CONDITIONS FOR STABLE IGNITION OF SOLID FUELS

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Results of an experimental and theoretical study to determine necessary and sufficient ignition conditions for wood and other solid fuel-based materials are presented.

To determine conditions for stable ignition of solid fuelds it is necessary to consider the effects of many interacting physical and chemical processes which occur simultaneously. Ignition conditions are functions of fuel compositions, heating methods, nonstationary nature of the process, parameters of the surrounding medium, and the kinetics of gas phase combustion and decomposition of the solid material, for example, wood. This is a question of interest from the viewpoint of fire safety.

Despite increasing interest in study of the combustion mechanism, only a few studies dedicated to wood ignition conditions have been performed [1-9].

It should be noted that the published studies on ignition conditions are contradictory in a number of cases and have not been confirmed experimentally. Thus, for example, it has been assumed that ignition of a solid fuel occurs if the specimen surface temperature T^*_{wt} [1-3], the incident radiant thermal flux density q^R_w [4, 5], the transverse flow density of fuel volatiles $(\rho v)_{vw}$ [6], dimensionless parameters characterizing development of combustion [1, 7], the heat of combustion of volatiles in the gaseous phase ΔH_v and other parameters in the boundary layer [8] reach certain values. In [9] ignition conditions for cellulose-like materials (characterizing only the onset of combustion, which may terminate) were given in the form

$$q^R_w = [2Q_v(\rho v)_v + q^\lambda_s]_w, \tag{1}$$

where Q_v is the heat of pyrolysis of the solid fuel. Condition (1) was obtained with the invalid assumption that $\Delta H_v = Q_v$.

In the present study ignition conditions for wood-based materials will be considered with interaction with a boundary layer. The following assumptions were made in deriving the equations: the solid fuel specimens are one-dimensional; attenuation of the radiant q^R_w and conductive q^λ_w components of the thermal flux due to presence of a flow of volatiles and their combustion in the boundary layer is negligibly small; thermophysical properties of the interacting media are constant; radiant heating of the specimen is defined by an absorption law

$$q_{Vy} = \varkappa_s q^R_w \exp(-\varkappa_s y), \tag{2}$$

where q^R_{Vy} is the internal radiant energy flux in the section y; $\varkappa_s$ is the solid fuel absorption coefficient; substrate heating ceases at the moment of ignition, i.e., at $\tau = \tau_i$.

With these assumptions we write the thermal conductivity equation for a fuel layer of thickness , which we then integrate from y = 0 to y = Λ at some moment τ:

$$\int_0^\Lambda (\lambda \partial^2 T/\partial y^2 - q^R_{Vy} + Q_v w_p + r w_e)_s \, dy = \int_0^\Lambda (c_p \rho \partial T/\partial \tau)_s \, dy, \tag{3}$$

where w_p is the rate at which volatiles are liberated from the specimen; w_e is the rate of moisture evaporation from the fuel; r is the heat of evaporation. According to [10] for cellulose materials

$$w_p = k^e W(y, \tau) \exp(-E_s/RT_s),$$
$$w_e = w_{eo} \exp(-k_s \tau),$$

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TABLE 1. Calculation of Conditions for Stable Independent Ignition of Wood, Corresponding to $Z \geqslant q_{w\text{T}}^{\lambda}$ at T_{*i} = 1340°K

τ_i, sec	T_i^*, K	$(\rho v)_{vw} \cdot 10^4$, kg/m² sec	$\bar{z} \cdot 10^{-2}$ W/m²	$A \cdot 10^{-2}$, (W/m²)²	$Z \cdot 10$ kW/m²	$q_{ws}^{\lambda} \cdot 10$, kW/m²
45	830	233	471	412	944	94
45	803	190	387	314	770	77
54	835	235	479	420	954	95
44	830	235	482	409	960	95
23	815	200	405	341	806	81
29	790	235	475	376	946	95
77	843	193	392	352	779	78
78	933	233	473	543	947	94

where

$$W(y,\ \tau) = W_0 \exp\left[k^{e} \int\limits_0^{\tau} \exp(-E_s/RT_s)\right] d\tau;$$

$$w_{e\varphi} = k_s \Delta G_V; \quad \Delta G_V = (G_{V0} - G_{V\text{K}})_b.$$

We supplement Eq. (3) by boundary conditions on the body surface (y = 0)

$$q_{ws}^{\lambda} = q_w^{\lambda} + q_w^{c} \tag{4}$$

and in the solid layer y = Λ (for a semiinfinite body $\Lambda = \infty$, for an axisymmetric thickness $2l$ we have $\Lambda = l$),

$$\partial T_s / \partial y = 0, \tag{5}$$

where q_w^c is the convective component of the thermal flux. In integrating Eq. (3) from 0 to ∞, in the last term on the left side instead of $\Lambda \to \infty$ we may take $\Lambda = l_r$, where l_r is the minimum depth of the substrate, at which $\partial T_s/\partial y = 0$. According to the experimental data of [10], for wood and other celluloselike fuels l_r = 7 mm.

In Eqs. (3)-(5), w_p, w_e, q_w^c, and q_{ws}^{λ} are functions of y and τ.

According to the theory of nonadiabatic ignition of a solid fuel [9], upon development of combustion the mean temperature in the solid phase should increase with time, i.e., the right side of Eq. (3) should be positive. Upon quenching of combustion the right side of Eq. (3) is negative. In the limiting case at $\tau = \tau_i$, corresponding to development of combustion [9]:

$$\int\limits_0^{\Lambda} \frac{\partial T_s}{\partial \tau}\, dy = \frac{\partial}{\partial \tau} \int\limits_0^{\Lambda} T_s\, dy = 0. \tag{6}$$

It follows from Eq. (4) that upon ignition the thermal flux into the wall

$$q_{ws}^{\lambda}(0,\ \tau_i) \sim (T_* - T_{ws}^*)_i, \tag{7}$$

where T_* is the temperature of the flame zone in the boundary layer. According to Eq. (4) and the theory of a reacting boundary layer [10], the necessary conditions for ignition are the attainment at $\tau = \tau_i$ of not only definite values of $T_{ws} \geqslant T_i^*$, but also maximum temperatures $T_{max} \geqslant T_{i*}$, since combustion of the volatiles liberated from the fuel occurs in the gaseous phase. The condition $T_{max} \geqslant T_i^*$ characterizes the reaction rate in the gas phase and heat liberation of the exothermal reaction due to homogeneous combustion in the reacting boundary layer. Consequently, from Eq. (3), considering Eqs. (4)-(7), we obtain the following conditions for stable ignition at $\tau = \tau_i$:

$$T_{ws} \geqslant T_i^*, \quad T_{max} \geqslant T_{*i}, \tag{8}$$

$$q_{ws}^{\lambda} + \int\limits_0^{\Lambda} (Q_V w_p - q_{Vy}^{R} + r w_e)_s\, dy = 0, \tag{9}$$

where condition (8) is necessary and condition (9), sufficient. According to Eqs. (8), (9), for solid fuel ignition not only must there by sufficiently high values of T_{*i} and T_i^* (necessary conditions) but effective heating of the substrate itself (sufficient conditions). As follows from Eqs. (4), (9), under these conditions the solid is heated by radiant and (or) convective fluxes.

Transforming the integral term in Eq. (9) with the aid of an asymptotic Laplace formula and considering that the maximum temperature of the solid occurs on its surface, we obtain

$$(q_{ws}^{\lambda})^2-(q_w^R-rw_e\Lambda)\,q_{ws}^{\lambda}+(Q_V\lambda_s w_p RT_s^2 E_s^{-1})_w=0, \quad (10)$$

where for semiinfinite bodies $\Lambda=l_r=7$ mm. Solving Eq. (10) for q_{ws}^{λ}, we obtain a sufficient condition for ignition in the form

$$z+\sqrt{z^2-(Q_V\lambda_s w_p RT_s^2 E_s^{-1})_w}-q_{ws}^{\lambda}\geqslant 0, \quad (11)$$

where $q_{ws}^{\lambda}=q_w^{\lambda}+q_w^c$, $z=(q_w^R-rw_e\Lambda)/2$. The minus sign before the radical is omitted, and Eq. (11) has no physical meaning. According to [9], in ignition of celluloselike fuels convective heat transfer may be neglected. It follows from Eq. (4) that at $\tau=\tau_i$ and $q_w^c=0$

$$q_w^{\lambda}=q_{ws}^{\lambda}\sim J\Delta H_V(\rho v)_{Vw},$$

where [10] J is the volatile burnup coefficient,

$$(\rho v)_{VW}=k^e W_0\int\limits_0^{\Lambda}\left[\exp\left(-\frac{E_s}{RT_s}\right)\int\limits_0^{\tau}\exp\left(-\frac{E_s}{RT_s}\right)d\tau\right]dy. \quad (12)$$

The physical meaning of ignition criteria (8) and (11) is as follows. The thermal flux due to radiant and (or) conductive heating and burning of volatiles at $T_{ws}\geqslant T_i^*$, $T_{max}\geqslant T_{*i}$ is equal to the total energy expended on phase conversions in the fuel layer, thermal decomposition of the substrate, and its conductive heating. In other words, according to Eq. (8) stable ignition of celluloselike materials occurs when the thermal flux supplied to the substrate (radiant in the given case) produces sufficient heating of the fuel layer, evaporation of moisture, and liberation of volatiles.

The limiting conditions for stable ignition of a solid fuel with minimal heating by an external source correspond to equality to zero of the terms on the left side of Eq. (11). If these terms are greater than zero, then development of combustion in the system is more probable than in the limiting case.

Experimental verifications of ignition conditions (8) and (11) for wood materials (of various species — pine, fir, oak) were carried out in an aerodynamic tube with vertical working section [10] using tensometric systems for recording specimen weight loss (specimen was in the form of plates 0.005-0.025 m thick with lateral surface 0.15 × 0.17 m, heated by a radiant source at wavelength 0.5-3.5 μm). The heat source had a power of $20\cdot10^4$ W/m². The experimental equipment and method for distinguishing convective and radiant thermal flux components were described in detail in [10].

The following parameter values were used in Eqs. (3)-(12): $k^e=10^{11}$ sec^{-1}, $E_s=136{,}530$ J/K·mole, $W_0=270$ kg/m³, $Q_V=90$ kJ/kg, $a_s=1.31\cdot10^{-7}$ m²/sec, $\rho_s=480$ kg/m³, $c_{ps}=1590$ J/kg·deg K, $\lambda_s=0.1$ W/m·deg K, $T_{0s}=293$°K, $\Lambda=0.025$ m, $J\Delta H_V=4.1\cdot10^6$ J/kg.

Results of calculating necessary and sufficient ignition conditions for wood and a comparison with the experimental data obtained in the present study [10] are presented in Table 1. For all cases considered Eqs. (8) and (11) are valid, while according to the table,

$$Z\geqslant q_{ws}^{\lambda},$$

where

$$A=(Q_V\lambda_s w_p RE_s^{-1}T_s^2)_w;\quad Z=\bar{z}+\sqrt{\bar{z}^2-A};$$

$$\bar{z}=0.5\,(q_w^*-r\,(\rho v)_m);\quad q_w^*=J\Delta H_V(\rho v)_{Vw}.$$

The conditions obtained, Eqs. (8) and (11), have a clear physical meaning, and are relatively simple for practical calculations. Equations (8)-(12) contain thermophysical parameters which have been determined for celluloselike materials. Conditions (8) and (11) can be used to calculate ignition for other solid fuels, if the power levels of the energy sources related to phase and chemical conversions are known. According to the table, the experimental tests of Eqs. (8) and (11) have confirmed their validity.

NOTATION

ρ, weight density; v, transverse velocity; λ, thermal conductivity; c_p, specific heat at constant pressure; Λ, characteristic dimension; k_s, drying coefficient; k^e, preexponential term; E, activation energy; R, universal gas constant; G, mass of material; W, weight of volatiles per unit volume of wood. Subscripts; e, during moisture evaporation; i, ignition delay; w, body surface; s, solid; v, volatile; V, parameters per unit body volume; m, moisture (water); *, combustion zone in boundary layer. Superscripts, R, λ, c, radiant, conductive, and convective thermal flux components; *, solid fuel ignition condition; S_w, evaporation surface area.

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THERMAL AND MATHEMATICAL MODELING OF OPTOELECTRONIC DEVICES

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Mathematical models describing the thermal regime of optoelectronic devices are substantiated, and a method for realizing such models is proposed — stage by stage modeling.

1. Formulation of the Problem. Optoelectronic devices (OED's) are complex systems consisting of component parts such as optical and mechanical parts, radiation detectors and sources, electronic circuits, etc. The thermal regime of an OED has an effect on both quality and reliability of operation of the individual components and the device as a whole.

A number of studies have analyzed the thermal regime of individual OED elements (mirror, lens, radiation detector) [1-4].

Below we will consider optoelectronic devices as a whole and offer a method for their thermal modeling, which permits analysis of temperature fields of individual OED elements with consideration of external effects and basic thermal linkages.

2. Heirarchical Principle of OED Composition. A detailed description of OED construction can be found in [5-7]; analysis of the literature permits us to classify the following structural levels.

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