Influence of gas temperature on ignition, burning and extinction of carbon particles-gas suspension

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Abstract. The ignition and burning of monodisperse and two-fraction suspensions of carbon particles at gas temperature in the range 1100 ÷ 1500 K are modeled. The critical gas temperature of the suspension ignition, the particles ignition delay and burning time, the burning temperature, and the extinction parameters are determined. The data obtained are compared with burning characteristics of single particle of equal size. The ignition temperatures of the fine fraction (the particle diameter 60 μm) and the coarse one (120 μm) are practically the same. The ignition temperatures of the equivalent single particles are much higher and they differ by 100 K and more. The gas temperature is found below which the ignition delay of the fine fraction exceeds the one of the coarse fraction. It is found that, at critical ignition temperatures the burning temperature of the fine fraction is lower than that of the coarse fraction. At gas temperatures above 1250 K, the burning temperature of the fine fraction is higher. It is established that, in contrast to single particles, the temperature difference between the particles and the gas is small during gas-suspension extinction. Further oxidation of the particles occurs in the kinetic regime, so it is possible to estimate the time of their complete conversion.

1. Introduction
The search for optimal operating conditions of carbon fuels combustion requires detailed experimental and theoretical studies of heat and mass transfer and chemical transformations of carbon particles [1]. There is a lack of published information on high-temperature heat and mass transfer of polydisperse carbon dust. The simplest case of a polydisperse suspension is a two-fraction one. The purpose of this work is to study the characteristics of the ignition, burning, and extinction of two-fraction carbon dust over a wide range of gas temperatures for different values of mass concentrations.

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 [1, 2]. We consider the high-temperature heat and mass transfer and the kinetics of the chemical transformation of a two-fraction particles-gas suspension with equal mass concentrations of the fractions and two-fold difference in particle size.

2. Calculation results and discussion
Figure 1 shows the particle diameters and temperatures histories of both fractions, the gas temperature, time derivative of the particles temperature, the oxygen content in the gas during combustion of a two-
fraction suspension with particle diameters: fine fraction $d_{b1} = 60 \, \mu m$, coarse fraction $d_{b2} = 120 \, \mu m$. These dependencies are calculated at a high gas temperature of $T_g = 1500 \, K$. For the initial fuel mass concentration $Cmb = 0.0244 \, kg/m^3$, the mass concentration of each fraction is $Cmb_1 = Cmb_2 = 0.0122 \, kg/m^3$; The countable concentration of the fine particles is $C_{N1} = 7.5 \times 10^7$, the large concentration is $C_{N2} = 9.3 \times 10^6$. This mass concentration corresponds to a stoichiometric air-fuel ratio $A/F = 1$ [2,3].

Extremes on the dependences $dT/\, dt$ allow to determine the ignition time (Point I) and the extinction (Point E) of the particles and to find the ignition delay and the burning time, respectively.

The analysis of the temperature and kinetic curves shows that, at high gas temperature, first ignition and burning of the fine fraction occurs. Particles of coarse fraction ignite shortly before the moment of extinction of fine particles. During the combustion of the fine fraction, the oxygen concentration decreases substantially, so the ignition and burning of the coarse particles occurs at low oxygen content (Figure 1, d).

![Figure 1](image)

**Figure 1.** Dependencies $T$, $T_g$, $dT/\, dt$, $d$, $n_{O_2,g}$ versus time for two-fraction gas suspension at $T_{gw} = T_w = 1500 \, K$. 1 - $d_{b1} = 60 \, \mu m$, 2 - $d_{b2} = 120 \, \mu m$, 3 - gas temperature $T_g$. $Cmb = 0.0244 \, kg/m^3$. 
Let’s consider the influence of the gas temperature on the burning and extinction characteristics of two-fraction suspension (Figure 2). It is shown on Figure 2, that the ignition delays of the fine and coarse fractions converge when the gas temperature decreases, and at \( T_g < 1400 \text{K} \) the coarse particles ignite faster than the fine ones. The increase in fine particles ignition delay compared to the coarse one at \( T_g < 1400 \text{K} \) is result of the increase of the small particles heat loss due to the high heat transfer coefficient. As a result, the chemical stage of the ignition delays increases, during which the gas temperature rises up to value necessary for the ignition of fine particles. Thus, over high-temperature range, the ignition delay of a two-fraction particles-gas suspension is determined by the ignition delay of small particles, and in the low-temperature range by the ignition delay of the coarse particles.

**Figure 2.** The ignition delay (\( t_{\text{ind}} \)), the burning time (\( t_{\text{bur}} \)), the diameter of extinction (\( d_E \)) and the maximum temperature (\( T_{\text{m}} \)) versus the gas temperature (\( T_g \)) for a two-fraction suspension (curves 1\( ' - \bullet \bullet \bullet \bullet \), \( d_{b1} = 60 \mu\text{m}, \) 2\( ' - \triangle \triangle \triangle \), \( d_{b2} = 120 \mu\text{m}, \) \( Cmb = 0.0244 \text{kg/m}^3 \)) and a single particle (curves 1\( - \circ \circ \circ \circ \), \( d_b = 60 \mu\text{m}, \) 2\( - \bigtriangleup \bigtriangleup \bigtriangleup \), \( d_b = 120 \mu\text{m} \)).
At the critical value of gas temperature $T_{cr}$ (Figure 2, a), the particles-gas suspension doesn’t ignite (the ignition delay is too long). It can be seen on Figure 2,a, that the critical ignition temperature of the two-fraction suspension is significantly lower than that of equal size single particle. Moreover, the ignition temperatures of single large ($T_{cr2}$) and fine ($T_{cr1}$) particles significantly differ, and they coincide in the two-fraction particles-gas suspension.

The combustion and extinction characteristics of the two-fraction particles-gas suspension and of a single particle are presented on Figure 2 b, c, d at different initial gas temperatures.

It is shown on Figure 2, b that the burning times of the fine and coarse particles in the suspension depend weakly on the gas temperature. The burning time of the coarse fraction exceeds about 4.5 times the burning time of the fine fraction, when the initial diameters differ by two times. The burning times of equivalent single particles are approximately 2 times less in comparison with suspension due to the oxygen excess.

The plot of dependence of the damping diameters of single particles and gas-suspension particles on the temperature of the surrounding gas Figure 2, c. Unlike single particles, the attenuation of particles of a gas suspension (point E, Figure 1, a, b, c) occurs in a degenerate regime, since at the final stage of combustion the temperature of particles and gas differ insignificantly. When the particle diameter reaches the value $d_E$ (Figure 1, b), the oxidation rate decreases slightly. After the moment of extinction, the particles are oxidized in the kinetic regime.

It follows from Figure 2, c that for a single particle the critical diameter $d_E$ characterizing the extinction does not depend on the initial diameter. Under gas-suspension conditions, critical diameters $d_E$ of coarse and fine fractions are different, since the extinction of fractions occurs at different gas temperatures (Figure 1, a). Large particles decay at a higher gas temperature and are characterized by a smaller damping diameter, compared to fine particles.

Let us consider the dependence of the burning temperature of carbon particles at various temperatures of the surrounding gas (Figure 2, d). The maximum burning temperature of single particles does not depend on their initial diameter, while the maximum combustion temperatures of the particles of coarse and fine fractions differ substantially. This difference increases in the region of high gas temperatures. In the region of low gas temperatures, the combustion temperature of the fine particles is smaller than the large one because of the larger heat dissipation and the lack of oxidizer in the combustion stage. Oxygen is consumed by burning large particles that ignite at low temperatures before.

Let us analyze the effect of the initial mass concentration of the gas suspension on the induction period and the completeness of combustion of the fuel at the moment of extinction. We reduce the initial mass concentration of fuel to $C_{mb} = 0.0016$ kg / m$^3$, which corresponds to an excess of oxygen in the air of 1.5 [3]. It follows from Figure 3, b a that an increase in the oxidizer excess factor by 50% slightly reduces the induction period of the two-fraction gas suspension. At the same time, the critical diameters of the extinction of particles of both fractions increase by 20-30%, especially at low temperatures. For a less dense gas suspension in the temperature range $T_{g} > 1350$ K, the mass concentration of unburnt fuel at the moment of extinction is approximately 50% lower than for a dense gas suspension (Figure 3, b). In the low-temperature region, the opposite effect is observed: the concentration of unburned fuel for a less dense gas suspension increases due to a stronger growth of the damping diameters.
**Figure 3.** Influence of initial mass concentration on induction period ($t_{ind}$) and mass concentration at the moment of extinction ($C_{mE}$) on gas temperature ($T_g$) for a two-fraction gas suspension. 1 – $C_{mb} = 0.016$ kg/m$^3$, 2 – $C_{mb} = 0.0244$ kg/m$^3$.

**Conclusions**

Thus, it has been established that at high gas temperatures, the induction period of the fine fraction is smaller than that of the large fraction, and vice versa at low temperatures, which is caused by the growth of molecular-convective heat losses to the surrounding gas medium for the fine fraction. It is shown that the ignition temperatures of small and large particles under conditions of a two-fraction gas suspension practically coincide, and for single particles of the same diameters differ substantially. It is proved that, at high initial gas temperatures, less dense gases are characterized by a larger damping diameter, but a smaller mass concentration of fuel that has not burnt down to the moment of extinction. In the temperature range close to the critical value, on the contrary - the completeness of combustion of dense gases is greater.

**References**

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