The conditions and characteristics of wood particles ignition in the stream of the high temperature gases

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Annotation. The results of the experimental and theoretical studies of the ignition processes of the single woody biomass particles have been given. The main parameters of heat transfer (the ambient temperature T_g) and the main characteristic of the process — the ignition delay time (t_{ign}) have been registered. According to the results of the experiments the mathematical model has been formulated describing the heating and thermal decomposition of the wood taking into account the formation of the gaseous and solid products. The model also describes the moisture evaporation, the thermochemical interaction of water vapor and carbon coke, oxidation of the pyrolysis products with oxygen in the gas area.
Key words: wet wood, ignition, biomass, heat and mass transfer.

1. Introduction

Wood biomass is becoming increasingly attractive as fuel for the thermal power plants [1] in some regions in recent years. To date, a small number of works has been published with the results, both experimental and theoretical studies of the processes of wood ignition. The vast majority of the studies in the framework of very simple mathematical models [2-6], which do not take into account the real complex of physical and chemical processes occurring in conjunction with intensive heating of the wood particles (the heat transfer between the particle and the external high-temperature environment through convection and radiation, thermal conductivity, moisture evaporation, filtration of water vapor to the surface heating, the thermal decomposition of wood with the formation of the gaseous products and ash, thermo-chemical interaction of water vapor and carbon coke,

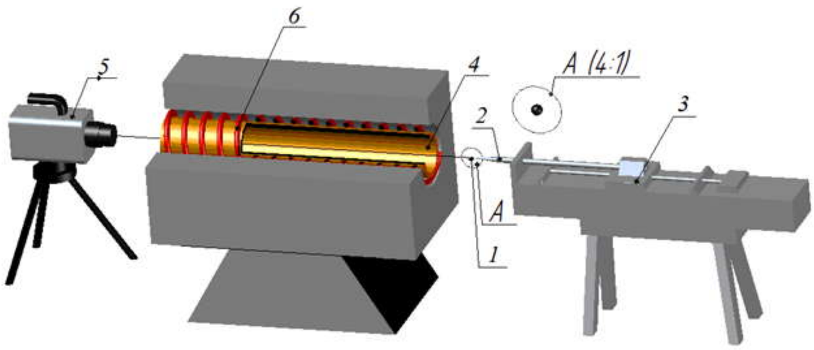


Fig. 1. The experimental setup

1 — the wood particle; 2 — the metal holder; 3 — the coordinate device;

4 — a hollow ceramic tube; 5 — a high-speed video camera;

6 — the electric heater.

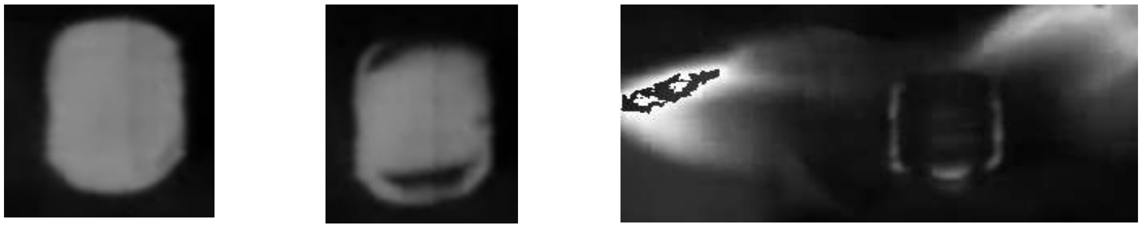
oxidation of the chemically active products of pyrolysis with air oxygen, diffusion of the combustible components adjacent to the surface of the particle layer of the external environment).

The purpose of the work is the experimental and theoretical research of the conditions and characteristics of the single particles ignition of wood in the flow of the high temperature gases within the mathematical model that takes into account the endothermic processes of moisture evaporation contained in the wood and the thermal decomposition.

2. Experiment

2.1 Methodology for conducting the experiments

The experimental studies have been made on the stand (figure 1). The wood particle has been pre-prepared and then it has been fixed on the sharpened needle-holder. The latter has been mounted on the movable platform of the remote-control module of the linear movement. It has made by the operator' command the input of the fuel particle in the hollow ceramic cylinder. The inner surface of the last has been heated to temperature 1270K by the electric heater. The registration processes of the thermal preparation and the ignition of the fuel particle has been carried out by the fast camcorder Photron FASTCAM CA4. The systematic error in the



(a) t=0 s. (b) t=1.75 s. (c) t=2.35 s.

Fig.2. Frames of a typical videogram of a moist wood particle ignition processes.

determination of the basic measurement parameters (T_g, t_{ign}) has not been more than 5 %. The confidence interval of the determination t_{ign} at confidential probability 0.95 does not exceed 17%.

2.2 The results of the experiment

The footage of the typical videogram of the ignition process of the particle with diameter $\delta=3\cdot10^{-3}$m (ambient temperature is T_g=1270K) has been shown on figure 2. The total time from the start of heating until ignition is $t_{ign}\approx10$ sec. As the videograms of the experiments show the process of heat training can be divided into a series of the sequential interrelated steps (inert heating, evaporation of water, thermal decomposition of the organic part of the fuel, ignition of the volatiles, the ignition of carbon). The frame analysis of the experiments videogram has showed that after the putting in operation of the wood particle in the high temperature environment, the intensive inert heating begins (frame a) transferring to the stage of evaporation of water and ending by the thermal decomposition of wood (frame b). The detailed analysis of frame b (at high magnification) shows a characteristic darkening of the surface of the particle. Ignition of the volatiles (frame c) occurs in $t=t_{ign}$ after the start of heating. It can be noted that the area of inflammation is localized in the upper hemisphere of the particle. The sphere of flame is formed after ignition of the volatiles, the typical size of which is 2-3 times greater than the particle diameter.

3. Statement of the problem

3.1 Physical formulation

At the initial time, the particle is introduced into the high temperature environment and is heated by convection and radiation. The process of evaporation of water is initiated as a result of the intensive heating. The evaporation front moves from the surface layers of the fuel to the deep layers. As the result, a porous wood frame with a high thermal resistance is formed. Water vapor formed during evaporation, are filtered through a layer of the dry fuel, engaging in the thermo-chemical interaction with carbon. Heating of the wood particle causes the thermal decomposition of the wood and volatiles. The latter, in conjunction with water vapor and products of the thermochemical interaction of carbon and water vapor are filtered to the surface of the fuel particle. As the result, a vapor-gas mixture is formed flammable when there are the critical values of the temperature and concentrations of fuel.

3.2 Mathematical formulation of the problem

The mathematical formulation of the problem of wood ignition, corresponding to the above formulated physical model, includes the system of the non-stationary differential equations. The solution scope of the problem (a particle in the shape of a sphere) can be divided into two parts. The first is the original still saturated with moisture fuel, the second is wood. The temperature distribution is in such an inhomogeneous heterogeneous system describes the energy equation, which takes into account the evaporation of water, the thermal decomposition of the fuel, thermochemical interaction of water vapor and carbon, as well as the movement of the water vapor and thermal decomposition products through the porous frame:

$$C_1(T)\cdot\rho_1(T)\cdot\frac{\partial T_1}{\partial t}=\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2\cdot\lambda_1\cdot\frac{\partial T_1}{\partial r}\right]-\frac{Q_{eva}\cdot W_{eva}}{h}\cdot\delta\left(r_{eva}\right)-\sum_{i=1}^{i=2}Q_i\cdot W_i$$
$$-C_s\cdot\rho_s\cdot U_s\cdot\frac{\partial T_1}{\partial r}\cdot\theta\left(r-r_{eva}\right) \tag{1}$$

Where: $\sum_{i=1}^{n=2}Q_i\cdot W_i=Q_{w\to vol}\cdot W_{w\to vol}+Q_{C+H_2O}\cdot W_{C+H_2O}$

$\delta(\mathbf{r_{eva}})$ — function of Dirac. $\theta(\mathbf{r}-\mathbf{r_{eva}})$ — function of Heaviside. The thermophysical characteristics (λ, C and ρ) have been calculated with taking into account the position of the evaporation front. The mass evaporation rate () has been calculated from the expression:

$$W_{eva}=W_f\cdot\exp\left(\frac{Q_{wat}\cdot\mu\cdot\left(T_{wat}-T_f\right)}{R\cdot T_f\cdot T_{wat}}\right) \tag{2}$$

The temperature distribution in the gas region is described by the energy equation. The latter takes into account the effects of the exothermic effects of oxidation reactions of the main combustible components of air:

$$C_g\cdot\rho_g\cdot\frac{\partial T_g}{\partial t}=\frac{\lambda_g}{r^2}\cdot\frac{\partial}{\partial r}\left[r^2\cdot\frac{\partial T_g}{\partial r}\right]+\sum_{i=1}^{i=3}Q_i\cdot W_i \tag{3}$$

Where: $\sum_{i=1}^{n=3}Q_i\cdot W_i=Q_{CH_4+O_2}\cdot W_{CH_4+O_2}+Q_{CO+O_2}\cdot W_{CO+O_2}+Q_{H_2+O_2}\cdot W_{H_2+O_2}$

There is a boundary condition of the 4-th kind at the interface of the system “a particle of wood — gas”. The exothermic effect of the reaction of carbon with oxygen is taken into account:

$$\frac{\partial T_1}{\partial r}=K_\lambda\frac{\partial T_g}{\partial r}+\frac{Q_{C+O_2}\cdot W_{C+O_2}+\varepsilon\cdot\sigma\cdot\left(T_e^4-T\big|_{r=r_{out}}^4\right)}{\lambda_1} \tag{4}$$

$$T_1\left(r_{out},t\right)=T_g\left(r_{out},t\right)$$

Where: $K_\lambda=\lambda_g/\lambda_1$

The rate of reaction has been calculated from the mathematical expression of the law of Arrhenius:

$$W_i = k_{C+O_2} \cdot \left(1 - \sum_{i=1}^{n} c_i\left(r_{out}, t\right) - c_{H_2O}\left(r_{out}, t\right)\right) \cdot \rho_g \cdot \exp\left(-\frac{E_{C+O_2}}{R \cdot T_1\left(r_{out}, t\right)}\right) \qquad (5)$$

The water vapor together with the products of the thermal decomposition move through the porous wood frame. The pressure distribution along the radius of the particle has been determined from the equation piezoconductivity:

$$\frac{\partial p}{\partial t} = \frac{\chi}{r^2} \cdot \frac{\partial}{\partial r}\left(r^2 \frac{\partial p}{\partial r}\right) - \frac{1}{m \cdot Z \cdot \rho_i} \cdot \sum_{i=1}^{n=2} \frac{f_i}{s} \qquad (6)$$

Where: $\sum_{i=1}^{n=2} f_i = W_{w \to vol} + W_{C+H_2O \to CO+H_2}$

f_i — the function that determines the change in the mass flow rate of vapor and gas mixture as a result of release of the volatiles and change in the concentration of water vapor during their thermochemical interaction with carbon. The filtration rate of vapor has been determined from the differential expression of Darcy’s law:

$$U_s = -\frac{K_P}{\nu} \frac{\partial p}{\partial r} \qquad (7)$$

When setting the problem, it is accepted that water vapor enters into the endothermic chemical reaction with coal (solid products of the thermal decomposition reaction). The rate of reaction has been calculated from the following expression:

$$W_{C+H_2O} = k_{C+H_2O} \cdot c_{H_2O} \cdot \rho_s \cdot \exp\left(-\frac{E_i}{R \cdot T}\right) \qquad (8)$$

The decomposition of the fuel with yield of the volatiles begins when there are the conditions on the particle surface $T_{sur} \geq T_{std}$ (T_{sur} — surface temperature of the particle, T_{std} — temperature of the thermal decomposition start). The process of thermal decomposition is described by the equation of chemical kinetics:

$$\frac{\partial \eta}{\partial t} = \left[1 - \eta\right] \cdot k_{w \to vol} \cdot \exp\left(-\frac{E_{w \to vol}}{R \cdot T}\right) \qquad (9)$$

The products of the thermal decomposition and chemical interaction of the solid residue and water vapor are blown into the “wall” area. The gas mixture is formed flammable when there are the critical values of temperature and concentration of fuel. The time period from the beginning of the thermal effects on the particle prior to the intensive chemical interaction of gas-vapor mixture with an oxidizing agent is the ignition delay time. The amount of heat generated from the oxidation of fuel exceeds the heat coming from the external environment. The following reactions have been considered in the vicinity from the surface of the particle:

a) $\mathbf{H_2 + 0.5 \cdot O_2} = H_2O$; b) $\mathbf{CO + 0.5 \cdot O_2} = CO_2$; c).

The rate of these reactions has been calculated from the mathematical expression of the law of Arrhenius:

$$W_i = k_i \cdot c_i \cdot \left(1 - \sum_{i=1}^{3} c_i - c_{H_2O}\right) \cdot \rho_i \cdot \exp\left(-\frac{E_i}{R \cdot T_g}\right) \quad (10)$$

The concentration of the combustible components (H_2, CO, and CH_4) in the wall area has been calculated when solving the diffusion equation for the corresponding component of the reaction:

$$\rho_g \frac{\partial c_i}{\partial t} = \frac{D_i \cdot \rho_g}{r^2} \frac{\partial}{\partial r}\left[r^2 \cdot \frac{\partial c_i}{\partial r}\right] - W_i \quad (11)$$

The concentrations of the water vapor and the wood of carbon dioxide emitted on the thermal decomposition has been determined similarly:

$$\rho_g \frac{\partial c}{\partial t} = \frac{D \cdot \rho_g}{r^2} \frac{\partial}{\partial r}\left[r^2 \cdot \frac{\partial c}{\partial r}\right] \quad (12)$$

The system of equations (1-12) has been solved under the following boundary conditions:

$$t = 0 \rightarrow \begin{cases} 0 < r < r_{out},\ T(r,0) = T_0 = 298K,\ p(r,0) = p_0,\ \eta(r,0) = \eta_0 \\ r_{out} < r < r_g,\ T(r,0) = T_g,\ c_i(r,0) = 0,\ i = 1..3 \end{cases}$$

$$\left.\frac{\partial T}{\partial r}\right|_{r=0}=0 \quad (13) \qquad \left.\frac{\partial^2 T_g}{\partial r^2}\right|_{r=r_g}=0 \quad (14) \qquad \left.\frac{\partial p}{\partial r}\right|_{r=r_{eva}}=-\frac{\nu}{K_P}u_s\left(r_{eva},t\right) \quad (15)$$

$$p|_{r=r_{out}}=p_{atm} \quad (16) \qquad \left.\frac{\partial c_i}{\partial r}\right|_{r=r_{out}}=\frac{W_i\cdot r_{out}}{\rho_g\cdot D_i} \quad (17) \qquad \left.\frac{\partial c_{wat}}{\partial r}\right|_{r=r_{out}}=\frac{W_{eva}\cdot r_{out}}{\rho_g\cdot D_1} \quad (18)$$

$$\left.\frac{\partial^2 c_{wat}}{\partial r^2}\right|_{r=r_g}=\left.\frac{\partial^2 c_i}{\partial r^2}\right|_{r=r_g}=0 \quad (19)$$

4. The results and their discussions

The comparative analysis of the experimental and calculated numerical values of delay times of the wood particles ignition ($\delta=3\cdot10^{-3}$ m) has been carried out for the purpose of verification of the mathematical model (1) — (19).

The experimental and theoretical (the numerical solution of the system (1)-

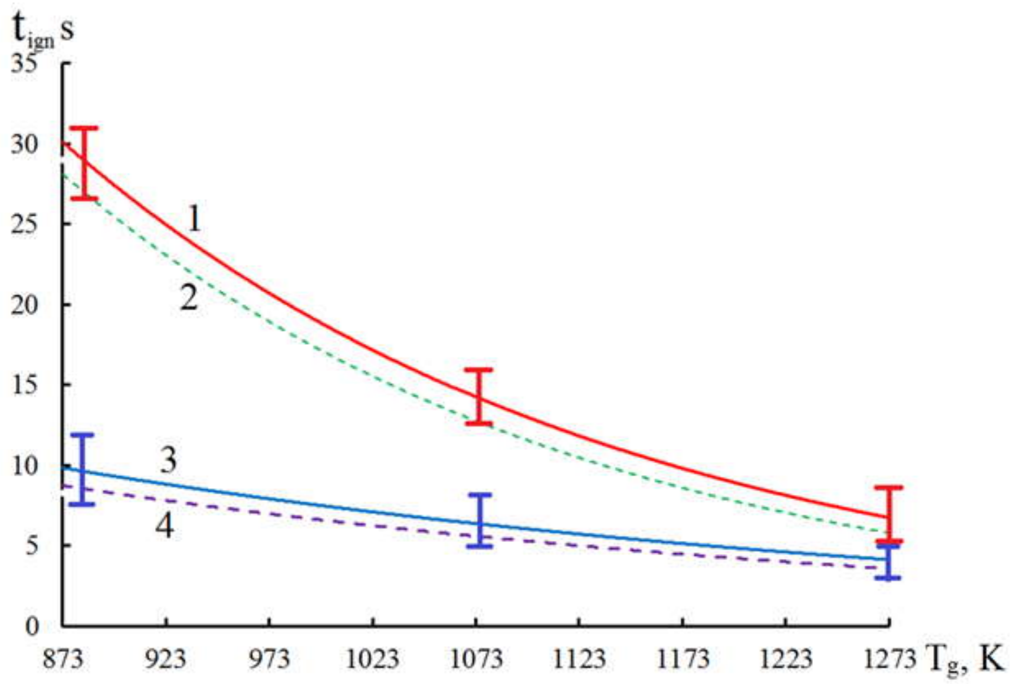


Fig.3. The dependence of the time delay ignition of the wood particle from the ambient temperature.

1,2 — the particle diameter $\delta=3{,}0\cdot10^{-3}$ m; 3,4 - $\delta=1{,}5\cdot10^{-3}$ m;

1,3 — the experiment; 2,4 — the numerical solution.

(19)) dependences of the delay times of the particle ignition from the ambient temperature have been shown in figure 3.The analysis of the experimental results shows that the ambient temperature has a significant influence on the dynamics of the thermal preparation and ignition of fuel. So, the temperature increase at 400K (from 873K to 1273K) leads to faster ignition, more than 4 times. The linear size of the particle also has a significant impact on the characteristics and conditions of ignition. So, the change in the particle diameter from $\delta = 3 \cdot 10^{-3}$ m to $\delta = 1.5 \cdot 10^{-3}$ m leads to faster ignition in 3 times (from t_{ign} = 30 s to t_{ign} = 10 s). It is also necessary to note the non-linear (it can be said exponential) nature of the curves (1) — (4) (figure 3.). The latter indicates a significant influence of the complex co-occurring in the induction period of thermal treatment processes (heat transfer by conduction, moisture evaporation, thermal decomposition of the organic part of the fuel, thermochemical interaction of water vapor and carbon coke, ignition of the volatiles). The analysis of dependences (1) — (4) (figure 3) shows that the differences of the theoretical values of t_{ign} from the experimental do not exceed 14% (in other words they are within the confidence interval) from the measurement results. Generally, a good correspondence between theoretical and experimental values of t_{ign} persists for the particles with a diameter of 1.5 mm.

Conclusion

The complex of the experimental researches of the ignition process of the wet wood fuel particle has been carried out. The basic laws of the processes occurring in the induction period have been established. The characteristic times of the processes of the thermal preparation and ignition of the wood particle have been determined. It has been established that the whole induction period can be divided into a series of the sequential and interrelated phases, characterized by the dominance of one among the physical processes. They include: inert heating, evaporation of the fuel moisture, thermal decomposition with the yield of the volatiles, their ignition and combustion, the carbon ignition.

According to the results of the experiments the mathematical model of the ignition process has been formulated. Mathematical model describes satisfactorily the processes occurring during the ignition of the wet wood particles according to the results of the comparison of the delay times of ignition obtained theoretically and experimentally.

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