

Numerical study of heat and mass transfer during ignition of thermal decomposition products of a coal particle

Dmitrii O. Glushkov^a and Olga V. Vysokomornaya

National Research Tomsk Polytechnic University, 634050 Tomsk, Russia

Abstract. A numerical research was executed for macroscopic regularities determination of heat and mass transfer processes under the conditions of phase transformation and chemical reaction at the ignition of vapour coming from fabrics impregnated by typical combustible liquid into oxidant area at the local power supply. Limit conditions of heterogeneous system “fabric – combustible liquid – oxidant” ignition at the heating of single metal particle was established. Dependences of ignition delay time on temperature and rates of local power source were obtained.

The mathematical modeling of interrelated processes of heat and mass transfer and chemical reacting was carried out at ignition of single coal particles with different sizes from 0.05 mm to 0.5 mm in air flow heated to moderate temperatures ($T < 500$ K).

A physical model of ignition process describes the more common scheme of investigating phenomena (Figure 1).

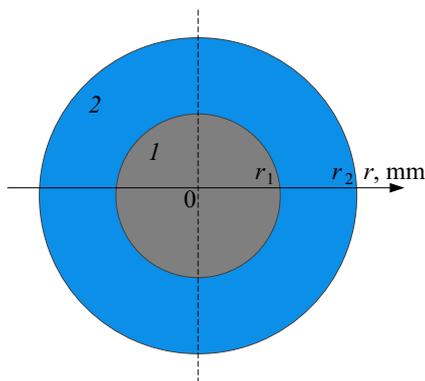


Figure 1. A scheme of research area at $0 < t < t_d$: 1 – coal particle, 2 – air.

At the initial time moment (Figure 1) a spherically-shaped coal particle with the radius of r_p was put into the oxidized area (air) with temperature higher than the initial temperature of the particle ($T_g > T_0$). It was assumed that the heat supply to the solid fuel particle occurs due to the mechanism of radiative and conductive heat transfer on the particle boundary with the surrounding gas area. The

^a Corresponding author: dmitriyog@tpu.ru

temperature of fossil fuel thermal decomposition is reached due to inert warming-up of particle during the heat conduction. Emitting volatile substances are blown into the air. A combustible mix is formed in the oxidized area due to the diffusion of gas-phase thermal decomposition products. Oxidation processes near the particle surface are accelerated due to the combustible mix heating. The ignition occurs when the temperature and the concentration of the volatiles have critical values.

Two ignition criteria were used. Their application was well tested at the solution of ignition problems for solid [1], liquid [2] and gel [3] fuels:

1. The heat released due to the oxidation reaction of the thermal decomposition products of fossil fuel in air is greater than the heat flux from the surrounding gas area to the particle.
2. The gas mixture temperature in the zone of exothermal reaction is greater than the initial air temperature T_g .

The basic elements of heat and mass transfer models at ignition of solid [1], liquid [2] and gel [3] condensed substances were used in the mathematical model development for investigating heat and mass transfer process. A formulated differential equation system of heat and mass transfer describes non-stationary processes of coal heating and thermal decomposition, devolatilization and gas mixture oxidation by oxygen. Finite-difference method, locally one-dimensional method, iteration method, sweep method using a four-point implicit difference scheme was used for the solution of the differential equations with the corresponding initial and boundary conditions. The adequacy of the numerical investigation results was determined owing to the low error (less than 2 %) of the energy conservation law implementation in the solution area, as well as a good correlation between the calculated values of ignition delay time and the experimental data [4].

Figure 2 shows the temperature distributions in the solution area for different time moments ($0 < t < t_d$) during the interaction between the coal particle with radius $r_p = 0.15$ mm and gas area ($T_g = 450$ K). It is obvious that heat transfer process in the system (Figure 1) is considerably nonstationary and nonlinear under taking into account the thermal decomposition of fossil fuel and the chemical reaction of volatiles in the oxidizer. The mechanism of its mutual influence is rather complicated.

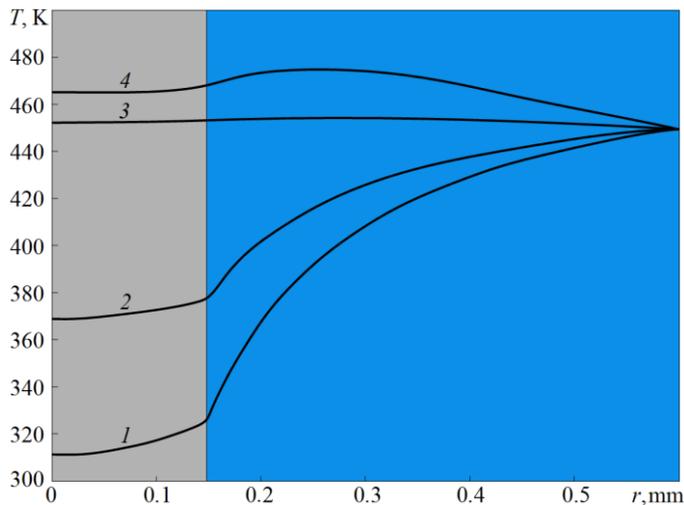


Figure 2. Temperature distributions in coal particle and gas mixture under the conditions of $r_p = 0.15$ mm and $T_g = 450$ K in different time moments: 1 – $t = 0.1$ s, 2 – $t = 0.5$ s, 3 – $t = 3$ s, 4 – $t = 5.6$ s.

During the devolatilization a large quantity of heat is absorbed. It leads to air temperature decreasing near the particle surface (curves no. 1 and 2 in Figure 2). During the combustible gas concentration increasing a heat release increases nonlinearly (curves no. 3, 4 in Figure 2) and oxidation reaction accelerating rapidly. It leads to temperature increasing near the “particle – gas” border and heating of the deeper layers in the coal particle. Increase of the oxidation rate of gas mix is connected with the decrease of combustible substance concentration in the exothermic reaction zone.

A stable gas-phase ignition occurs at sufficient concentrations and temperatures of combustible mixture (volatiles with air oxygen).

Table 1 shows the extreme values of air temperature at which stable ignition of thermal conduction coal particle products is realized. The determined temperatures T_g^{\min} are lower (about 12–16 K) than the values adopted as a permissible maximum [5, 6] at thermal power plants operating by solid fossil fuel. Under conditions of the real technological process the duration of investigating process is an important characteristic for the evaluation of its potential danger.

Table 1. The minimum values of oxidizer temperature, sufficient for stable ignition of a coal particle with different sizes.

r_p , mm	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
T_g^{\min} , K	450	442	434	427	421	417	413	410	407	405

The ignition delay times for coal particles on condition of oxidizer temperature $T_g=450$ K are given in Table 2. The maximal value of t_d for the coal particles with sizes $r_p=0.05$ – 0.5 mm are not exceed 21 s.

Table 2. The ignition delay time of a coal particle under condition of $T_g=450$ K.

r_p , mm	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
t_d , s	4.7	5.1	5.6	6.8	8.5	10.4	12.6	15.1	17.7	20.5

The obtained values of coal ignition delay time under relatively low air temperature help to explain the possible causes of coal powder self-ignition in fuel preparation system of thermal power station. In particular, coal powder with particle sizes $r_p=0.05$ – 0.5 mm may be for a long time period (significantly greater than t_d in Table 2) in a oxidized area with temperature $T_g=300$ – 500 K during technological processes of fuel preparation for combustion in the boiler. Considering a polydisperse composition of coal powder, the implementation of ignition conditions, at least for one of the particles, leads to other particle ignition near the center of combustion. It is caused by low distance between zone of intense chemical reaction (ignition) of volatiles and particle surface.

The developed prognostic mathematical model of heat and mass transfer considering a chemical reaction allowed setting the extreme conditions of the gas-phase ignition of coal particles in the low-temperature air flow. The calculated values of the minimal temperature ($T_g^{\min}=400$ – 450 K) sufficient for ignition of the gas-phase thermal decomposition coal particle products and determined ignition delay times ($t_d < 21$ s) allow concluding that the ignition of coal powder possible at temperatures lower than accepted temperatures as permissible limit [5, 6] for the fuel preparation system of thermal power plants.

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References

1. D.O. Glushkov, G.V. Kuznetsov, P.A. Strizhak, Russ. J. Phys. Chem. B **8**, 196 (2014)
2. D.O. Glushkov, G.V. Kuznetsov, P.A. Strizhak, Adv. Mech. Eng. **2014**, 764537 (2014)
3. G.V. Kuznetsov, P.A. Strizhak, J. Eng. Phys. Thermophys. **86**, 695 (2013)
4. T.V. Vilensky, D.M. Hzmalyan, *Dynamics of Burning of Dust-Like Fuel* (Energiya, Moscow, 1977)
5. G.T. Levit, *Coal Powder Production on Thermal Power Plants* (Energoatomizdat, Moscow, 1991)
6. Yu.I. Rubtsov, A.I. Kazakov, V.A. Rafeev, Chemistry of Solid Fuel. **2**, 24 (2000)