

NUMERICAL RESEARCH OF HEAT AND MASS TRANSFER DURING LOW-TEMPERATURE IGNITION OF A COAL PARTICLE

by

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Numerical researches have been carried out to study the influence of air flow temperature and a fossil fuel particle rate on sufficient conditions of ignition in a "coal particle – air" system. Developed mathematical model takes into account interconnected processes of heat transfer in a coal particle and gas area, thermal decomposition of organic material, diffusion and gas-phase oxidation of volatiles, heating of a coke (carbon) and its heterogeneous ignition. The effect of low-temperature (about 600 K) ignition for a single coal particle is impossible even at variation of its rate (radius) from 0.05 mm to 0.5 mm. Nevertheless this process is possible for group of particles (two, three, et al.) situated at close-range from each other. The physical aspects of the problem are discussed.

Key words: *heat and mass transfer, coal particle, low-temperature air flow, ignition, numerical research*

Introduction

In recent years, energy conservation programs [1-4] are implemented in most countries in Europe, Asia, and America. The problem of improving industrial production efficiency is particularly relevant for industrially developed countries, where the heavy industry is a significant part of the country economy. Increase in the share of nuclear energy is not very high. Alternative energy sources are not widely used in the industry for objective reasons (low power generation). Therefore, modern thermal power plants are promising energy sources in the near future.

The main fuel for thermal power plants in the coming decade will be coal [5]. Its total reserves in Russia, China, USA, India, Australia, Kazakhstan, Poland, Germany, and others are more than 900 billion tons. According to the forecast of world energy development [5] in 2040 the volume of coal consumption will increase by 1.5 times (compared to 2010) and will be equal to 25.6% of all the types of used primary energy resources of the world community. An important fact is that a significant part (about 60%) of the world's coal reserves is low-rank coal with unstable power characteristics (in particular, the heat effect of oxidation reaction).

In the long term, the particular attention should be paid to solve the problem of preventing and reducing the risk of technological accidents [6, 7] at thermal power plants. Improving the safety of technological process, especially in fuel preparation system, is relevant for

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newly introduced into operation thermal power plants, as well as for modernized in order to convert to low-rank fossil fuel. In the widely used fuel preparation systems fuel humidification and maintenance of relatively low ambient temperatures are provided to reduce the risks of coal powder self-ignition. However, due to the high susceptibility of fuel preparation systems even to slight process conditions changes (fuel quality, ambient temperature, etc.), there is an increased risk of technological accidents (coal powder self-ignition).

Currently, for the possible optimization of pulverized fuel firing technique in thermal power plants, numerical researches of high-temperature ($T > 1200$ K) ignition and combustion of coal particles [8-10], as well as gas-coal dust mixtures [11-13] have been carried out by the authors [8-13]. However, the features and the characteristics of low-temperature coal particles ignition processes may differ significantly from the known results of numerical and experimental researches [8-10]. To explain the cause of accidents and reduce the risks of new technological accidents in thermal power plants, related to pulverized coal ignition, more detailed representations of patterns and characteristics of heat and mass transfer processes at low-temperature ($T < 500$ K) coal particle ignition are required.

The purpose of present work is the mathematical simulation of heat and mass transfer processes at low-temperature coal particle ignition and analysis of boundary ignition conditions of components (volatiles and carbon), formed as a result of coal particle thermal decomposition.

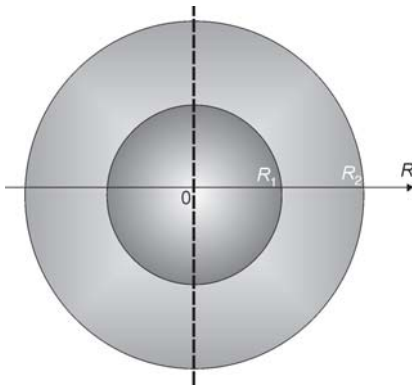


Figure 1. Schematic diagram of the solution domain area for the ignition problem; 1 – carbon (coal particle at $\tau = 0$), 2 – gas mixture of air and volatiles (air at $\tau = 0$)

Problem formulation

A schematic diagram of investigated process is shown in fig. 1. A coal particle in the shape of sphere with the radius R_p ($R_p = R_1$) and the initial temperature Θ_0 is placed into oxidizer (air) with a higher temperature Θ_a ($\Theta_a > \Theta_0$). During the processes of thermal conductivity and thermal radiation heat exchange on the “particle-air” boundary happens. Heat supply occurs to the near-surface layer of a coal particle. Heating of condensed substance is implemented due to thermal conductivity. Thermal decomposition of organic matter on carbon and volatiles happens during gradual heating of particle. Gaseous products (volatiles) flow into external gas area from the particle surface. In the vicinity of a particle the mixture of volatiles with oxidizer (air) is formed.

Gas-phase ignition of volatiles occurs at critical values of its concentration and temperature in the system (fig. 1). Thermal emission as a result of the exothermic oxidation reaction leads to the rising of temperature on the coke surface. According to provisions of [8-10] it was considered that the coke part of coal particle consists of carbon after completion of thermal decomposition process. Heterogeneous ignition of carbon occurs at the achievement of critical temperature [9] on particle surface.

Due to implementation of the complex heat and mass transfer mechanism, it was assumed the following ignition conditions for coal particle [14]:

- the heat released at the heterogeneous oxidation of carbon is more than the heat transferred to the particle from external gas area, and
- temperature on the particle surface exceeds the temperature Θ_c of carbon ignition [9].

Mathematical model and numerical methods of research

The axisymmetric problem of heat and mass transfer processes in a “coal particle – air” system was solved in a spherical co-ordinate (fig. 1). Mathematical model includes the system of non-linear non-stationary differential equations in dimensionless variables [15, 16] and corresponding initial and boundary conditions.

For $0 \leq \tau \leq \tau_i$ (the time interval from the moment of placing of a coal particle with the initial temperature Θ_0 to oxidizer with a temperature Θ_a until the moment of volatiles ignition):

- the heat balance equation for a particle ($0 < R < R_1$)

$$\frac{1}{Fo_1} \frac{\partial \Theta_1}{\partial \tau} = \frac{1}{R^2} \frac{\partial}{\partial R} \left(R^2 \frac{\partial \Theta_1}{\partial R} \right) - \frac{Q_1 W_1 r_m^2}{\lambda_1 \Delta T} \quad (1)$$

- the heat balance equation for the gas mixture of air and volatiles ($R_1 < R < R_2$)

$$\frac{1}{Fo_2} \frac{\partial \Theta_2}{\partial \tau} = \frac{1}{R^2} \frac{\partial}{\partial R} \left(R^2 \frac{\partial \Theta_2}{\partial R} \right) + \frac{Q_2 W_2 r_m^2}{\lambda_2 \Delta T} \quad (2)$$

- the diffusion equation of volatiles in gas mixture ($R_1 < R < R_2$):

$$\frac{\partial \gamma_g}{\partial \tau} = \frac{D_2 t_m}{r_m^2} \frac{1}{R^2} \frac{\partial}{\partial R} \left(R^2 \frac{\partial \gamma_g}{\partial R} \right) - \frac{W_2 t_m}{\rho_2} \quad (3)$$

- the balance equation for components of the gas mixture ($R_1 < R < R_2$)

$$\gamma_g + \gamma_a = 1 \quad (4)$$

The following scale values were used for converting the dimensional variables to the dimensionless variables: time $t_m = 1$ s, temperature $T_m = 1000$ K, and size $r_m = 1$ mm.

Initial conditions at $\tau = 0$ (fig. 1):

$$\Theta_1 = \Theta_0, \quad \varphi_1 = \varphi_0 \quad \text{at } 0 < R < R_1 \quad (5)$$

$$\Theta_2 = \Theta_a, \quad \gamma_g = 0, \quad \gamma_a = 1 \quad \text{at } R_1 < R < R_2 \quad (6)$$

Boundary conditions at $0 < \tau \leq \tau_i$ are presented in tab. 1.

Table 1. Boundary condition

Boundary	Conditions
$R = 0$	$\frac{\partial \Theta_1}{\partial R} = 0$
$R = R_1$	$\frac{\partial \Theta_1}{\partial R} = \frac{\partial \Theta_2}{\partial R} \frac{\lambda_2}{\lambda_1} + (\Theta_2^4 - \Theta_1^4) \frac{\varepsilon \sigma \Delta T^3 r_1}{\lambda_1} - \frac{Q_1 W_1 r_1^2}{\lambda_1 \Delta T}, \quad \rho_2 D_2 \frac{\partial \gamma_g}{\partial R} = W_{1\Sigma} r_1$
$R = R_2$	$\Theta_2 = \Theta_a, \quad \frac{\partial^2 \gamma_g}{\partial R^2} = 0$

According to the basic provisions of diffusion and heat transfer theory [16] in chemical kinetics rates of fuel thermal decomposition, volatiles outflow from the surface of a coal particle to outside gas area, and oxidation reaction in gas mixture, respectively, are defined as:

$$W_1 = \varphi_1 \rho_1 k_1^0 \exp\left(-\frac{E_1}{R_1 T_1}\right) \quad (7)$$

$$W_{1\Sigma} = \int_{r=0}^{r=r_1} \varphi_1 \rho_1 k_1^0 \exp\left(-\frac{E_1}{R_1 T_1}\right) dr \quad (8)$$

$$W_2 = k_2^0 \rho_2 \gamma_g \gamma_a \exp\left(-\frac{E_2}{R_1 T_1}\right) \quad (9)$$

The changing of organic matter quantity in a coal particle (that equal to the quantity of volatiles come from the surface of a coal particle to outside gas area) according to [16] is defined as:

$$\frac{d\varphi_1}{d\tau} = \varphi_1 k_1^0 t_0 \exp\left(-\frac{E_1}{R_1 T_1}\right) \quad (10)$$

Heterogeneous ignition of carbon (at $\tau_i < \tau \leq \tau_d$) after thermal decomposition process of a coal particle is described by elements of the numerical solution algorithm for investigation of burning process of a moving carbon particle in oxidizer [9]. The heat balance eq. [9] in dimensionless variables for the particle (assuming uniformity of the temperature field) is written as:

$$\frac{d\Theta_1}{d\tau} = \frac{6t_m(q_{ch} - q_g - q_w)}{\rho_{1c} C_{1c} \Delta T r_m 2R_1} \quad (11)$$

It was assumed that on the “particle – air” boundary heterogeneous oxidation reactions ($C + O_2 \rightarrow CO_2$ and $2C + O_2 \rightarrow 2CO$) occur at the same time [9].

The quantity of heat released during chemical reactions is given by [9]:

$$q_{ch} = \left[k_{3,1}^0 \exp\left(-\frac{E_{3,1}}{R_1 T_1}\right) Q_{3,1} + k_{3,2}^0 \exp\left(-\frac{E_{3,2}}{R_1 T_1}\right) Q_{3,2} \right] \rho_{2c} \gamma_a \quad (12)$$

Convective and radiative heat fluxes at the boundary “particle – air” are calculated by [9]:

$$q_g = \alpha(T_1 - T_2) + 0.5\rho_{2c} C_{2c} U_{2c} (T_1 + T_2) \quad (13)$$

$$q_w = \varepsilon\sigma(T_1^4 - T_2^4) \quad (14)$$

Distribution of temperature in the solution domain area (fig. 1) were determined as a result of heat and mass transfer processes research during volatiles ignition described by eqs. (1)-(10). Calculated values of temperature in the “particle – air” system were used as initial conditions for solution of eq. (11).

The system of differential eqs. (1)-(4) described heat and mass transfer processes during the gas-phase ignition of volatiles ($0 < \tau < \tau_i$) with corresponding initial (5)-(6) and boundary (tab. 1) conditions was solved by the method of finite differences similar to [17-19]. The local 1-D method was applied to solve different analogues of differential equations. The sweep method using the implicit four-dot difference scheme was applied to solve 1-D difference equations. The co-ordinate step $5 \cdot 10^{-6}$ m and the time step 10^{-5} s were set to calculate integral characteristics of process (in particular, ignition delay time).

Testing of numerical research methods and elements of solution algorithm for the system of differential eqs. (1)-(4) with initial (5)-(6) and boundary (tab. 1) conditions was carried out on the example of non-linear heat conduction problems [20] and chemical kinetics problems [21].

The reliability of numerical research results was determined by the verification of difference scheme conservation as described in [17-19]. The error of heat conservation law implementation in the field of the solution area (fig. 1) is not exceeding 2.4%.

Results and discussion

Numerical results were carried out at the following values of process parameters [22-25]: the initial temperature of a coal particle $\Theta_0 = 0.3$; the initial temperature of air $\Theta_a = 0.4-0.5$; the temperature of carbon ignition $\Theta_c = 1.9$; the initial quantity of volatile products in a coal particle $\varphi_0 = 0.1$; kinetic parameters of chemical processes $k_1^0 = 2.82 \cdot 10^6 \text{ s}^{-1}$, $E_1 = 80 \cdot 10^3 \text{ J/mol}$, $Q_1 = 187.6 \cdot 10^3 \text{ J/kg}$, $k_2^0 = 1.964 \cdot 10^{12} \text{ s}^{-1}$, $E_2 = 103.5 \cdot 10^3 \text{ J/mol}$, $Q_2 = 47.3 \cdot 10^6 \text{ J/kg}$, $k_{3,1}^0 = 4.5 \cdot 10^4 \text{ m/s}$, $E_{3,1} = 140.03 \cdot 10^3 \text{ J/mol}$, $Q_{3,1} = 12.3 \cdot 10^6 \text{ J/kg}$, $k_{3,2}^0 = 13 \cdot 10^4 \text{ m/s}$, $E_{3,2} = 154 \cdot 10^3 \text{ J/mol}$, $Q_{3,2} = 6.843 \cdot 10^6 \text{ J/kg}$; radius of particle $R_p = 0.05-0.5$; radius of solution domain area $R_m = 1$. The heat transfer coefficient at the “particle – air” boundary ($\alpha = 5 \text{ W/m}^2\text{K}$) and relative velocity of air flow ($U_{2c} = 1 \text{ m/s}$) is average for values considered in [9].

It is known that values of kinetic parameters and thermal effect for chemical reactions of thermal decomposition of coal and combustion of volatiles and carbon depend on intensity of heat transfer processes in the system (fig. 1) determined by the temperature of oxidizer. Therefore, thermogravimetric analysis (fig. 2) of coal particles pyrolysis and coal particle thermal decomposition was carried out at low rate changing of external gas temperature ($5 \text{ }^\circ\text{C}/\text{min}$). Obtained parameters were used for numerical research of ignition process with characteristics of chemical reactions corresponding to real values.

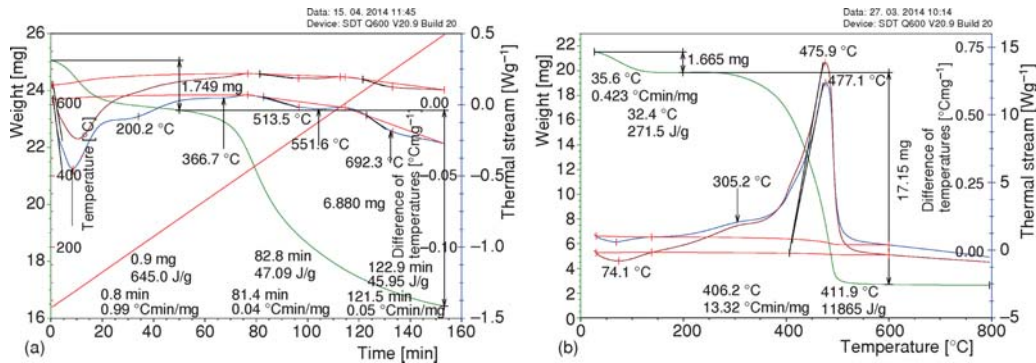


Figure 2. Typical curves of thermogravimetric analysis of coal particles pyrolysis (a) and coal particle thermal decomposition (b)

Thermophysical characteristics [22-26] of components (fig. 1) are:

- coal: $\rho_1 = 1500 \text{ kg/m}^3$, $C_1 = 2130 \text{ J/kgK}$, $\lambda_1 = 0.149 \text{ W/mK}$,
- volatiles: $\rho_{21} = 0.449 \text{ kg/m}^3$, $C_{21} = 1131.5 \text{ J/kgK}$, $\lambda_{21} = 0.031 \text{ W/mK}$, $D_{21} = 9.694 \cdot 10^{-6} \text{ m}^2/\text{s}$,
- air: $\rho_{22} = 1.161 \text{ kg/m}^3$, $C_{22} = 1190 \text{ J/kgK}$, $\lambda_{22} = 0.026 \text{ W/mK}$, $D_{22} = 0.561 \cdot 10^{-6} \text{ m}^2/\text{s}$, and
- carbon: $\rho_{1c} = 1.59 \text{ kg/m}^3$, $C_{1c} = 947 \text{ J/kgK}$.

Thermophysical characteristics of gas mixture (air and volatiles) are defined as:

$$\rho_2 = \rho_{21}\gamma_g + \rho_{22}\gamma_a \quad (\rho_{2c} = \rho_2) \quad (15)$$

$$C_c = C_{21}\gamma_g + C_{22}\gamma_a \quad (C_{2c} = C_2) \quad (16)$$

$$\lambda_2 = \lambda_{21}\gamma_g + \lambda_{22}\gamma_a \quad (17)$$

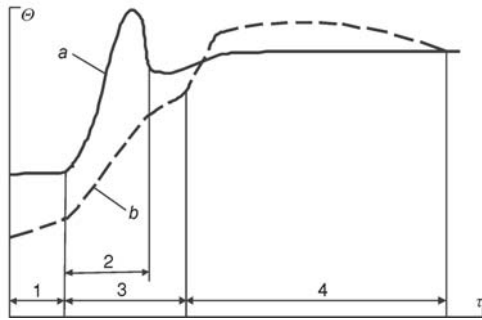


Figure 3. A schematic diagram of combustion process for a coal particle [27]

(a) – a gas temperature near a particle, (b) – a particle temperature, 1 – period of inert heating of a coal particle, 2 – period of gas-phase combustion of volatiles, 3 – period of inert heating of carbon, 4 – period of heterogeneous combustion of carbon

process ($\Theta_a < 1$) of a coal particle the temperature of its surface will not increase such quickly. Nevertheless this process can become the reason of technological accidents in fuel preparation system. Intensity of heat and mass transfer processes and sufficient ignition conditions of carbon will depend on quantity of additional heat released during volatiles combustion in gas mixture.

Figure 4 shows temperature distribution in the field of the solution area (fig. 1), concentration of volatiles in gas mixture and quantity of volatile products in a coal particle at the moment of gas-phase ignition ($\tau = \tau_i$).

From the fig. 4(a) we see that the temperature distribution in the system (fig. 1) is non-uniform at the ignition moment of volatiles in gas mixture. High temperature ($\Theta \approx 2$) near a particle surface is only short time interval. Under such conditions the highest temperature of carbon particle surface (Θ_s) is about 0.6. At high-temperature ignition of a coal particle this value is significantly higher ($\Theta_s > 1$). Because of at the low temperature ($\Theta_s = 0.6$) of the particle surface and nonuniform warming of particle, fig. 4(a), rate of coal thermal decomposition and rate of volatiles flow into external gas area from the particle surface is not high. This is the main cause of low concentration of gaseous products of thermal decomposition near the particle, fig. 4(b). Values of gas mixture temperature and volatiles concentration γ_g is enough for its gas-phase ig-

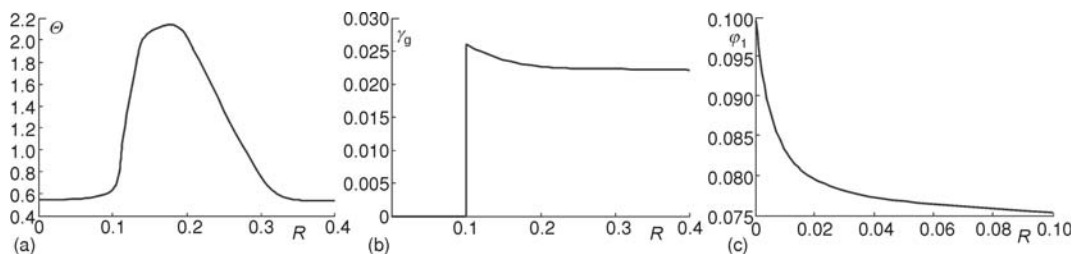


Figure 4. Temperature distribution (a), concentration of volatiles (b), and quantity of volatile products in a coal particle (c) at the ignition moment of volatiles in gas mixture ($\tau = \tau_i$) for conditions $R_p = 0.1, \Theta_a = 0.5$

$$D_2 = D_{21}\gamma_g + D_{22}\gamma_a \quad (18)$$

As a result of the analysis of high-temperature ignition processes ($\Theta_a > 1$) for a coal particle several time intervals (fig. 3) were established [27]. In these conditions ($\Theta_a > 1$) dimensionless ignition delay time τ_d of a coal particle with radius $R_p = 0.5$ does not exceed 2. Figure 3 shows that the stage of heterogeneous ignition 4 follows after carbon heating 3 by the heat released during gas-phase oxidation of volatiles in gas mixture 2.

For real technological processes of fuel combustion in coal-fired power stations temperature of oxidizer (air) is more than 1200 K ($\Theta_a > 1.25$) [28, 29]. Under such conditions the temperature of particle surface will increase quite intensively relatively to the initial value even in a short time interval ($\tau < 0.1$). For low-temperature ignition

nitiation. However, in this moment ($\tau = \tau_i$) the process of thermal decomposition of coal in deep layers ($R \rightarrow 0$) of the particle is not completed fully, fig. 4(c). Under such conditions steady ignition of a coal particle is impossible. Heat liberation during the stage of volatiles burning out is not enough for warming of carbon surface to temperature sufficient for its heterogeneous ignition. Thermal decomposition of a coal particle goes on fig. 4(c) after volatiles burning out in gas mixture. These stages can repeat before the complete thermal decomposition of a coal particle ($\varphi_1 \rightarrow 0$ at $R \rightarrow 0$).

Figure 5 depicts dependences of ignition delay time of volatiles at initial air temperature $\Theta_a = 0.5$ and minimum temperature of external gas area sufficient to ignition of volatiles at heating of a coal particle with various values of its radius $R_p = 0.05-0.5$.

Ratios of $\tau_i = f(R_p)$ and $\Theta_a^{\min} = f(R_p)$ allow to make a conclusion about high probability of gas-phase ignition in the “coal particle – air” system at relatively low temperature ($\Theta_a = 0.4-0.5$) of oxidizer. However subsequent heterogeneous ignition of carbon (after full thermal decomposition of a single coal particle) is impossible. It can be explained by the low value of particle surface temperature $\Theta_s \approx 0.8$ after period of gas-phase combustion of volatiles (fig. 3). More high temperature ($\Theta_a > 1$) of gas mixture is necessary during the long time interval for homogeneous warming of a carbon particle and its steady ignition. Chemical reactions of $C + O_2 \rightarrow CO_2$ and $2C + O_2 \rightarrow 2CO$ occur with high rate and a coal particle burns down in a few seconds under conditions of sufficient oxidizer concentration for heterogeneous ignition of carbon. In this case the time interval between the moment of heterogeneous ignition of carbon τ_d and the moment of gas-phase ignition of volatiles τ_i does not exceed 0.1 [27]. Such conditions are possible in the “several coal particles – air” system.

Numerical research of ignition process for two identical coal particles located at a close distance was executed. The purpose of such investigation is definition of joint effect of two particles on conditions of their ignition at low temperature of oxidizer. We considered that two coal particles located at the distance $L = 0.25 R_p$. Initial temperature of oxidizer (air) is $\Theta_a = 0.5$. Temperature of flame after gas-phase ignition of volatiles is $\Theta_i \approx 2.1$. During the time interval about 0.2 temperature of gas mixture significantly decreases to $\Theta_1 = 1$ in an oxidation reaction zone. Under such conditions we carried out an assessment of ignition delay time for carbon heterogeneous ignition at various values of surface temperature of particles after volatiles burn out. Results of numerical research are shown in tab. 2.

Table 2. The time interval between gas-phase ignition of volatiles (τ_i) and heterogeneous ignition of carbon (τ_d) for a coal particle with radius $R_p = 0.1$ at various values of surface temperature of carbon (Θ_s) after volatiles burn out

Θ_s	0.80	0.85	0.90	0.95	1.00	1.05	1.10	1.15	1.2
$\tau_d - \tau_i$	9.269	2.986	1.099	0.453	0.206	0.102	0.055	0.031	0.019

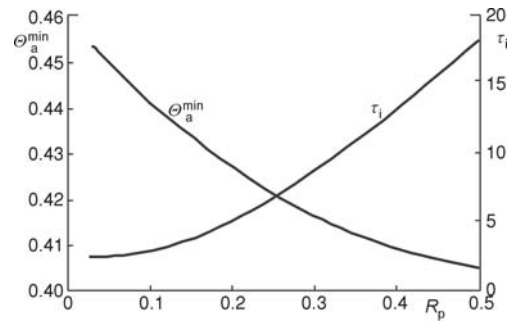


Figure 5. Ignition delay time (τ_i) of volatiles in gas mixture at initial air temperature $\Theta_a = 0.5$ and minimum temperature (Θ_a^{\min}) of air sufficient to ignition of volatiles at various values of coal particle radius

From tab. 2 it has been observed that time interval $\tau_d - \tau_i$ at $\Theta_s > 1$ is less than 0.2. It can be concluded about possibility of heterogeneous ignition of two coal particles located at the small distance $L < 0.25 R_p$ even at low temperature ($\Theta_a = 0.4-0.5$) of oxidizer. It is apparent that in systems with a large number of coal particles (three, four, five, *et al.*) distance between them sufficient for steady heterogeneous ignition of carbon at initial air temperature $\Theta_a = 0.4-0.5$ can be comparable with R_p or greater than it.

Conclusions

In the present paper we have theoretically studied the interconnected processes of heat and mass transfer and chemical reaction during low-temperature ($\Theta_a = 0.4-0.5$) ignition of a small-size ($R_p = 0.05-0.5$) coal particle. We can conclude the following results from our investigation.

- The rate of thermal decomposition of a coal particle decreases with decreasing of oxidizer initial temperature from $\Theta_a = 1$ to $\Theta_a = 0.5$. It leads to partial thermal decomposition of coal at the moment of gas-phase ignition of volatiles.
- Quantity of heat released during gas-phase ignition of volatiles as a result of a coal particle thermal decomposition is not enough for heterogeneous ignition of carbon because of nonuniform warming of a particle and low temperature of its surface.
- Larger quantity of volatiles and respectively heat is allocated at the thermal decomposition of two coal particles located at the small distance ($L < 0.25 R_p$) and subsequent volatiles combustion. As a result enough quantity of heat is released necessary for warming of carbon to the temperature of heterogeneous ignition.
- At heating three and more particles by low-temperature ($\Theta_a = 0.4-0.5$) air their ignition is possible at large ($L > 0.25 R_p$) distance between each other. This result should be considered for prevention of some technological accidents in fuel preparation system of coal-fired power stations.

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Nomenclature

C	– constant specific heat, [$\text{Jkg}^{-1}\text{K}^{-1}$]	q_g	– convective heat flux, [$\text{Jm}^{-2}\text{s}^{-1}$]
D	– diffusion coefficient, [m^2s^{-1}]	q_w	– radiative heat flux, [$\text{Jm}^{-2}\text{s}^{-1}$]
E	– activation energy, [Jmol^{-1}]	R	– dimensionless analog of spherical co-ordinate r ($= r/r_m$), [–]
Fo	– Fourier number, [–]	R_m	– dimensionless analogues of r_m , [–]
k_0	– pre-exponential factor, [s^{-1}]	R_p	– dimensionless analogue of r_p ($= r_p/r_m$), [–]
L	– dimensionless distance between two coal particles, [–]	R_t	– ideal gas constant ($= 8.31$), [$\text{Jmol}^{-1}\text{K}^{-1}$]
Q_1	– heat released during coal thermal decomposition, [Jkg^{-1}]	r	– co-ordinate of cylindrical system, [m]
Q_2	– heat released during volatiles oxidation, [Jkg^{-1}]	r_m	– solution domain radius, [m]
$Q_{3,1}$	– heat released during chemical reaction $\text{C} + \text{O}_2 \rightarrow \text{CO}_2$, [Jkg^{-1}]	r_p	– radius of a coal particle, [m]
$Q_{3,2}$	– heat released during chemical reaction $2\text{C} + \text{O}_2 \rightarrow 2\text{CO}$, [Jkg^{-1}]	T	– temperature, [K]
q_{ch}	– chemical heat, [$\text{Jm}^{-2}\text{s}^{-1}$]	T_0	– initial temperature of a coal particle, [K]
		T_m	– temperature scale, [K]
		ΔT	– temperature differential ($= T_m - T_0$), [K]
		t	– time, [s]
		t_m	– time scale, [s]

U	– velocity, [ms^{-1}]	Θ_s	– dimensionless temperature of coal particle surface, [–]
W_1	– mass rate of coal thermal decomposition, [$\text{kgm}^{-2}\text{s}^{-1}$]	λ	– thermal conductivity, [$\text{Wm}^{-1}\text{K}^{-1}$]
$W_{1\Sigma}$	– mass rate of volatiles outflow from the particle surface, [$\text{kgm}^{-2}\text{s}^{-1}$]	ρ	– density, [kgm^{-3}]
$W_{2\Sigma}$	– mass rate of volatiles oxidation, [$\text{kgm}^{-2}\text{s}^{-1}$]	σ	– Stefan-Boltzmann constant ($= 5.67 \cdot 10^{-8}$), [$\text{Wm}^{-2}\text{K}^{-4}$]
Greek symbols		τ	– dimensionless time ($= t/t_m$), [–]
α	– heat transfer coefficient, [$\text{Wm}^{-2}\text{K}^{-1}$]	τ_d	– dimensionless ignition delay time of carbon, [–]
γ_a	– dimensionless concentration of oxidizer (air), [–]	τ_i	– dimensionless ignition delay time of volatiles, [–]
γ_g	– dimensionless concentration of volatiles, [–]	φ_0	– initial quantity of volatile products in a coal particle, [–]
ε	– blackness degree of a particle, [–]	φ_1	– quantity of volatile products in a coal particle, [–]
Θ	– dimensionless temperature ($= (T - T_0)/\Delta T$), [–]	Subscripts	
Θ_0	– dimensionless initial temperature of a coal particle, [–]	1	– coal particle
Θ_a	– dimensionless temperature of air, [–]	1c	– carbon
Θ_i	– dimensionless temperature of flame, [–]	2	– gas mixture
Θ_c	– dimensionless temperature of carbon, [–]	2c	– volatiles
		3,1	– chemical reaction $\text{C} + \text{O}_2 \rightarrow \text{CO}_2$
		3,2	– chemical reaction $2\text{C} + \text{O}_2 \rightarrow 2\text{CO}$

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