Flame propagation features in still wood dust suspension in the air

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Abstract. This paper presents the numerical investigation on combustion of a still wood dust suspension on the air. The aim of the research is to determine the flame propagation features through the suspension under changing the size and mass concentration of the dust particles. The manuscript also provides data on parametric analysis of the problem. The conducted simulation has shown that the shape of the flame depends on the size, the particle mass concentration and the content of volatile components in the particles.

1. Introduction
Fire and explosion risk at the industrial enterprises is one of the urgent problems for the modern physics of combustion and explosion. A potential threat at coal mining and wood processing enterprises is organic dust, which is a byproduct of the production. Depending on the environmental conditions and dust characteristics, potentially hazardous situations may arise at the plants.

By analogy with coal dust, the governing factors of the wood dust burning rate are the composition and concentration of the dust in the air. The composition is determined by the size and mass concentration of the dust particles, the content of volatile components in the particles, and the moisture content of the dust. The concentration of the dust in the air can be distributed heterogeneously, therefore it is necessary to solve the combustion problem of the wood dust in a two-dimensional formulation.

The aim of this study is to define the effect of the wood dust composition on the propagation velocity of the combustion front in a still wood dust-air suspension.

2. Mathematical model and solution method
The mathematical formulation of the problem is based on study [1]. The problem is solved in the 2D formulation. Wood dust particles are assumed to be immobile and irregularly distributed along the vertical coordinate. This situation may arise, for example, during the wood processing with the absence of ventilation in a working space. Wood dust can contain a fraction of volatile components. The particle size, mass concentration of the dust and the content of volatile components are set by the values \( r_s, \rho_d(y) \) and \( V_C \), respectively. The distribution of the particle mass concentration obeys the law,

\[
\rho_d(y) = m_{dust} \left( 1 + \sin\left( \pi y / L_y \right) \right), \quad 0 \leq y \leq L_y,
\]

where \( m_{dust} \) corresponds to the minimum particle mass concentration along the \( y \) axis for the given interval. The particle distributions along the \( x \) direction are uniform. The model takes into account the drying of wood dust and the emission of volatile components with subsequent combustion of the particle and volatile components.
It is assumed that all the processes related to the wood dust drying, such as emission and combustion of the volatile components, combustion of the dust coke residue, do not occur until the wood dust reaches the temperature of 150°C. The model takes into account the consumption of the oxidizer in two reactions: heterogeneous on the surface of the particles and homogeneous in the gas. The volatile components from particles evolve according to the first-order Arrhenius law. The released volatiles transform into the gas and are capable of chemical reaction with the oxidizer. The rate of a homogeneous reaction between gaseous volatiles and oxygen is defined by the second-order Arrhenius law. The first-order heterogeneous oxygen reaction proceeds on the particle surface. The rate of the heterogeneous reaction takes into account mass transfer [1]. The diffusion and thermal conductivity coefficients for the gas depend on temperature [1]. The temperature inside the particle is assumed to be uniform. The physico-mathematical formulation of the problem under the made assumptions can be written as the set of equations.

The heat transfer equation for the gas is

$$c_{g}\rho_{g}\frac{\partial T_{g}}{\partial t} = \frac{\partial}{\partial x}\left(\lambda(T_{g})\frac{\partial T_{g}}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda(T_{g})\frac{\partial T_{g}}{\partial y}\right) + \alpha_{i}\rho_{i}n_{i}(T_{g} - T_{s}) + c_{i}T_{i}(G_{2} + G_{i}) + Q_{i}\rho_{i}\rho_{g}k_{01}\exp\left(-\frac{E_{i}}{RT_{g}}\right),$$

the energy equation for the particles is

$$c_{i}\rho_{i}\frac{\partial T_{i}}{\partial t} = -\alpha_{i}n_{i}S_{k}(T_{i} - T_{s}) - c_{i}T_{i}(G_{2} + G_{i}) + Q_{i}G_{2} - Q_{i}G_{s},$$

the oxidizer mass-conservation equation is

$$\frac{\partial \rho_{a}}{\partial t} = \frac{\partial}{\partial x}\left(D(T_{g})\rho_{g}\frac{\partial a_{i}}{\partial x}\right) + \frac{\partial}{\partial y}\left(D(T_{g})\rho_{g}\frac{\partial a_{i}}{\partial y}\right) - \alpha_{i}G_{2} - \alpha_{i}\rho_{i}\rho_{g}k_{01}\exp\left(-\frac{E_{i}}{RT_{g}}\right),$$

the volatile mass-conservation equation in the gas is

$$\frac{\partial \rho_{v}}{\partial t} = \frac{\partial}{\partial x}\left(D(T_{g})\rho_{g}\frac{\partial a_{i}}{\partial x}\right) + \frac{\partial}{\partial y}\left(D(T_{g})\rho_{g}\frac{\partial a_{i}}{\partial y}\right) + G_{i} - \rho_{i}\rho_{g}k_{01}\exp\left(-\frac{E_{i}}{RT_{g}}\right),$$

the particle mass-conservation equation is

$$\frac{d \rho_{p}}{dt} = -G_{s} - G_{s},$$

the volatile mass-conservation equation in the particles is

$$\frac{d \rho_{v}}{dt} = -G_{s},$$

the mixture mass-conservation equation is

$$\frac{d}{dt}(\rho_{g} + n_{i}\rho_{i}) = 0.$$

The initial conditions are

$$T_{g}(0, x, y) = T_{0} + T_{io}\exp\left(-x/L_{io}\right), \quad T_{s}(0, x, y) = T_{0}, \quad \rho_{i}(0, x, y) = \rho_{ib}, \quad \rho_{s}(0, x, y) = 0,$$

$$\rho_{g}(0, x, y) = \rho_{gb}, \quad r_{i}(0, x, y) = r_{ib}, \quad \rho_{s}(0, x, y) = m_{i,0}\left(1 + \sin\left(\pi y/L_{y}\right)\right),$$

$$\rho_{v}(0, x, y) = \rho_{v0}V_{C}\left(1 + \sin\left(\pi y/L_{y}\right)\right), \quad n_{i}(0, x, y) = \rho_{i}/V_{i}\rho_{i}^{0}.$$
The boundary conditions are

\[
T_s(t, 0, y) = T_b + T_{hot}, \quad \frac{\partial \rho_1(t, 0, y)}{\partial x} = \frac{\partial \rho_2(t, 0, y)}{\partial x} = 0, \quad \frac{\partial \rho_1(t, L_x, y)}{\partial x} = \frac{\partial \rho_2(t, L_x, y)}{\partial x} = 0, \quad \frac{\partial \rho_1(t, x, 0)}{\partial y} = \frac{\partial \rho_2(t, x, 0)}{\partial y} = 0, \quad \frac{\partial \rho_1(t, x, L_y)}{\partial y} = \frac{\partial \rho_2(t, x, L_y)}{\partial y} = 0.
\]

The following notation is used in equations (1) - (9): \(\rho_g\) is the gas density, \(\rho_1\) is the distributed particle mass per unit volume, \(\rho_2\) is the distributed mass of the volatiles in the particles, \(\rho_1\) is the oxygen partial density, \(\rho_2\) is the volatiles density in the gas, \(t\) is the time, \(x, y\) are the longitudinal and transverse coordinates, \(r_i = (3(\rho_i - \rho_2))/4\pi \rho_i (1 - V_e)\) is the particle radius, \(Q\) is the thermal effect of the reaction, \(k_0\) is the constant of the chemical reaction rate, \(T\) is the temperature, \(E\) is the activation energy, \(R\) is the universal gas constant, \(c_p\) is the specific heat of gas at a constant pressure, \(c_k\) is the specific heat of coal dust particles, \(\lambda_i\) is the thermal conductivity coefficient of the gas, \(D_i\) is the gas diffusion coefficient, \(\alpha_k = Nu_k \lambda_k /2 r_i\) is the heat transfer coefficient between the gas and the particles, \(S_k, V_k\) are the surface area and volume of the particles, respectively. The rate of the particle mass change during combustion is defined by the equation \(G_z = n_x S_k j_z \rho_{oz}\), where \(j_z = \beta_m k_{oz} \exp(-E_z/R_n T_e) / [\beta_m + k_{oz} \exp(-E_z/R_n T_e)]\) is the rate of the heterogeneous reaction on the particles, \(\beta_m = \lambda_k (T) Nu_p \left(c_p r_i \beta_m\right)\) is the mass transfer coefficient for the particles [2]. The particles mass change rate during the volatile evolving is determined as \(G_z = n_x V_c j_3\), where \(j_3 = \rho_{oz} k_{oz} \exp(-E_z/RT_e)\) is the rate of the heterogeneous gasification reaction of the volatile components, \(V_c\) is the percentage of the volatile components in the particle. Indices: 0 is for the initial values of the state parameters, \(k\) – particle parameters, \(g\) – gas parameters, 1, 2, 3 – indices for the kinetic parameters of the homogeneous reaction in the gas, for the heterogeneous reaction on the particle surface, and for the homogeneous gasification reaction of the volatile components, respectively.

The problem is solved by the longitudinal-transverse sweep method [3]. The reliability of the calculations is verified by solving the model problems. According to the test calculation of the adiabatic temperature of the particle combustion, the calculation error does not exceed 3%. The grid step is equal to \(h_x = 3 \times 10^{-5} \text{ m}, h_y = 3 \times 10^{-5} \text{ m}\). The Courant number is equal to 1. The calculations are performed for the area within the coordinates \(L_x = 0.02 \text{ m}, L_y = 0.06 \text{ m}\).

3. Results

The kinetic parameters of the volatile evolving and combustion of the coke residue have been borrowed from the candidate thesis [4]. The kinetic constants of the volatile burning rate correspond to [1]. Volatile components released during the combustion of coal and wood dust are a mixture of light gases such as methane and hydrogen and combustible resins. The study [1], according to the monograph [5], uses the parameters corresponding to the burning of resins to generalize the combustion reaction of volatile components. The present model implies the same assumption.

Figures 1 – 3 show the results of the numerical simulation of the wood dust combustion in the air. The gas temperature flowfields at different time moments corresponding to the combustion front position along \(x\)-axis \(x_j = 0.2 L_x\) (a), 0.4 \(L_x\) (b), 0.6 \(L_x\) (c), 0.8 \(L_x\) (d) are shown in figures 1-2. The coordinate of the combustion front has been determined for the longitudinal coordinate \(y = L_y/2\). The radius of the particles in the wood-air suspension is \(3 \times 10^{-5} \text{ m}\), the mass concentration \(m_{dust} = 0.1 \text{ kg/m}^3\) (figure 1) and \(m_{dust} = 0.15 \text{ kg/m}^3\) (figure 2), and the mass fraction of volatile components in the particles is \(V_c = 0.1\).
According to figures 1 – 2, the combustion front for the selected air suspension compositions moves with almost the same speed and same nature of the temperature distribution along the area. The highest temperature is observed on the left border of the area and on the side surfaces. The combustion processes presented on figures 1-2 proceed with a lack of oxidizer.

Figure 1. Gas temperature in the time moments $t = 0.142$ s (a), $t = 0.367$ s (b), $t = 0.601$ s (c), $t = 0.836$ s (d), $m_{\text{dust}} = 0.1$ kg/m$^3$, $V^c = 0.1$, $r_k = 3 \cdot 10^{-5}$ m.

Figure 2. Gas temperature in the time moments $t = 0.142$ s (a), $t = 0.369$ s (b), $t = 0.607$ s (c), $t = 0.845$ s (d), $m_{\text{dust}} = 0.15$ kg/m$^3$, $V^c = 0.1$, $r_k = 3 \cdot 10^{-5}$ m.

The calculation presented in figure 3 corresponds to the case of oxidizer-rich combustion, and for the suspension with the particle mass concentration of $m_{\text{dust}} = 0.075$ kg/m$^3$. Figure 3 is plotted at the time moments when the coordinate of the combustion front is equal to $x_f = 0.1 \ L_x$ (a), 0.2 $L_x$ (b), 0.3 $L_x$ (c), 0.4 $L_x$ (d), 0.5 $L_x$ (e), 0.6 $L_x$ (f). With the excess of oxidizing agent, the maximum gas temperature is noticed in the center, the temperature at the side is lower. The velocity of the combustion front is slightly lower than the velocity shown in figures 1 – 2.

The calculation results show that for the suspension with the particle radius of $3 \cdot 10^{-5}$ m and for the mass concentration of wood dust $m_{\text{dust}} = 0.075 - 0.15$ kg/m$^3$, the flame propagation velocity along the $x$ axis is nearly the same. With a lack of oxidizer, the highest gas temperature is observed in the area of the lowest particle concentration. In the case of an oxidant-rich mixture, the maximum gas temperature is inside the region of the maximum particle concentration.
The study [1] claims that for coal dust suspension with a high content of volatile components in the particles, the flame front moves asymmetrically. In this work, we have calculated the problem (1)–(9) for a mixture with the particle radius of $10^{-6}$ m, with the mass concentration of 0.1 kg/m$^3$ and the mass fraction of volatile components in the particles of 0.1 and 0.4. The calculation results are presented in figures 4–5.

**Figure 3.** Gas temperature in the time moments $t = 0.05$ s (a), $t = 0.149$ s (b), $t = 0.262$ s (c), $t = 0.38$ s (d), $t = 0.5$ s (e), $t = 0.621$ s (f), $m_{dust} = 0.075$ kg/m$^3$, $V^c = 0.1$, $r_k = 3 \cdot 10^{-5}$ m.

**Figure 4.** Gas temperature in the time moments $t = 0.04$ s (a), $t = 0.122$ s (b), $t = 0.21$ s (c), $t = 0.298$ s (d), $m_{dust} = 0.1$ kg/m$^3$, $V^c = 0.4$, $r_k = 10^{-6}$ m.
According to figure 4, the combustion front has a prolate form with a maximum achieved on axis $y = L_y/2$, when there is a high content of volatile components in the particles. With a decrease in the content of volatile components, the shape of the combustion front changes and the maximum temperature is observed along $y = L_y$ and $y = 0$. These facts are explained by the distribution law of the particle mass concentration, since the value $y = L_y/2$ corresponds to the maximum of the law function, whilst the axes $y = L_y$ and $y = 0$ correspond to the minimum of the function. Therefore, the maximum temperature is observed in the area with the high concentration of the reactive gas components. With a low concentration of volatile components, higher temperature is achieved in the areas where the ratio between fuel and oxidizer is close to stoichiometric.

From a comparison of figures 1 and 5, we can conclude that the particle size affects the pattern of flame propagation in the suspension. With the same percentage of volatile components in the particles and with the same particle mass concentration, the suspension with small particles has higher burning rate.

4. Conclusion
We have solved the problem of the combustion front propagation through a still wood dust air suspension with an inhomogeneous dust distribution. It has been shown that the shape of the flame depends on the size, the particle mass concentration and the content of volatile components in the particles. We have distinguished the patterns of the flame along the $y$ axis. The possibility of flame formation along the $y = L_y/2$ has been shown.

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