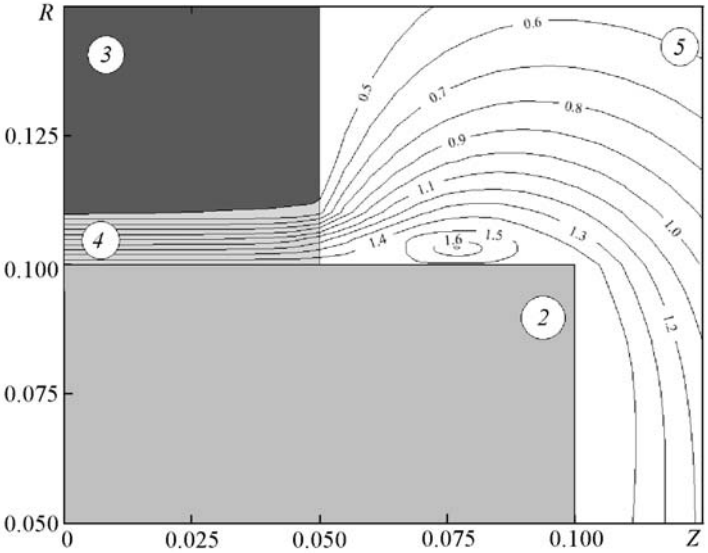

Fig. 5. Isotherms (Θ) of the steel particle–kerosene film–air system at the instant of ignition ($\tau_d = 0.093$) at $\Theta_p = 1.5$, $R_p = Z_p = 0.1$, and $U_0(R, Z, 0) = 0.1$. Notation 2–5 is the same as in Fig. 1.

The form of the resulting nonlinear surface allows the conclusion on the complex "joint" influence of the forced convection of the oxidant and the heat content of the heating source on the ignition characteristics. As the velocity of air-mass motion increases and the particle temperature decreases, the oxidant convection is accelerated, whereas the convective fuel-vapor transfer slows down. As a consequence, the inertia of ignition grows. Conversely, as the velocity of air-mass motion decreases and the particle temperature increases, the oxidant convection slows down, whereas the convective fuel-vapor transfer is accelerated. This causes the ignition-delay time to decrease. However, forced convection of the oxidant and convective transfer of the fuel vapor exert the opposite influence on the ignition characteristics in a fairly wide range of variation in the air velocities and particle temperatures.

From the data of Figs. 2–4, we can draw a conclusion on the substantial scale of influence of the forced oxidant convection on the ignition characteristics. The calculated limiting values $U_{\text{lim}}(R, Z, 0)$ for which the ignition conditions are still realized enable us to additionally separate the limiting value of the Reynolds number. To compute the Reynolds number we use the following expressions:

$$\mathrm{Re} = \frac{2u_{\text{lim}}(r, z, 0)\, z_p \rho_5(T)}{\mu_5(T)} .$$

Formulas for determining $\rho_5(T)$ and $\mu_5(T)$ have been presented in [9].

It has been established that for particles with a nearly maximum initial temperature ($\Theta_p = 2$) and for $R_p = Z_p = 0.1$, ignition of the liquid combustible occurred only when $\mathrm{Re} < 1.3 \cdot 10^3$. The limiting Reynolds number was $8 \cdot 10^2$ under the conditions of relatively low temperatures ($\Theta_p = 1.3$). This result points once again to the nonlinearity of the investigated process of ignition and to the complexity of the "joint" influence of several factors on its characteristics.

Earlier [8–10], in investigating numerically the conditions of ignition of liquid substances by single particles we revealed the possibility of realizing three ignition regimes: the first regime was characterized by the location of the ignition zone near the liquid-evaporation boundary, the second was characterized by the ignition zone in the gas region above the ignition source, and the third regime was characterized by the ignition zone in the vapor gap between the heating source and the liquid substance. When the first regime was realized, the ignition delays were minimum. The second regime corresponded to the maximum delay times and hence the maximum inertia. The third regime was characterized by the intermediate τ_d values in relation to the first two regimes.

An analysis of the ignition process under mixed-convection conditions (Fig. 1) shows that depending on the energy content of the particle the ignition zone can be located either near the lateral faces of the heating source (first regime) or in the region of the vapor gap between the particle and the liquid (third regime). The second regime cannot be realized.

When $U_0(R, Z, 0) \neq 0$ the components of the vapor-gas mixture move away from the particle once they have been warmed up by its heat. Vortices of the vapor flows occur only near the lateral faces of the warmed-up particle. Both the concentration of the fuel vapor and the vapor-gas-mixture temperature increase in these zones. Thus, e.g., at $\Theta_p = 1.5$ and $U_0(R, Z, 0) = 0.1$, the ignition zone is located in the small vicinity of the lateral face of the particle (Fig. 5). When the initial heating-source temperature increases to $\Theta_p = 2$ the ignition zone moves to the region of the vapor gap between the particle and the liquid. Analogous regularities have also been established in the systems "single warm-up particle–liquid fuel–air" for $U_0(R, Z, 0) = 0$ [8–10].

CONCLUSIONS

1. An analysis of the results of the present work shows that mixed convection of the fuel vapor and the oxidant influences, in a complex manner, "jointly" the conditions and characteristics of ignition of a film of liquid condensed substance by a warned-up particle with a finite energy content.

2. The motion of a cold oxidant substantially complicates the process of ignition of the liquid. The ignition conditions are stably realized only for moderate velocities ($\mathrm{Re} < 1 \cdot 10^3$) of oxidant motion and high temperatures of the heating source ($\Theta_p > 1.5$).

3. Unlike the problems of ignition at $U_0(R, Z, 0) = 0$ [8–10], under the conditions of forced oxidant convection ($U_0(R, Z, 0) \neq 0$), the zone of ignition of the fuel film can be located only near the particle–fuel boundary.

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NOTATION

C, specific heat, J/(kg·K); C_{wat}, mass concentration of the steam in the vapor-gas mixture; C_{wat0}, initial mass concentration of the steam in air; C_f, mass concentration of the fuel vapor in the vapor-gas mixture; C_o, mass concentration of the oxidant in the vapor-gas mixture; E, activation energy, kJ/mole; Fo, Fourier number; Gr, Grashof number; k_0, preexponential factor for determining the mass velocity of oxidation of the fuel vapor in air, sec^{-1}; Pr, Prandtl number; Q_e, thermal effect of evaporation of the liquid, kJ/kg; Q_c, thermal effect of crystallization of the particle, kJ/kg; Q_o, thermal effect of oxidation of the fuel vapor in air, MJ/kg; R, dimensionless analog of the coordinate of the cylindrical system r; $R_{\mathrm{v.g}}$, dimensionless vapor gap; R_s, dimensionless dimension of the solution domain along the coordinate R; R_p, dimensionless particle radius; Re, Reynolds number; t_{sc}, time scale, sec; Sh, Strouhal number; Sc, Schmidt number; T, temperature, K; T_{sc}, temperature scale, K; ΔT, temperature difference ($\Delta T = T_{\mathrm{sc}} - T_0$), K; U and V, dimensionless components of the fuel-vapor velocity in the projection onto the R and Z axes; $U_0(R, Z, 0)$, initial dimensionless velocity of air-mass motion in the projection onto the R axis; u_{sc}, velocity scale, m/sec; $u_{\mathrm{lim}}(r, z, 0)$, limiting initial velocity of air-mass motion in the projection onto the r axis, m/sec; $U_{\mathrm{lim}}(R, Z, 0)$, dimensionless analog of $u_{\lim}$; $V_0(R, Z, 0)$, initial dimensionless air-mass velocity in the projection onto the Z axis; V_{sc}, velocity of convection of the fuel vapor near the evaporation boundary, m/sec; W_c, mass velocity of crystallization of the metal particle, kg/(m^2·sec); W_o, mass velocity of oxidation of the fuel vapor in air, kg/(m^3·sec); Z, dimensionless analog of the coordinate of the cylindrical system z; Z_{liq}, dimensionless liquid-film thickness; z_p, characteristic dimension of the particle along the coordinate z, m; Z_p, dimensionless analog of z_p; z_s, characteristic dimension of the solution domain along the coordinate z, m; Z_s, dimensionless analog of z_s; Θ, dimensionless temperature; Θ_0, dimensionless initial temperature of the liquid film; Θ_{air}, dimensionless initial temperature of air; Θ_c, dimensionless crystallization temperature of the particle material; Θ_p, dimensionless initial temperature of the particle; λ, thermal conductivity, W/(m·K); ρ, density, kg/m^3; μ, dynamic viscosity, kg/(m·sec); τ, dimensionless time; τ_d, dimensionless ignition-delay time; Ω, dimensionless analog of the vorticity vector; Ψ, dimensionless analog of the stream function. Subscripts: 0, initial instant of time; 1, air; 2, particle; 3, liquid; 4, fuel vapor; 5, vapor-gas mixture; 6, steam (water vapor); wat, water; air, air; f, fuel; liq, liquid; d, delay; e, evaporation; c, crystallization; sc, scale; o, oxidation; lim, limit; v.g, vapor gap; s, solution; p, particle.

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