A Numerical Analysis of Single Char Particle Heated by a Laser

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An unsteady state boundary layer model was developed in order to analyse the combustion of single char particles in radiation fields. The model is based on the following assumptions, a spherical char particle with small diameter is combusted at atmospheric pressure, the temperature difference between the surface and the inside of the particle is negligible, particle diameter shrinks due to the reaction on the char surface, the surrounding gas is stagnant, but Stefan flow is taken into consideration and bulk gas flow is neglected. The model predicts the particle temperature increase and the distributions of gas temperature and gas components in the boundary layer. The computed distribution of gas component proves clearly that the reaction rate is mainly controlled by oxygen diffusion in the boundary layer except during the initial heating and reaction. Using the simulation model, the effects of particle size, oxygen content in bulk gas and input laser power is discussed. The results predict that smaller particles heat up faster in initial heating and higher laser input has the same effect. Further, it is shown that a higher oxygen content raises the sustained combustion temperature and shortens the combustion period.

KEY WORDS: char; laser; combustion; simulation model.

1. Introduction

Pulverized coal combustion comprises two overlapping processes namely the decomposition and combustion of volatile matter, and the combustion of char. Though these two processes affect each other, they need to be investigated separately for analysing the reaction in combustion processes and for developing combustion technology of pulverized coal. Zhang *et al.*¹⁾ proposed ignition mechanisms where the precedence of ignition between heterogeneous reaction on particle surface and homogeneous reaction in gas phase depends on the volatile matter content. In practical combustion processes, according to Lassat de Pressigny *et al.*,²⁾ char combustion begins after exhaustion of volatile matter and maintains for much longer duration in blast furnace coal injection processes. Thus, in the context of effective combustion, it is clear that char particle combustion is the most important process.

We have already developed a new device for rapid heating using CO₂ laser in order to examine coal combustion without any influence of volatile combustion. The temperature increase of coal particles has been examined.³⁾ In this work, a new simulation model is developed based on the experiments to describe the char combustion process and the effects of several operational parameters by referring to the experimental results of coal combustion.

Although the mathematical combustion model of single carbon particles has been studied since 1920's, little is

known about the unsteady state of the process. In recent years, there has been a renewal of interest in the unsteady state combustion model with a boundary layer which can be described in terms of the distribution change of gas contents, gas temperature and particle temperature.

The first model^{4–6)} is based on an energy balance on the particle surface and considers the combustion as time proceeds. By the simple models, the analytical solutions for particle temperature are given as a function of time. But the models do not consider the distribution of gas temperature and composition around a particle. Both the heterogeneous reaction on particle surface and the homogeneous reaction in gas phase surrounding a particle were coupled for analysis of the combustion in steady state or quasi-steady state^{7–11)} with boundary layers. In order to simplify the analysis of surrounding gas phase, a single film model and a double film were proposed for small particles and large particles, respectively.

In the rate control process in combustion, generally diffusion of gas is dominant at higher temperatures and chemical reaction is dominant at lower temperatures.¹²⁾ In the complicated combustion phenomena which occur when pulverized coal and char are blown into a high temperature radiation field, the particle size, its physical properties, the gas temperature and gas composition all change with time. Steady state models or quasi-steady state models are useless for analysing the rate control process.

Recently an unsteady state combustion model has been

developed by Ösüm *et al.*¹³⁾ In this model, the surrounding gas space is divided into small control volumes. Mass transfer, heat transfer and chemical reactions are balanced over small time periods. The solutions are obtained by numerical analysis. Although the analysis requires long time even by high speed computers, it is very important to understand the functions of gas composition and temperature distribution in detail. The model is based on experimental results of pulverized coal combustion in an entrained flow reactor by Waters *et al.*¹⁴⁾ and proved that the effect of the CO combustion to CO₂ in gas phase on particle temperature should not be ignored. Using a similar method, Yamamoto *et al.*¹⁵⁾ analysed N₂O synthesis and its decomposition during single coal particle combustion.

In results computed from the unsteady state models, some oxygen remains unreacted near the particle surface. This contradicts experimental results which show that the combustion is diffusion controlled at high temperature.¹⁶⁾ Unsteady state model must be refined further and evaluated against the results from experiments using controlled combustion technique and measurement systems.

More recently, laser heating techniques are employed to investigate the combustion process.¹⁷⁻¹⁹⁾ Using this technique, a substantial amount of understanding on the complicated phenomena of coal combustion has been achieved. In this work, an unsteady state boundary layer simulation model of a single char particle heated by CO₂ laser is developed and the effect of particle size, radiation intensity and oxygen content of surrounding gas is discussed.

2. Mathematical Model

2.1. Outline of the Model

The model is illustrated in Fig. 1. A single char particle is heated externally by a laser beam. Three chemical reactions in Table 1 are considered in this model. Char is exhausted by the heterogeneous reactions shown in (1) and (2) on the particle surface. The homogeneous reaction shown in (3) produces CO₂ in the gas phase of the boundary layer.

The symbols β_i , M_i , V_j in Eq. (3), introduced to match the dimensions with those of (1) and (2), are explained in the nomenclature.

Fig. 1. Schematic representation of single particle combustion model.

Table 1. Chemical reactions and their kinetic data.

Reaction	Kinetic data (kg/s)
$2C + O_2 = 2CO$	$R_1 = 87100 \exp(-17976/T_p) P_{O_2} S$ $T_p \leq 1650 \text{ K}^{20)}$ $R_1 = (3.85 \times 10^{-3} T_p - 4.9) P_{O_2} S$ $T_p > 1650 \text{ K}$ (1)
$C + CO_2 = 2CO$	$R_2 = 6 \times 10^{11} T_p^{-1} \exp(-29794/T_p) P_{CO_2} S^{71})$ (2)
$2CO + O_2 = 2CO_2$	$R_{3i} = 8.3 \times 10^9 \exp(-1303/T_g) C_{O_2} C_{CO} \beta_i M_i V_j^{21})$ (3)

The model assumes; ① spherical single particles, ② temperature difference between the surface and the inside of particle is negligible as the sample's diameter is small, ③ solid carbon reacts only on the surface, the particle shrinks uniformly, and an reacted shell of ash is leftover, ④ atmospheric pressure, ⑤ Stefan flow occurs in a stagnant gas mixture of nitrogen and oxygen.

2.2. Equations in the Model

Under the assumptions, equation of state (4), continuity equation (5), mass and energy conservation for solid particle ((6) and (7)), mass and energy conservation in a gas phase ((8) and (9)) are given in control volume j . These equation can be solved simultaneously by numerical computation.

$$\rho_g = \frac{P\bar{M}}{RT_g} \quad \text{.....(4)}$$

$$\frac{\partial \rho_g}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \varphi) = 0 \quad \text{.....(5)}$$

$$-\frac{d(\rho_p V_p)}{dt} = R_1 + R_2 \quad \text{.....(6)}$$

$$\frac{d}{dt} (\rho_p V_p C_p T_p) = \frac{1}{4} \alpha Q_L S - Q_N - Q_{rs} + \xi(Q_1 + Q_2) \dots \text{.....(7)}$$

$$\frac{\partial}{\partial t} (\rho_g Y_i) + \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \varphi Y_i) = \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 D_i \rho_g \frac{\partial Y_i}{\partial r} \right) + R_{3i} \quad \text{.....(8)}$$

$$\frac{\partial}{\partial t} (\rho_g C_p T_g) + \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \varphi C_p T_g) = \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \lambda \frac{\partial T_g}{\partial r} \right) + Q_3 + Q_d + Q_{rg} + (1 - \xi)(Q_1 + Q_2) \quad \text{.....(9)}$$

where Q_L is input laser energy, Q_1 , Q_2 and Q_3 are the heats of Reactions (1), (2) and (3), respectively. The proposed distribution laws of the surface reaction heat depend on the quoted reactor models; the heat is given only to the particle²²⁾ or divided between particle and gas phase according to some distribution law.²³⁻²⁵⁾ The heat is defined here to be apportioned equally between the particle and the gas phase as in Luo *et al.*²⁵⁾ Q_N is the heat conductivity given in Eq. (11). Q_{rs} is the total radiation energy on the particle surface calculated by Eq. (12) where input radiation from CO₂ gas is taken into account. Q_d is the heat resulting from molecular diffusion of each gas components and is given by Eq. (13). Q_{rg} is the change of radiation energy in a control volume j given by Eq. (14).

$$\varphi = \rho_g v \quad \dots\dots\dots(10)$$

$$Q_N = h(T_p - T_g)S \quad \dots\dots\dots(11)$$

$$Q_{rs} = \varepsilon_p \sigma (T_p^4 - T_0^4) S - \sum_j \left[\varepsilon_p \varepsilon_{gj} \sigma T_{gj}^4 S \prod_{\delta} (1 - \varepsilon_{\delta}) \right] \quad \dots\dots(12)$$

$$Q_d = \sum_i \left\{ \left[S_v \rho_g D_i \frac{\partial Y_i}{\partial r} \int_{T_0}^T C_{p_{gi}} dT \right]_{j+dr/2} - \left[S_v \rho_g D_i \frac{\partial Y_i}{\partial r} \int_{T_0}^T C_{p_{gi}} dT \right]_{j-dr/2} \right\} \quad \dots\dots(13)$$

$$Q_{rg} = \frac{\sigma}{V_j} \left\{ \varepsilon_g \varepsilon_p S (T_p^4 - T_0^4) \prod_{\delta} (1 - \varepsilon_{\delta}) - 2 \varepsilon_g S_v T_g^4 + \sum_k \left[\varepsilon_g \varepsilon_{gk} S_{vk} T_{gk}^4 \prod_{\delta} (1 - \varepsilon_{\delta}) \right] \right\} \quad \dots\dots\dots(14)$$

where ε_g is emissivity of CO_2 gas derived from Hottel's chart.²⁴⁾ Other symbols are listed in the nomenclature.

Boundary conditions are derived from the assumption that the composition and temperature of gas is uniform outside the N control volumes. N indicates the boundary layer thickness and the thickness depends on the gas velocity around the particle. In order to examine impact of the thickness, simulation was carried out for different boundary layer thicknesses. The results show the nature of the curves of gas temperature and gas components do not change significantly, but for minor changes in the gradient. In this simulation, we resulted the thickness of 1.4 mm as the most appropriate from the experimental system.³⁾

The boundary conditions are follows;

$$T_g = T_0 = \text{const.} \quad \text{in } j > N \quad \dots\dots\dots(15)$$

$$\frac{\partial Y_i}{\partial r} = 0 \quad \text{in } j > N \quad \dots\dots\dots(16)$$

The initial conditions are follows;

$$T_p = T_g = T_0 \quad \text{at } t = 0 \quad \dots\dots\dots(17)$$

$$Y_{ij} = Y_{i0} \quad \text{at } t = 0 \quad \dots\dots\dots(18)$$

The equations were solved numerically by Thomas's exponential method after making differential equations by implicit method. A super computer (HITAC S-3800/380) was used for the highly non-linear problem to get numerical solutions. The significant parameters used in the calculation are shown in Table 2.

3. Results and Discussion

3.1. Combustion Process and Simulation Model Predictions

Figure 2 shows the simulated profiles of the temperatures and gas components in the control volume adjacent to the particle surface, namely, at the distance of 0.05 mm from the surface. In this computation, we have used 1.85 W/mm² laser input, 21 % oxygen content of initial surrounding and bulk gas, and 0.2 mm particle diameter.

In Fig. 2 particle temperature T_p increases with laser heating at first and gas temperature T_g follows up gradually due to radiation from the particle surface.

Table 2. Physical data used in the calculations.

$T_{p(t=0)} = 298 \text{ (K)}$	$T_{g(t=0)} = 298 \text{ (K)}$
$\alpha = 0.95$	$\varepsilon_p = 0.95$
$\rho_p = 1060 \text{ (kg/m}^3\text{)}$	$\xi = 0.5$
$\sigma = 5.669 \times 10^{-8} \text{ (W/m}^2 \cdot \text{K}^4\text{)}$	
$C_{p_p} = 837 + 1.482(T - 273) - 4.4 \times 10^{-4}(T - 273)^2 \text{ (J/kg} \cdot \text{K)}$	
$C_{p_{\text{CO}_2}} = 44.14 + 9.04 \times 10^{-3}T - 8.54 \times 10^{-5}T^{-2} \text{ (J/mol} \cdot \text{K)}$	
$C_{p_{\text{O}_2}} = 30 + 4.2 \times 10^{-3}T - 1.7 \times 10^{-5}T^{-2} \text{ (J/mol} \cdot \text{K)}$	
$C_{p_{\text{CO}}} = 28.4 + 4.1 \times 10^{-3}T - 0.46 \times 10^{-5}T^{-2} \text{ (J/mol} \cdot \text{K)}$

Fig. 2. Simulation results on the change of temperature and gas contents. T_g and gas contents are at 0.05 mm from the particle surface.

Approximately 200 ms later, the temperature increases rapidly due to the acceleration of chemical reactions and an inflection is observed on the temperature curve. The particle burnt out after a stable state from 260 to 560 ms and the temperature reduced to that of the resultant ash.

The configuration of char particle temperature curve in Fig. 2 is similar to that of experimental temperature curve in Fig. 3, however the experiment was performed with several carbon particles.³⁾ In our previous work, we reported that it is more convenient to analyse the carbon particle combustion by dividing the process into three stages along the heating curves as shown in Fig. 3. The simulated particle temperature curve reinforces that observation. The part before the point of inflection is the 'initial heating stage', the stable temperature part is the 'sustained combustion stage' and the intermediate portion containing the ignition point is the 'ignition stage'. Henceforth, we will refer to these three parts in Fig. 3 to explain combustion process.

In the gas phase, the gas temperature T_g at 0.05 mm from the surface is lower than the particle temperature T_p at the beginning. T_g goes up rapidly with increasing T_p and rises higher than T_p in the sustained combustion

Fig. 3. Typical experimental temperature curves of carbon particles and separated combustion stages. I is initial heating stage, II is ignition stage and III is sustained combustion stage. (Laser input = 2.59 W/mm², D_p = 0.2 mm, 20 particles, O₂ = 50 %)

stage. Accumulated oxygen content decreases with increase of particle temperature. It is obvious that the oxygen diffusion from bulk gas is slower than the oxygen consumption on the surface shown in Eq. (1). In the sustained combustion stage, the oxygen content falls to 10^{-4} . To the best of our knowledge, to date, this result has not been obtained. On the other hand CO content rises as oxygen content falls. At the same time, CO₂ increases drastically and then takes a small dip because of insufficient oxygen supply. It is clear that surrounding oxygen is consumed rapidly at the beginning by Eq. (1) and diffused oxygen from bulk gas reacts with CO in the gas phase. In this simulation, at around 260 ms *i.e.* after consumption of the initial oxygen, the reaction rate is controlled by oxygen diffusion.

Because oxygen supply from bulk gas is insufficient, the endothermic reaction of Eq. (2) dominates on the surface rather than the exothermic reaction of Eq. (1). Reaction (2) suppresses the surface temperature of the particle. In the gas phase, exothermic reaction of Eq. (3) occurs this results in gas heating faster than the particle. Comparison of specific heat C_p , char (1.65) and gas (1.2) at around 1000 K, would be insignificant to explain the large gradient in temperature between the gas and the particle.

The particle temperature curve is similar to the predictions by Ösüm *et al.*¹³⁾ and Yamamoto *et al.*¹⁵⁾ The appearance of the point of inflection caused by acceleration of reaction and the combustion temperature range approximately 1500 K, tallies nicely. However the radiation conditions are assumed to be that of an entrained flow reactor in Ref. 13) and a swirling flow turbulent coal combustor in Ref. 15). Sustained combustion is also observed in their works, though there is a slight and gradual temperature decrease. But their results predicted an accumulation of oxygen up to 2–4 % in the gas phase at maximum temperature. It can be explained that because the reaction shown in (3) is not as fast compared to gas diffusion, oxygen accumulates

Fig. 4. Effects of gas radiation: change of temperature gas component. T_g and gas contents are at 0.05 mm from the particle surface.

and the heat by reaction shown in (3) cannot sustain the temperature. Ösüm *et al.*¹³⁾ carried out simulations for a gas composition which contained H₂O. Because the chemical reaction rate constant for a composition containing H₂O is smaller than that of a heterogeneous Reaction (3) which does not contain H₂O, accumulated oxygen was higher than our results. Kanury's description that oxygen diffusion is the key to rate control in combustion at high temperatures supports our results.¹²⁾ But the estimation of the rate of the reaction shown in (3) is an open problem. It needs to be done by comparing accurate experiments with precise models.

3.2. Radiant Heat from CO₂ Gas

For computational purpose, simplification of the simulation model is required. To ensure that the calculated results are not affected by the simplification, we estimated the impact of two aspects of this simulation model.

The previous works^{13,15)} on unsteady state model ignore the heat transfer by radiation from gas. And Yamamoto *et al.*¹⁵⁾ did not consider the heat transfer by molecular diffusion. But, it will be useful to estimate the effect of the heat transfer by molecular diffusion on the simulation model.

Figure 4 shows the effect of radiant heat from CO₂ gas on the temperatures and the gas composition adjacent to the particle surface. In the case with 21 % oxygen as shown in Fig. 4, it is clear that the effect of radiant heat from CO₂ gas on the temperatures and gas composition is negligibly small. Furthermore, same result is given in the case with pure oxygen. Thus we drop the radiant from the gas phase in our simulation model.

3.3. Heat Transfer by Molecular Gas Diffusion

Let us now attempt to estimate the impact of heat transfer by molecular gas diffusion. Figure 5 gives us the predicted curves of temperature changes and gas composition changes with and without the heat transfer. In the case with the heat transfer, the sustained combustion temperature shifts slightly lower and combustion period extends 4%. The reason for this is not difficult to ex-

Fig. 5. Effect of heat transfer by molecular gas diffusion: change of the temperature and gas component change. T_g and gas contents are at 0.05 mm from the particle surface.

plain: since the heat generated by Reaction (1) diffuses accompanied by molecular diffusion, the temperature in the gas phase and that on the particle surface goes down slightly and Reaction (1) is suppressed. Thus, if a model does not include the heat transfer by molecular diffusion, the predicted temperatures of particle and gas phase are likely to be a little higher than the true temperatures. And also CO and CO₂ content can be obtained higher and lower respectively in sustained combustion stage. The results also show a difference of 1.5% in particle temperature, 3% in gas temperature, 12% in CO concentration and 10% in CO₂ concentration (Fig. 5). The nature of the curve is not significantly affected.

3.4. Distribution of Gas Temperature

Figures 6(a)–6(d) show the distribution change of gas temperature and gas composition during heating. The gas temperature decreases monotonically with increasing distance from the particle at the beginning of the combustion and the distribution shifts upward with time. A temperature peak appears at a short distance from the surface after 260 ms when sustained combustion begins (Fig. 2). At the same time, oxygen content reduced to near zero at the surface. CO content shift upward in contrary synchronizing with oxygen. The distribution of CO₂ is lifted in a manner similar to the gas temperature and a peak corresponding to the gas temperature appears.

Figure 7 shows a typical distribution of gas temperature at 300 ms in sustained combustion stage. Concentration of accumulated oxygen falls to near zero at 0.05 mm from the surface and rises gradually up to bulk concentration as distance increases. It can be assumed that the diffusing oxygen from bulk gas to the surface has reacted rapidly with CO by (3) as far as 0.05 mm and, oxygen and CO do not accumulate near the particle surface. Owing to the insufficiency of oxygen after the initial oxygen consumption, CO₂ is consumed by the

Fig. 6. Simulation results on the distribution changes of gas temperature and contents. (Laser input = 1.85 W/mm², particle diameter = 0.2 mm, O₂ = 21%)
(a) Gas temperature, (b) O₂ mole fraction, (c) CO mole fraction, (d) CO₂ mole fraction.
— at 170 ms, $T_p = 1191$ K, $D_p = 0.1997$ mm, ... at 200 ms, $T_p = 1259$ K, $D_p = 0.1990$ mm, ---- at 240 ms, $T_p = 1369$ K, $D_p = 0.1980$ mm, - · - at 250 ms, $T_p = 1420$ K, $D_p = 0.1970$ mm, --- at 260 ms, $T_p = 1463$ K, $D_p = 0.1950$ mm, ----- at 300 ms, $T_p = 1491$ K, $D_p = 0.1860$ mm

endothermic Reaction (2). Thus CO content increases by Reaction (2) and CO₂ content decreases near the surface.

3.5. Oxygen Concentration

The simulated result with different oxygen concentration of bulk gas are shown in Figs. 8(a)–8(f). In Fig. 8(a), the same observation applies to the form of the curves, *i.e.* ignition point and sustained combustion appear except in the case of pure nitrogen. But the oxygen increase has some significant impacts. *Viz* an earlier appearance of ignition, an acceleration of particle temperature increase after ignition, higher gas and par-

Fig. 7. Distribution of surrounding gas contents and temperature at 300 ms. (Laser input = 1.85 W/mm², D_p = 0.2 mm, O₂ = 21 %)

ticle temperature level during sustained combustion. The effects of oxygen concentration as predicted by the model tally well with the experimental results,³⁾ however the experimental results were obtained with the several coals.

The near zero accumulation of oxygen at the surface, even in 100 % oxygen, implies that a higher oxygen flux is accompanied by a faster rate of Reaction (1). Thus total combustion period reduces with increased oxygen content.

3.6. Input Radiation Energy

Figures 9(a)–9(f) show the change of the temperatures and gas contents with different input laser power. In this figure, it is observed that the higher laser input results in a higher heating rate during the initial heating stage and raises the sustained combustion temperature level slightly. Higher input laser energy will have little effect on the gas temperature and the time period of sustained combustion. The experimental results showing that laser input affects the heating rate only in initial stage is also predicted in this model.

3.7. Particle Size

Substituted char particle diameter was also changed in the simulation. To avoid the temperature difference between the surface and the inside of a particle, the simulation was carried out for diameters up to 0.3 mm. Figures 10(a)–10(f) show the predicted results. Smaller particle size increases the temperature more rapidly dur-

Fig. 8. Effects of oxygen concentration on coal char combustion. (Laser input = 1.85 W/mm², D_p = 0.2 mm)
(a) Particle temperature, (b) gas temperature, (c) carbon conversion, (d) O₂ mole fraction, (e) CO mole fraction, (f) CO₂ mole fraction
Gas temperature and contents are at 0.05 mm from the particle surface.
— pure N₂, ··· 10% O₂, ---- 21% O₂, -.- 50% O₂, ——— pure O₂

Fig. 9. Effects of laser input on coal char combustion. ($D_p = 0.2$ mm, $O_2 = 21$ %)
 (a) Particle temperature, (b) gas temperature, (c) carbon conversion, (d) O_2 mole fraction, (e) CO mole fraction, (f) CO_2 mole fraction
 Gas temperature and contents are at 0.05 mm from the particle surface.
 — 1.48 W/mm², ··· 1.85 W/mm², ---- 2.59 W/mm²

ing the initial heating stage and raises the temperature level slightly in sustained combustion. Compared to larger particles, smaller particles receive more energy per unit mass and offer a larger reaction area per unit mass. Thus small particles heat up more rapidly. Of course larger particles take longer to burn out.

It is predicted that particle size gives no significant effect on gas temperature (Fig. 10(b)), larger particles raise the CO content little higher (Fig. 10(e)) and reduce the CO_2 content in sustained combustion (Fig. 10(f)). The effects are explained not from equilibrium of gas contents, but from the larger volume of reacting mass on the particle surface owing to the larger reacting area.

We have concluded experimentally with coal that the particle diameter has not significant effect on sustained temperature. It is confirmed by the simulated results in Fig. 10(a).

4. Conclusion

An unsteady state combustion model, which takes into account the homogeneous reaction of surrounding gas, was developed to understand the small char particle combustion in laser radiation. The heat radiation of CO_2 gas is negligibly small in the model. The heat transfer by gas molecular diffusion was found significant and has been retained in the simulation.

The simulation results predict the following;

The gas temperature is predicted to be higher than particle temperature. In the sustained combustion stage, surface reaction rate is controlled by Reaction (2). Because CO reacts rapidly with diffused oxygen, the accumulated concentration of CO and oxygen falls to nearly zero at close to the particle surface. CO_2 content has a peak near the particle surface.

In addition, the effects of particle size, laser input energy and oxygen contents on the combustion were discussed. The results predict that smaller particles heat up faster during initial heating and higher laser input has the same effect. And, higher oxygen content raises the sustained combustion temperature and shortens the combustion period.

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Nomenclature

C : mole concentration of gas (mol/m³)
 C_{p_p} , C_{p_g} : specific heats of particle and gas (J/kg·K)
 D : molecular diffusion coefficient (m²/s)

Fig. 10. Effects of particle size on coal char combustion. (Laser input = 1.85 W/mm^2 , $\text{O}_2 = 21\%$)
 (a) Particle temperature, (b) gas temperature, (c) carbon conversion, (d) O_2 mole fraction, (e) CO mole fraction, (f) CO_2 mole fraction
 Gas temperature and contents are at 0.05 mm from the particle surface.
 — $D_p = 0.3 \text{ mm}$, $\cdots$ $D_p = 0.2 \text{ mm}$, $----$ $D_p = 0.15 \text{ mm}$, $-.-$ $D_p = 0.10 \text{ mm}$

D_p : particle diameter (m)
 h : heat transfer coefficient ($\text{W/m}^2 \cdot \text{K}$)
 M : molecular weight (kg/mol)
 P : gas pressure (atm)
 Q_1, Q_2 : heats of Reactions (1) and (2) (J/s)
 Q_3 : heat of Reaction (3) ($\text{J/m}^3 \cdot \text{s}$)
 Q_d : heat of molecular diffusion ($\text{J/m}^3 \cdot \text{s}$)
 Q_L : laser input energy (J/s)
 Q_N : conduction heat between gas and solid particle (J/s)
 Q_{rg} : radiant heat in control volume of gas ($\text{J/m}^3 \cdot \text{s}$)
 Q_{rs} : radiant heat from particle surface (J/s)
 r : distance from the center of particle (m)
 R : gas constant ($8.314 \text{ J/mol} \cdot \text{K}$)
 R_1, R_2 : reactions rate (1) and (2) (kg/s)
 R_3 : reaction rate (3) (kg/s)
 S : surface area of a particle (m^2)
 S_v : input or output area of gas control volume (m^2)
 t : time (s)
 T_p, T_g : temperatures of a particle and gas (K)
 T_0 : temperature of bulk gas (K)
 V_p, V_j : volumes of particle and control volume (m^3)
 Y : mole fraction of gas (—)
 Y_0 : mole fraction of bulk gas (—)
 α : laser absorptivity of a particle (—)

β : stoichiometric coefficient (—)
 ϵ_p, ϵ_g : emissivities of a particle and gas (—)
 λ : conduction heat coefficient ($\text{W/m} \cdot \text{K}$)
 ξ : disproportionation factor for heat released to solid (—)
 ρ_p, ρ_g : densities of particle and gas (kg/m^3)
 σ : Stefan-Boltzmann constant ($5.669 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$)
 v : gas velocity (m/s)
 φ : mass velocity of gas ($\text{kg/m}^2 \cdot \text{s}$)
 Δr : thickness of control volume (m)
Subscripts
 i : gas species
 j : numbers of control volume
 k : numbers of control volume
 N : a number of control volumes
 δ : numbers of control volume through which radiant heat pass

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