

FEATURES OF IGNITION AND COMBUSTION OF A TWO-COMPONENT GAS SUSPENSION OF COAL PARTICLES

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Physical and mathematical modeling of high-temperature heat and mass transfer and combustion kinetics of a two-fraction gas suspension of carbon particles at different gas temperatures is carried out. It was assumed that two parallel chemical reactions occur on the surface of the carbon particles: $C + O_2 = CO_2$ (I), $2C + O_2 = 2CO$ (II). Molecular-conjugate heat exchange of particles with gas was taken into account, as well as heat exchange by radiation with the walls of the reaction apparatus. As a result of the numerical experiment, the characteristics of ignition and combustion of gas-suspension particles in air at various temperatures of the surrounding gas are determined. For calculations, a two-fraction gas suspension was chosen with equal mass fractions and particle diameters, which differ by a factor of 2: $d_{b1} = 60 \mu\text{m}$, $d_{b2} = 120 \mu\text{m}$. The range of the initial gas temperatures studied is 1100...1500 K. As a result of the calculations carried out, it was established that as the gas temperature decreases, the coarse fraction can ignite earlier than the fine fraction. At high gas temperatures, on the contrary: the induction period of fine particles is much larger than the period of induction of coarse particles. Critical parameters of ignition of two-fraction gases are found. The main characteristics of combustion are the time and temperature of combustion of the particles. It is proved that under the conditions of a two-fraction gas suspension the burning time of the particles depends weakly on the temperature of the gas. It has also been established that in the region of low gas temperatures, the combustion temperature of the fine fraction is smaller than that of the large fraction. This is explained by the large heat removal from small particles by the molecular-convective process and by the lack of oxidizer in the combustion stage. Oxygen is consumed in the combustion of large particles, which, at low temperatures, ignite earlier. The burning times of particles of coarse and fine fractions of a gas suspension were found. Comparison of the combustion time of small and large particles led to the conclusion that under the conditions of a gas suspension with an excess of an oxidizer close to unity, the particles burn in a diffusion mode. It is shown that the extinction of particles is degenerate. After the moment of extinction, the particles are oxidized in the kinetic regime at a high gas temperature.

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1. PHYSICO-MATHEMATICAL MODELING

The use of plasma processes to activate the combustion of pulverized coal dictates the need to clarify the patterns of coal combustion in a high-temperature gaseous oxidant. The fuel used for combustion in power plants has a polydisperse composition. The particle size and their concentration in the gas suspension affect the heat and mass exchange rate with the oxidant gas and the plant walls [1].

Two fraction dust-air mixture is a simplest case of polydisperse suspension. So the purpose of this work is to study the characteristics of ignition and combustion of a two-fraction suspension of carbon particles in air at different temperatures. The main characteristics of fuels combustion are the ignition delay (induction period), the burning temperature and time, critical parameters (temperature, the particles diameters and mass concentrations), corresponding to fuel ignition and extinction.

The physico-mathematical model of high-temperature heat and mass transfer of carbon particles-gas suspension includes the differential equations of thermal and mass balances for the particles of each fraction and the corresponding equations for oxidizing gas [2, 3].

When particles hit a heated oxidizer, chemical reactions begin to occur on their surfaces and in the pores, as a result of which, the particles ignite and burn.

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The total density of chemical heat release for a particle of the i -th fraction as a result of surface and internal reaction with two parallel reactions ($C+O_2=CO_2$ (I), $2C+O_2=2CO$ (II)), we find from the expression [2]:

$$q_{chi} = (k_{1i}q_1 + k_{2i}q_2)\rho_g n_{O_2,si} (1 + K_i), \quad K_i = \frac{k_{vi}}{k_{1i} + k_{2i}} \quad (1),$$

q_{chi} – the total density of chemical heat release at the surface and in the pores of the particle, k_{1i} , k_{2i} – the rate constants of chemical reactions (I) and (II), q_1, q_2 – thermal effects of chemical reactions (I) and (II), ρ_g – gas density, $n_{O_2,si}$ – the relative mass concentration of oxygen on the surface of the carbon particle, K_i – the ratio of the constants of the internal and surface responses, k_{vi} – effective internal reaction constant [3].

In the combustion chamber, molecular-convective ($q_{\alpha i}$) and radiant heat exchange (q_{wi}) of particles with heated gas and with walls of the reaction volume occurs. The densities of these flows can be found from the equations:

$$q_{\alpha i} = q_{\lambda i} + q_{sfi}, \quad q_{\lambda i} = \alpha_i(T_i - T_g), \quad (2)$$

$$\alpha_i = \frac{Nu\lambda_g}{d_i}.$$

$$q_{wi} = \varepsilon \sigma (T_i^4 - T_w^4). \quad (3)$$

Where $q_{\lambda i}$ – is the component of the heat flux density due to molecular-convective heat transfer, q_{sfi} – component of the heat flux density due to the Stefan flow [4], α_i – coefficient of heat exchange of a particle with a gas, T_i, T_g, T_w – respectively, the temperature of the particle, gas and walls of the reaction chamber, λ_g – coefficient of thermal conductivity of gas, d_i – particle diameter.

Let us write the heat and mass balance equations for a particle of the i -th fraction:

$$\frac{c\rho_i d_i}{6} \frac{\partial T_i}{\partial t} = q_{chi} - q_{\alpha i} - q_{wi}, \quad T_i(t=0) = T_{ib}, \quad (4)$$

$$-\frac{1}{2} \rho_i \frac{\partial (d_i)}{\partial t} = W_{s_i}, \quad W_{s_i} = \frac{M_C}{M_{O_2}} (k_{1i} + 2k_{2i}) n_{O_2, s_i} \rho_g, \quad d_i(t=0) = d_{b_i}, \quad (5)$$

$$-\frac{1}{6} d_i \frac{\partial (\rho_i)}{\partial t} = W_{s_i} K_i, \quad \rho_i(t=0) = \rho_{b_i}. \quad (6)$$

Here c – specific heat of the particle; ρ_i – particle density; t – time; M_C, M_{O_2} – molar masses of carbon and oxygen, respectively.

When burning pulverized coal suspended in the reaction volume, over time, the temperature of the gas and the concentration of oxygen change. Equations of heat and mass balances for gas with allowance for external heat and mass transfer have the form:

$$c_g \rho_g \frac{\partial T_g}{\partial t} = \sum_{i=1}^n S_i C_{N_i} q_{\alpha i} + \alpha_g F_g (T_g - T_{g\infty}), \quad (7)$$

$$T_g(t=0) = T_{g\infty},$$

$$-\frac{\partial n_{O_2, g}}{\partial t} = \sum_{i=1}^n C_{N_i} S_i n_{O_2, s_i} (k_{1i} + k_{2i} + k_{3i}) - F_g \beta_g (n_{O_2, \infty} - n_{O_2, g}), \quad (8)$$

$$n_{O_2, g}(t=0) = n_{O_2, \infty},$$

where c_g – the specific heat of the gas; S_i – the surface area of the particle; F_g – the specific surface of the gas suspension; $n_{O_2, g}$ – the relative mass concentration of oxygen in the gas; $\alpha_g \cdot \beta_g$ – the coefficients of heat exchange and mass transfer of the gas suspension with the surrounding medium; C_{N_i} – the numerical concentration of particles of the i -th fraction, which is related to the mass concentration of carbon fuel relationship:

$$C_{m_i} = \frac{1}{6} \pi \cdot d_i^3 \cdot \rho_i \cdot C_{N_i}, \quad C_m = \sum_{i=1}^n C_{m_i}.$$

2. CALCULATION RESULTS AND DISCUSSION

Let us calculate the ignition and combustion of a two-fraction gas suspension of carbon particles with particle diameters that differ by several times and equal to the mass concentrations of the fractions.

Fig. 1 shows the time dependences of the temperatures and particle diameters of each of the fractions, the gas temperature in the combustion of a slurry with initial particle diameters: $d_{b1} = 60 \mu\text{m}$ (fine fraction) and $d_{b2} = 120 \mu\text{m}$ (coarse fraction) for different initial gas temperatures. The initial mass concentration of carbon fuel in the gas suspension was $C_{mb} = 0.016 \text{ kg/m}^3$, the mass concentrations of each fraction were: $C_{mb1} = C_{mb2} = 0.008 \text{ kg/m}^3$. The gas suspension data are loose and are characterized by an excess oxygen factor of 1.5.

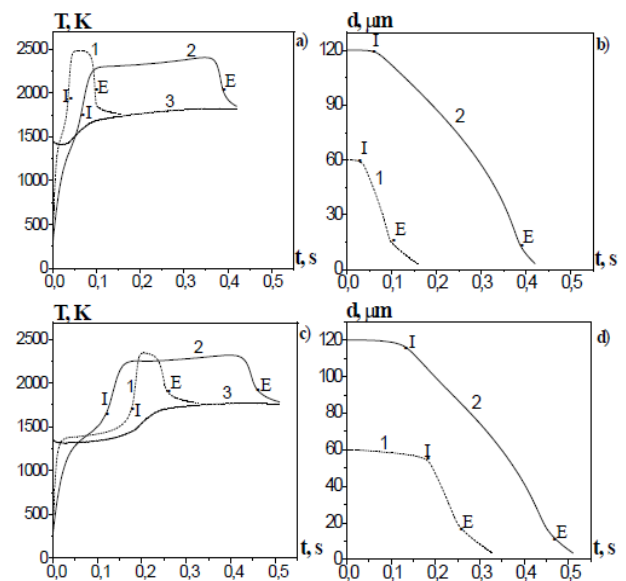


Fig. 1. Dependences of T, T_g, d on time. a, b:

$$T_{g\infty} = T_w = 1450 \text{ K}; \quad c, d \quad T_{g\infty} = T_w = 1350 \text{ K}.$$

$$1 - d_{b1} = 60 \mu\text{m}; \quad 2 - d_{b2} = 120 \mu\text{m};$$

$$3 - \text{gas temperature } T_g$$

The points I and E in (see Fig. 1) characterize, respectively, the moments of ignition and extinction of the particles. The time from the start of warming up to point I determines the period of induction (t_{ind}), and from point I to point E – the burning time (t_{bur}) of the particles. The diameter of the particles in the combustion stage (see Fig. 1, b, d) decreases rapidly until the moment of extinction (p.E). At this point, there is a decrease in the rates of chemical reactions on the surface of the carbon particles, which is characterized by a fracture in the dependences $d(t)$. As follows from the figures, after the moment of extinction, the particle diameter continues to decrease, but at a slower rate. Oxidation of the particle takes place in the kinetic regime. Consequently, in contrast to single particles, the attenuation of the particles of a gas suspension is degenerate. Analysis of the dependences $d(t)$ makes it

possible to determine the time of the complete transformation of the particles.

Analysis of the temperature curves shows that at a high gas temperature, ignition and burnup of the fine fraction first occurs (see Fig. 1,a,b). Particles of coarse fraction ignite shortly before the extinction of fine particles. During the burnout of the fine fraction, the oxygen concentration decreases substantially, so that combustion and subsequent combustion of the coarse fraction occur at low values. At a lower gas temperature (Fig. 1,c,d), larger particles ignite earlier (curves 2). According to formulas (2), fine particles have a higher heat transfer coefficient α , which leads to an increase in the heat flux density q_a . Therefore, the increase in the ignition time of the fine fraction in comparison with the coarse fraction is explained by the increase in the heat flux from particles of small dimensions with a decrease in the gas temperature. In this case, the time of the chemical component of the induction period greatly increases [5].

At a certain critical gas temperature (ignition temperature) T_{cr} (Fig. 2), the gas suspension is not ignited. The critical ignition temperature of a two-fraction gas suspension is significantly lower than the ignition temperature of single particles of the same diameter. Moreover, the critical ignition temperatures for single large and small particles are significantly different, and under conditions of a two-fraction gas suspension practically coincide.

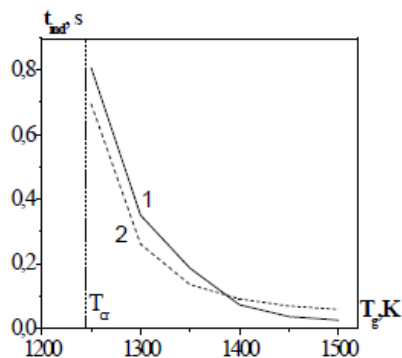


Fig. 2. Dependences of the induction period of the gas suspension from the initial gas temperature: 1 – $d_{b1}=60 \mu\text{m}$; 2 – $d_{b2}=120 \mu\text{m}$

Let us analyze the burning characteristics of a two-fraction gas suspension. It can be seen from Fig. 3,a that the burning time of the fine and coarse fractions of the gas suspension depends only slightly on the temperature of the gas. The burning time of the coarse fraction is almost 4 times that of the fine fraction with a ratio of their initial diameters $d_{b1}/d_{b2}=2$. This indicates that the combustion of particles under gas-suspension conditions occurs in the diffusion regime.

The combustion temperature of fine particles in the region of low gas temperatures is less than the burning temperature of large particles (see Fig. 3,b). This is due to two reasons: a large heat loss to the gas by a molecular-convective route and a lack of an oxidizer at the stage of burning of small particles. A significant decrease in the concentration of the oxidant occurs as a

result of its intensive consumption by burning large particles that ignited earlier (see Fig. 1,c).

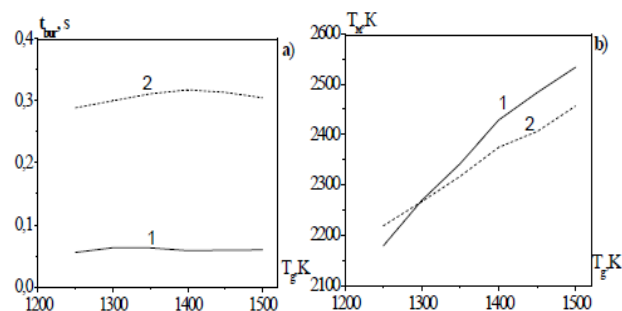


Fig. 3. Dependences of the burning time (a) and the maximum burning temperature (b) of the particles on the gas temperature: 1 – $d_{b1}=60 \mu\text{m}$; 2 – $d_{b2}=120 \mu\text{m}$

CONCLUSIONS

It has been established that at gas temperatures above 1400 K, the ignition delay time (induction period) of a two-fraction gas suspension is determined by the ignition time of the fine fraction, below this value by the ignition time of the coarse fraction. For example, for a gas temperature of 1500 K, the induction period of fine particles (fraction of 60 μm) is half the time of induction of large particles (fraction of 120 μm). At gas temperatures below 1400 K, the induction period of the fine fraction is larger than that of the large fraction, and this difference increases with decreasing gas temperature. This is due to the increase in heat loss by molecular convection to the surrounding gas environment for the fine fraction.

The ignition temperatures of the two-fraction gases are found. The critical temperature of ignition of particles in the gas suspension is significantly lower than for single particles of the same diameter. The lowering of the ignition temperature of the gas suspension is due to the heating of the gas due to the heat of chemical reactions during the oxidation of the aggregate of particles. Moreover, for large and small single carbon particles, the critical gas temperatures differ substantially, and under conditions of a two-fraction gas suspension, they practically coincide.

The temperature range of the ambient gas and the walls of the reaction unit is determined, for which the combustion temperature of the fine particles is less than that of the coarse fraction of the gas suspension. So for gas temperatures above 1300 K, the combustion of the fine fraction occurs at higher temperatures. It is found that for a gas temperature of 1500 K, the combustion temperature of fine particles is more than 200 degrees higher than the burning temperature of large particles of a gas suspension. Unlike single particles, the gas-suspension damping proceeds in a degenerate regime, since the temperature difference between the particles and the gas is small. In this case, the oxidation of particles of the gas suspension takes place in the kinetic regime, which makes it possible to estimate the time of their complete conversion.

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ОСОБЕННОСТИ ВОСПЛАМЕНЕНИЯ И ГОРЕНИЯ ДВУХКОМПОНЕНТНОЙ ГАЗОВЗВЕСИ УГЛЕРОДНЫХ ЧАСТИЦ

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Проведено физико-математическое моделирование высокотемпературного теплообмена и кинетики горения двухфракционной газовой взвеси углеродных частиц при различных температурах газа. Предполагалось, что на поверхности углеродных частиц протекают две параллельные химические реакции: $C+O_2=CO_2$ (I), $2C+O_2=2CO$ (II). Учитывался молекулярно-конвективный теплообмен частиц с газом, а также теплообмен излучения со стенками реакционной установки. В результате проведенного численного эксперимента определены характеристики воспламенения и горения частиц газовой взвеси в воздухе при различных температурах окружающего газа. Для расчетов выбиралась двухфракционная газовая взвесь с равными массовыми концентрациями фракций и диаметрами частиц, которые отличаются в 2 раза: $d_{b1}=60$ мкм, $d_{b2}=120$ мкм. Диапазон исследуемых начальных температур газа 1100...1500 К. В результате проведенных расчетов установлено, что при уменьшении температуры газа частицы крупной фракции могут воспламеняться раньше, чем частицы мелкой фракции. При высоких температурах газа наоборот: период индукции мелких частиц значительно превышает период индукции частиц крупной фракции. Найдены критические параметры воспламенения двухфракционных газовой взвесей. Основными характеристиками горения являются время и температура горения частиц. Доказано, что в условиях двухфракционной газовой взвеси время горения частиц слабо зависит от температуры газа. Также установлено, что в области низких температур газа температура горения частиц мелкой фракции меньше, чем крупной. Это объясняется большим теплоотводом от мелких частиц молекулярно-конвективным путем и недостатком окислителя на стадии горения. Кислород расходуется при горении крупных частиц, которые при низких температурах воспламеняются раньше. Найдены времена горения частиц крупной и мелкой фракций газовой взвеси.

ОСОБЛИВОСТІ ЗАЙМАННЯ ТА ГОРІННЯ ДВОКОМПОНЕНТНОГО ГАЗОЗАВИСУ ВУГЛЕЦЕВИХ ЧАСТИНОК

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Проведено фізико-математичне моделювання високотемпературного теплообміну та кінетики горіння двофракційного газозавису вуглецевих частинок при різних температурах газу. Передбачалося, що на поверхні вуглецевих частинок протікають дві паралельні хімічні реакції: $C+O_2=CO_2$ (I), $2C+O_2=2CO$ (II). Враховувався молекулярно-конвективний теплообмін частинок з газом, а також теплообмін випромінювання зі стінками реакційної установки. В результаті проведенного чисельного експерименту визначені характеристики займання і горіння частинок газозавису в повітрі при різних температурах навколишнього газу. Для розрахунків вибирався двофракційний газозавис з рівними масовими концентраціями фракцій і діаметрами частинок, які відрізняються в 2 рази $d_{b1} = 60$ мкм, $d_{b2} = 120$ мкм. Діапазон досліджуваних початкових температур газу 1100...1500 К. В результаті проведених розрахунків встановлено, що при зменшенні температури газу частинки великої фракції можуть займатися раніше, ніж частинки дрібної фракції. При високих температурах газу навпаки: період індукції дрібних частинок значно перевищує період індукції частинок великої фракції. Знайдено критичні параметри займання двофракційного газозавису. Основними характеристиками горіння є час і температура горіння частинок. Доведено, що в умовах двофракційного газозавису час горіння частинок мало залежить від температури газу. Також встановлено, що в області низьких температур газу температура горіння частинок дрібної фракції менше, ніж великої. Це пояснюється великим тепловідводом від дрібних частинок молекулярно-конвективним шляхом і недостатком окислювача на стадії горіння. Кисень витрачається на горіння великих частинок, які при низьких температурах спалахують раніше. Знайдено часи горіння частинок великої і дрібної фракцій газозавису.