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ASSESSMENT OF THE STABILITY OF CONDENSED SOLID SUBSTANCE IGNITION BY A HOT PARTICLE

Dmitrii O. Glushkov[a], Galina S. Nyashina, Ksenia Yu. Vershinina

National Research Tomsk Polytechnic University, 634050 Tomsk, Russia

Abstract. The paper presents a numerical simulation of composite fuel ignition by a disc-shaped hot metal particle. The study establishes the temperature and the source size limits, which are necessary and sufficient for condensed substance ignition. A diagram with coordinates "a heat flow the amplitude – ignition delay time" has been presented. The diagram shows the area of the sustainable initiate combustion of composite solid fuel at local heating by the source with limited energy capacity.

1. INTRODUCTION

The results of the research of solid condensed substances ignition [1–4] are important in the structural design of power plants for various purposes. To date, one of the main problems [5] is to determine the conditions of transition stability, when the initiation stage turns into the stationary self-sustaining combustion of condensed substances without additional energy supply from an external source. It is of great interest to define the range of the sustainable ignition of typical composite solid fuel by a local energy source during conductive heating.

Unlike convective and radiative heating mechanisms, the ignition of a condensed substance by a local (conductive) energy source is possible only within a certain temperature range. Previous study [6] established experimentally that single metal particles, heated do high temperatures, are the sources of the sustainable ignition of composite fuel based on ammonium perchlorate and butyl rubber. Studies [6] were performed within a quite narrow range (805–1040 K) of the initial temperature of an energy source in the shape of disk with dimensions r_p=3 mm, z_p=2 mm. The study [6] proposed the relation $t_d=f(T_p)$ between the delay time of fuel composition ignition and the temperature of a hot particle. In the study, it was found the minimum initial temperature of an energy source T_0=805 K, when the stable ignition of composite fuel occurred. However, the relation $t_d=f(T_p)$ [6] does not identify the boundaries of the sustainable ignition of composite fuel, when the characteristics of the source vary over a wide range. Therefore, it is advisable to conduct numerical investigations of heat transfer, to describe chemical reactions in the condensed phase, and to estimate theoretically the stability of typical composite solid fuel ignition, when heating by a local energy source.

2. Problem Statement

[a] Corresponding author: dmitriyog@tpu.ru

Fig. 1 shows a diagram of the investigated process. We studied the ignition of composite fuel with known thermal and kinetic properties. The ignition occurred as a result of heating by a local energy source. As the energy source we used a steel particle in the shape of a disk heated to high temperatures.

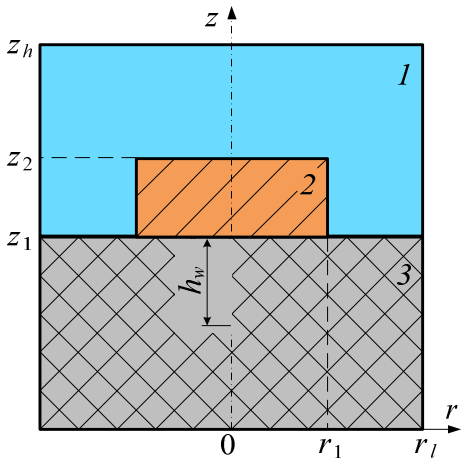

Figure 1. A diagram of the solution area for the problem of ignition: *1* – inert gas, *2* – hot particle, *3* – composite solid fuel.

We have taken the following method for the simulated process [7]. A hot particle, being in contact with the fuel surface, heats the subsurface layer of fuel. As the temperature increases, the rate of oxidation increases exponentially according to the Arrhenius law [8]. The exothermic process becomes irreversible after reaching the boundary conditions appropriate to the criteria of ignition. Solid-phase fuel ignition occurs.

The following conditions of ignition have been taken for the system (Fig. 1):

1. The rate of heat gain exceeds the rate of heat transfer from the hot particle to the fuel and the surrounding gas due to the exothermic reaction in the subsurface layer of the condensed substance.

2. The temperature of the condensed substance in the oxidation area is higher that the initial temperature of the energy source.

3. Mathematical Model and Solution Method

We have solved the problem of composite solid fuel ignition by a hot particle in the shape of disk. The problem has been solved in a cylindrical coordinate system (Fig. 1). The system of differential equations in partial derivatives describes heat transfer in the particle, fuel and gas, as well as the exothermic reaction in the subsurface layer:

a heat equation for gas ($r_1<r<r_l$, $z_1<z<z_2$; $0<r<r_l$, $z_2<z<z_h$):

$$\rho_1 C_1 \frac{\partial T_1}{\partial t} = \lambda_1 \left(\frac{\partial^2 T_1}{\partial r^2} + \frac{1}{r}\frac{\partial T_1}{\partial r} + \frac{\partial^2 T_1}{\partial z^2} \right); \quad (1)$$

a heat equation for a hot particle ($0<r<r_1$, $z_1<z<z_2$):

$$\rho_2 C_2 \frac{\partial T_2}{\partial t} = \lambda_2 \left(\frac{\partial^2 T_2}{\partial r^2} + \frac{1}{r}\frac{\partial T_2}{\partial r} + \frac{\partial^2 T_2}{\partial z^2} \right); \quad (2)$$

an energy equation for composite solid fuel ($0<r<r_l$, $0<z<z_1$):

$$\rho_3 C_3 \frac{\partial T_3}{\partial t} = \lambda_3 \left(\frac{\partial^2 T_3}{\partial r^2} + \frac{1}{r} \frac{\partial T_3}{\partial r} + \frac{\partial^2 T_3}{\partial z^2} \right) + Q_3 W_3 ; \quad (3)$$

We calculated the mass rate of the exothermic reaction in the heated part of the subsurface layer according to the Arrhenius law [8]:

$$W_3 = \rho_3 k_3^0 \exp\left(-\frac{E_3}{R_t T_3} \right). \quad (4)$$

Symbols: t – time, s; t_d – ignition delay time, s; r, z – cylindrical system coordinates, m; r_l, z_h – characteristic dimensions of the solution area, m; r_p, z_p – heat source dimensions (r_p=r_1, z_p=z_2–z_1); T – temperature, K; λ – thermal conductivity, W/(m·K); ρ – density, kg/m^3; C – specific heat capacity, J/(kg·K); Q_3 – thermal effect of the exothermic reaction in the heated part of the subsurface surface layer of fuel, J/kg; W_3 – mass velocity of the exothermic reaction, kg/(m^3·s); k_3^0 – pre-exponential factor, s^{-1}; E_3 – activation energy, J/mol; R_t – universal gas constant, J/(mol·K); indexes “1”, “2”, “3” correspond to gas, a hot particle, fuel.

Initial conditions (t=0):

$T=T_0$, $0<r<r_l$, $0<z<z_1$; $r_1<r<r_l$, $z_1<z<z_2$; $0<r<r_l$, $z_2<z<z_h$. (5)

$T=T_g$, $0<r<r_1$, $z_1<z<z_2$. (6)

Boundary conditions ($0<t<t_d$):

z=0, $0<r<r_l$: $$\frac{\partial T_3}{\partial z} = 0 ; \quad (7)$$

$z=z_1$, $0<r<r_1$: $$\lambda_3 \frac{\partial T_3}{\partial z} = \lambda_2 \frac{\partial T_2}{\partial z}, \; T_3=T_2; \quad (8)$$

$z=z_1$, $r_1<r<r_l$: $$\lambda_3 \frac{\partial T_3}{\partial z} = \lambda_1 \frac{\partial T_1}{\partial z}, \; T_3=T_1; \quad (9)$$

$z=z_2$, $0<r<r_1$: $$\lambda_2 \frac{\partial T_2}{\partial z} = \lambda_1 \frac{\partial T_1}{\partial z}, \; T_2=T_1; \quad (10)$$

$z=z_h$, $0<r<r_l$: $$\frac{\partial T_1}{\partial z} = 0 ; \quad (11)$$

r=0, $r=r_l$, $0<z<z_1$: $$\frac{\partial T_3}{\partial r} = 0 ; \quad (12)$$

r=0, $z_1<z<z_2$: $$\frac{\partial T_2}{\partial r} = 0 ; \quad (13)$$

r=0, $z_2<z<z_h$: $$\frac{\partial T_1}{\partial r} = 0 ; \quad (14)$$

$r=r_1$, $z_1<z<z_2$: $$\lambda_2 \frac{\partial T_2}{\partial r} = \lambda_1 \frac{\partial T_1}{\partial r}, \; T_2=T_1; \quad (15)$$

$r=r_l$, $z_1<z<z_h$: $$\frac{\partial T_1}{\partial r} = 0 . \quad (16)$$

The system of differential equations (1) – (3) with the corresponding initial (5) – (6) and boundary (7) – (16) conditions has been solved by the finite difference method. The difference analogues of differential equations have been solved by a local one-dimensional method. The system of one-dimensional difference equations has been solved by an iterative method and a sweep method at each iteration, when using a four-point implicit difference scheme.

4. Results and Discussion

Numerical studies have been performed for the following parameter values: the initial temperature of fuel and gas T_0=293 K, a hot particle T_p=700–1500 K; the dimensions of a particle r_p=1–8 mm (r_p=r_1), z_p=2 mm (z_p=z_2–z_1); the dimensions of the solution area r_l=20 mm, z_h=20 mm.

The thermophysical characteristics of substances (Fig. 1):

λ_1=0.026 W/(m·K); ρ_1=1.161 kg/m^3; C_1=1190 J/(kg·K);

λ_2=49 W/(m·K); ρ_2=7831 kg/m^3; C_2=470 J/(kg·K);

λ_3=0.418 W/(m·K); ρ_3=1750 kg/m^3; C_3=1260 J/(kg·K).

The kinetic parameters of fuel ignition E_3=50·10^3 J/mol, $Q_3k_3{}^0$=0.88·10^9 J/(kg·s) have been determined from experimental relation t_d=f(T_p) [6].

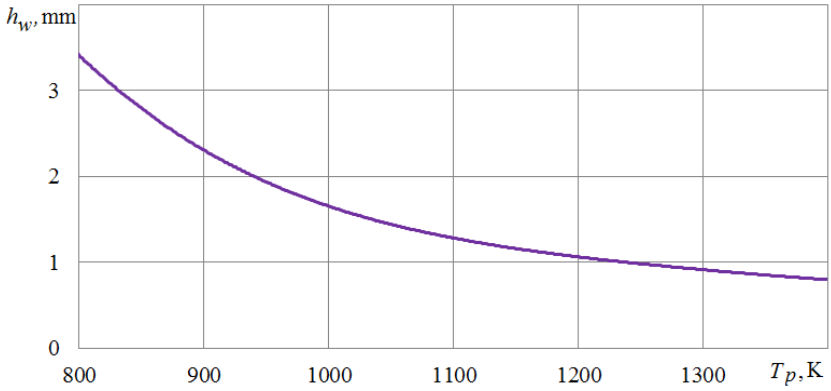

Figure 2. The dependence of the heating depth of the fuel subsurface layer at the time of fuel ignition from the initial temperature of a heat source when r_p=3 mm.

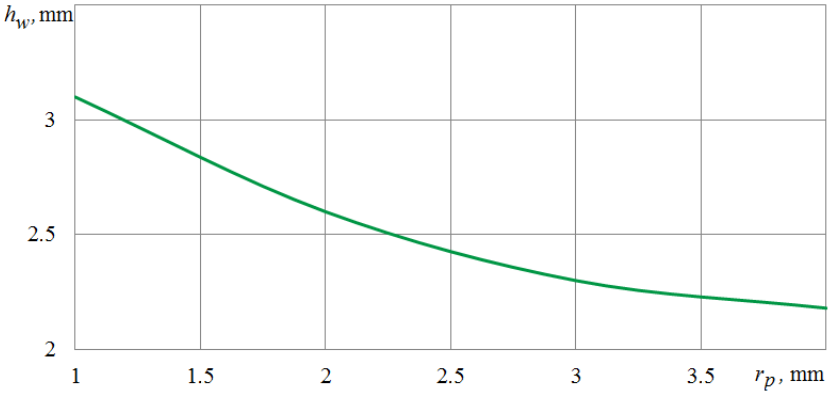

Figure 3. The dependence of the depth of fuel surface layer heating at the time of ignition from the characteristic size of an heat source at T_p=900 K.

Numerical investigations established the dependencies of the depth of the heated fuel subsurface layer from the initial temperature (Fig. 2) and the characteristic size (Fig. 3) of an energy source at the time of ignition. When the heat content of a local energy source increases (due to the initial temperature and size), the depth of the area of the inert heating (h_w) of the fuel subsurface layer decreases. The integral characteristics of the process, such as t_d and h_w, change considerably less at T_p=1200–1500 K and r_p=4–8 mm, than at relatively low values T_p and r_p. The minimum value h_w=0.52 mm, obtained by numerical simulation, at the time of sustainable ignition (when T_p=1500 K

and r_p=8 mm), significantly exceeds the theoretical value [9] of depth of the fuel heated layer at its stationary combustion. Established rations $h_w=f(T_p)$ and $h_w=f(r_p)$ can be explained by the following statement. When the heat content of a single particle increases, heat flux (q) from the energy source to the fuel increases as well. Thereby, the temperature growth in the thin subsurface layer accelerates.

Fig. 4 shows the area of the sustainable ignition of composite fuel by the source with limited energy consumption in the coordinates "a heat flow amplitude – ignition delay time". The boundaries of the area are the limits of analyzed characteristic dimensions of a hot particle: upper right – r_p=1 mm, bottom left – r_p=8mm.

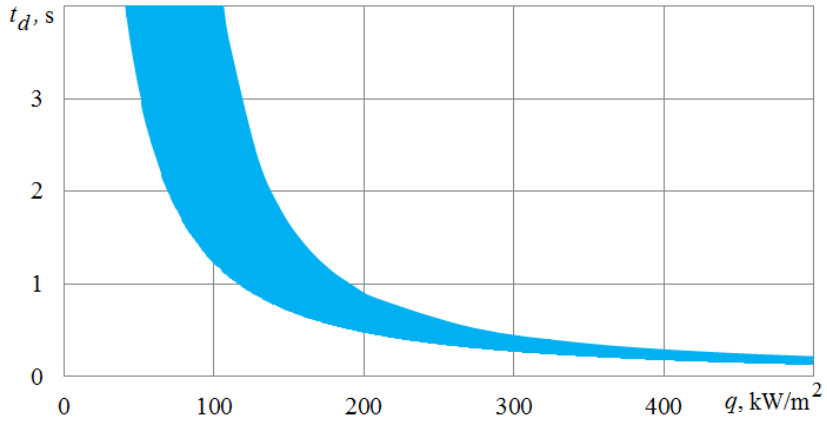

Figure 4. The area of the stability of composite fuel ignition by a single hot particle (highlighted in color).

This section has reviewed the stable ignition in the system "a particle – fuel – gas" at conductive heat transfer from the power source to the condensed phase. It has been found out, that such ignition occurs when the value of heat flow exceeds the minimum limit value, equal to q=30 kW/m^2. At relatively high values of q, the change of heat content of a hot particle has less effect on ignition delay time.

5. Conclusions

The developed mathematical model of solid-phase composite fuel ignition proved the following statements:

1. The limit value of the heat flux q=30 kW/m^2 is minimum at the conductive heat transfer from the power source to the condensed phase. When exceeding this limit, stable ignition occurs in the system "a particle – fuel – gas".

2. The minimum value of the depth (h_w=0.52 mm) of the heated subsurface layer at the time of sustainable fuel ignition, when the initial temperature and the characteristic size of a "hot" particle change in a quite wide range (T_p=700–1500 K and r_p=1–8 mm), exceeds considerably the theoretically determined value [9] of the depth of the fuel heated layer during its stationary combustion.

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