Theoretical Study on Combustion of Injected Pulverized Coal in the Blast Furnace Blowpipe Zone*

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Synopsis

Pulverized coal is being used increasingly as a blast furnace injectant. It is injected into a blowpipe zone where spontaneous ignition and combustion occur by mixing with the hot blast.

A theoretical study is made on the ignition and combustion of injected coal particles in the blowpipe zone. The theory uses a simple combustion model in which diffusion of gaseous oxygen is dominant for the combustion rate. The derived results show the effects of coal properties and blast and injection conditions on the degree of burn out and the blast gas temperature at the tuyere nose. These results are compared qualitatively with reported experiments and reasonable agreement is obtained.

In spite of some severe assumptions used in the theory for simplicity, the present objective is satisfied, which is to provide preliminary information for optimization of the injection conditions.

I. Introduction

In order to reduce coke consumption in blast furnace operations, auxiliary fuel such as oil or natural gas is injected into the blast furnace. However, since the oil crisis, the utilization of coal has become very important and pulverized coal is used increasingly to replace oil as a blast furnace injectant.

Like oil and natural gas injection, pulverized coal is injected into a blowpipe immediately upstream of the tuyere nose followed by the coke combustion or 'raceway' zone. Through the injection practices of pulverized coal in various countries, some problems have been experienced.¹⁾ These problems include handling and dispensing the powdered coal, the lower combustibility of pulverized coal relative to oil and natural gas and the ash deposition in the tuyeres and its behaviour within the blast furnace.

Some solutions for these problems have been demonstrated by various researchers. For instance, coal handling processes with dense bulk transportation lines are being developed or improved in order to achieve a stable injection of fine coal at a desired injection rate (Wakuri *et al.*,²⁾ Shinozaki *et al.*,³⁾ Reintjes and Tamura,⁴⁾ Hetherington.⁵⁾ From the Weirton and Bruceton furnace practices, Ostrowski¹⁾ has recommended the use of coals with low ash content and ash of high ash fusibility (low ash fusion temperature) to minimize build-ups of frozen ash and slag mixtures near tuyeres or blowpipes leading to tuyere or blowpipe failure.

The combustion rate of pulverized coal is relatively low compared to that of oil, which is also a very important factor to be taken into account in the design of coal injection systems. If injected coal particles remain unburnt in the raceway region,

they could possibly become lodged in the interstices of the coke bed, decrease the bed permeability and produce detrimental effects on the hot gas flow distribution in the burden. According to Ostrowski,¹⁾ changes in gas flow distribution would form accretions with liquid metal on the furnace walls and cause severe slips. Therefore, for good furnace operation with pulverized coal injection, it is of great importance that all the injected coal particles are burnt out before reaching the raceway boundary.

The present work is aimed at developing a simple model for examining the ignition and combustion of pulverized coal injected into a blast furnace blowpipe region. The complex interactions which occur within the raceway zone are not examined at this stage, since it is the intention of the present work to provide preliminary information on the degree of combustion of injected coal at the tuyere nose as a function of coal properties, blast conditions and injection lance position.

II. Model for Blowpipe-tuyere Combustion Zone

Figure 1 shows the diagram of pulverized coal injection into a one-dimensional (X -direction) adiabatic blowpipe. For simplicity, the coal particles are assumed to be mono-sized spheres and dispersed uniformly along the cross section of the blowpipe.

As the injected coal particles encounter the blast gas at a temperature greater than 1 000 K, they are warmed up, ignited and burnt during passage through the blowpipe.

The present blowpipe model comprises two zones along the X -direction, one is the warm-up zone and the other is the burning zone. The warm-up zone is defined as the region between the injection point and the point at which the temperature of particles reaches the ignition temperature, T_{ig} . The region further downstream where the particles burn is

Fig. 1. Model of blowpipe-tuyere combustion zone.

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denoted as the burning zone.

III. Theoretical

Coal particles are injected into a blowpipe at the mass rate of F . Then, the number injection rate of coal particles per unit cross sectional area of the blowpipe, N , can be represented by,

$$N = 4F/(\pi D^2 M_0) \dots\dots\dots(1)$$

where, $M_0 = (\pi/6)D_{p0}^3\rho_s$
 D : the diameter of pipe
 D_{p0}, ρ_s : the diameter and density of particles, respectively.

The velocity of particles, V_p at a distance X is defined by,

$$V_p = dX/dt \dots\dots\dots(2)$$

The relative velocity, U is,

$$U = V_a - V_p \dots\dots\dots(3)$$

where, V_a : the blast gas velocity.
 U can be obtained from the following differential equation with respect to the drag force on a particle.

$$M_e dU/dt = -C_f A_s (\rho U^2/2) \dots\dots\dots(4)$$

where, $M_e = (\pi/6)D_{pe}^3\rho_s = M_0 C_{ash} + M(t)$
 $A_s = (\pi/4)D_{pe}^2$

C_{ash} is the mass fraction of ash in the original coal, ρ is the air density, and C_f is the resistance coefficient given by,

$$\begin{aligned} C_f &= 24/Re & \text{if } Re = D_{pe}U\rho/\mu < 2 \\ C_f &= 10/Re^{0.5} & \text{if } 2 < Re < 5 \times 10^2 \\ C_f &= 0.44 & \text{if } 5 \times 10^2 < Re < 2 \times 10^5 \end{aligned} \dots\dots\dots(5)$$

where, Re : Reynolds number
 μ : the viscosity of gas.

M_e in Eq. (4) is the mass of a particle at time t following the injection at $t=0$, which comprises the mass of ash, $M_0 C_{ash}$ and that of unburnt fuel of the particle at time t , $M(t)$. D_{pe} and A_s in Eq. (4) are the apparent diameter and projected surface area of the particle at time t where the particle is assumed to be non-porous.

1. Length of the Warm-up Zone

The following main assumptions are made in the theoretical derivation in the warm-up zone;

- (1) There is no temperature distribution inside the coal particles.
- (2) There is no pressure gradient in the warm-up zone.
- (3) Of the radiation from hot gas and the inside wall of blowpipe, only that from the inside wall is taken into account for the temperature rise of the particles since the main components of the gas (N_2 and O_2) are ineffective for radiation. The rate of radiant heat from the inside wall to a particle, Q_r can be conveniently represented by,

$$Q_r = \pi D_{p0}^2 F_p A_p E_w \sigma T_0^4 \dots\dots\dots(6)$$

where, A_p : the absorptivity of particle
 E_w : the emissivity of the wall
 σ : the Stefan-Boltzmann constant
 F_p : the modified view factor (see Appendix A).

(4) There is no mass loss of solid particles in the warm-up zone so that D_{pe} is equal to D_{p0} in Eqs. (4) and (5).

(5) The effect of volatile matter on the temperature rise of particles is very small compared with that of convection (see Appendix B).

(6) The gas temperature, T_g is constant (see Appendix B) so that the gas velocity does not vary.

(7) In Eq. (5) the Allen region, $C_f = 10/Re^{0.5}$, may be reasonably accepted (see Appendix B).

Using assumptions (4), (6) and (7), Eq. (4) can be solved and the particle velocity, V_p is given by,

$$\begin{aligned} V_p &= V_{a0} - \{(V_{a0} - V_{p0})^{-0.5} + 0.5B_1 t\}^{-2} \\ B_1 &= 7.5(\rho_0 t)^{0.5}/(\rho_s D_{p0}^{1.5}) \end{aligned} \dots\dots\dots(7)$$

where, V_{a0}, V_{p0} : the velocities of blast gas and particles at $X=0$, respectively.

Integration of Eq. (2) using Eq. (7) gives the position of particles at time t in the blowpipe, injected at $t=0$, as follows;

$$\begin{aligned} X &= V_{a0} t - (2/B_1)[(V_{a0} - V_{p0})^{0.5} \\ &\quad - \{(V_{a0} - V_{p0})^{-0.5} + 0.5B_1 t\}^{-1}] \end{aligned} \dots\dots\dots(8)$$

Consider a single particle travelling from X to $X+dX$ in a small period of time, dt . Using assumptions (3) and (5), a heat balance around the particle becomes,

$$\begin{aligned} \frac{dT_s}{dt} &= A_1 \{h(T_g - T_s) + G_m\} \\ D_{p0} h/K_c &= 2 + 0.6Re^{1/2} Pr^{1/3} \\ A_1 &= 6/(D_{p0} \rho_s C_{ps}) \\ G_m &= F_p A_p E_w \sigma T_0^4 \end{aligned} \dots\dots\dots(9)$$

where, C_{ps} : the specific heat of solid
 K_c : the thermal conductivity of gas
 Pr : the Prantdl number
 h : the heat transfer coefficient.

When the particle reaches the boundary of the warm-up and burning zones ($X=X_p$ or $t=t_1$), its temperature, T_s attains the ignition temperature, T_{ig} . From the solution of Eq. (9), the time that the particle reaches the boundary, t_1 is obtained by,

$$t_1 = \frac{1}{A_1 h} \ln \frac{h(T_{s0} - T_0) - G_m}{h(T_{ig} - T_0) - G_m} \dots\dots\dots(10)$$

where the heat transfer coefficient, h is regarded as constant and is calculated by using Re based on the average relative velocity, U equal to $V_{a0} - X_p/t_1$. Substituting the above equation into Eq. (8), the length of the warm-up zone, X_p can be calculated as $X(t_1)$.

2. Length of the Burning Zone

At the boundary of the warm-up and burning

zones, the injected coal particles start to burn and heat the surrounding gas. In the burning zone, therefore, the velocity, density and temperature of gas vary in the X -direction.

The equations of mass and energy balances at steady state in the gas phase and the ideal gas law can be given as follows;

(mass)
$$-\frac{d(\rho V_a)}{dX} + \frac{N}{V_p} \left\{ -\frac{dM(t)}{dt} \right\} = 0$$
 or
$$(\rho/\rho_0)(V_a/V_{a0}) = 1 + Y(\theta) \dots\dots\dots(11)$$

(energy)
$$-\frac{d}{dX} \{ \rho V_a (H G_q + 0.5 V_a^2) \} + \frac{G_q Q_s N}{V_p} \left\{ -\frac{dM(t)}{dt} \right\} = 0$$
 or
$$\{1 + Y(\theta)\} \{Y_a (T_g/T_0) + 0.5 (V_a/V_{a0})^2\} = Y_a + Y_b Y(\theta) + 0.5 \dots\dots\dots(12)$$

(ideal gas law)
$$(P/P_0) = (\rho/\rho_0)(T_g/T_0) \dots\dots\dots(13)$$

where, $Y(\theta) = \{NM_0(1 - C_{ash})/(\rho_0 V_{a0})\} \{1 - M_d(\theta)\}$
 $Y_a = G_q C_p T_0/V_{a0}^2$
 $Y_b = G_q Q_s/V_{a0}^2$
 $M_d(\theta) = M(t)/\{M_0(1 - C_{ash})\}$
 $\theta (=t - t_1)$: the time variable indicating the burning period
 G_q : the conversion factor ($G_q = 1 \text{ kgm}^2/\text{Js}^2$)
 H : the enthalpy per unit mass of gas given as $C_p T_g$ where C_p , the specific heat of gas, is assumed to be constant
 Q_s : the heat of combustion per unit mass of particle.

For further simplicity, the following assumptions are introduced;

- (8) The pressure is constant (see *Appendix C*).
- (9) The particle velocity, V_p is equal to that of blast gas, V_a (see *Appendix C*).

Using Eqs. (11) to (13) and assumption (8), V_a and T_g can be represented as follows:

$$V_a/V_{a0} = [-Y_a + \{Y_a^2 + 2(1 + Y(\theta))(Y(\theta)Y_b + Y_a + 0.5)\}^{0.5}]/\{1 + Y(\theta)\} \dots\dots\dots(14)$$

$$T_g/T_0 = (V_a/V_{a0})/\{1 + Y(\theta)\} \dots\dots\dots(15)$$

From assumption (9), the distance, X from the injection lance (the position of particles in the blowpipe at time θ) can be obtained by,

$$X = \int_0^\theta V_a d\theta + X_p \dots\dots\dots(16)$$

Thus, the time, t_s or $\theta_s (=t_s - t_1)$ when the injected particles reach the tuyere nose (the edge of blowpipe) can be evaluated by substituting X_b in X in Eq. (16).

3. Combustion Rate of Coal

The above equations (14) to (16) include $M_d(\theta)$, the dimensionless mass of unburnt fuel of the particle at time θ . For the combustion of a single particle,

diffusion of oxygen is assumed to be dominant. Then, the rate of combustion can be represented by,⁶⁾

$$M_0(1 - C_{ash}) \left\{ -\frac{dM_d(\theta)}{d\theta} \right\} = (1/\alpha) \pi D_p^2 k_o C_g \dots\dots\dots(17)$$

where α is the number of moles of oxygen consumed per unit mass of particle burnt and k_o is the mass transfer coefficient which is obtained by assuming that the Sherwood number is equal to 2, that is,

$$k_o = 2D_{ff}/D_p \dots\dots\dots(18)$$
$$D_{ff} = D_o(101/P_0)(T_g/298)^{1.75}$$

where, D_{ff} , D_o : the diffusion coefficients at P_0 and T_g and at standard state (101 kPa and 298 K), respectively.

In Eq. (17), C_g is the oxygen concentration at $X=X$ (or $\theta=\theta$) which is obtained by taking a oxygen balance of the blast gas along the X -direction in the blowpipe,

$$\frac{\pi D^2}{4} (C_{g0} V_{a0} - C_g V_a) = \alpha F (1 - C_{ash}) \{1 - M_d(\theta)\} \dots\dots\dots(19)$$

$$C_g = C(P_0/RT_g) \dots\dots\dots(20)$$

where, C_{g0} : the oxygen concentration at $X=0$
 C : the oxygen content at $X=X$.
Rearranging Eq. (19) gives,

$$C = \{C_0 - 28.8 \times 10^{-3} \alpha Y(\theta)\} / \{1 + Y(\theta)\} \dots\dots\dots(21)$$

where, C_0 : the initial oxygen content of the blast gas at $X=0$.

Using Eqs. (18), (20) and (21), Eq. (17) is reduced to,

$$-\tau_0 \frac{dM_d(\theta)}{d\theta} = \frac{3}{2} M_d(\theta)^{1/3} (T_g/T_0)^{0.75} (C/C_0) \dots\dots\dots(22)$$

where, $\tau_0 = K_{do}(298/T_0)^{0.75}(0.21/C_0)D_{p0}^2$
and $K_{do} = (298/101/0.21)R\rho_s(1 - C_{ash})\alpha/(8D_o)$

Equation (22) can be solved analytically if the value of $(T_g/T_0)^{0.75}(C/C_0)$ can be regarded as constant, which might be reasonable because the value of (T_g/T_0) increases with increasing time θ whereas (C/C_0) decreases with θ . Assuming the mean values T_A and C_A for T_g and C , integration of Eq. (22) becomes,

$$M_d(\theta) = (1 - \theta/\tau_A)^{3/2} \dots\dots\dots(23)$$

$$\tau_A = K_{dA} D_{p0}^2 \dots\dots\dots(24)$$

$$K_{dA} = K_{do}(298/T_A)^{0.75}(0.21/C_A)$$

$$T_A/T_0 = \{1 + (T_r/T_0)\}/2$$

$$C_A/C_0 = \{1 + (C_r/C_0)\}/2$$

where T_r and C_r are the gas temperature and the oxygen content at the tuyere nose and are obtained by substituting θ_s into θ in Eqs. (15) and (21), respectively.

Figure 2 shows the validity of the assumption to

Fig. 2. Fraction of unburnt fuel of a particle in relation to dimensionless burning time.

derive Eq. (23), where the coal injection rate (2.8×10^{-3} kg/s) is about a half the stoichiometric value.

Additionally, τ_A in Eq. (24) is the time required for complete combustion of a particle of a diameter D_{p0} under the condition of T_A and C_A . Further, the degree of burn-out of particles at $X = X_b, C_d$, becomes $1 - M_d(\theta_s)$.

IV. Calculated Results and Discussion

Two series of experiments of pulverized coal combustion (Burgess *et al.*⁷⁾ and McCarthy *et al.*⁸⁾) are referred to for comparing with the theory. Both used pilot scale blast blowpipe-tuyere combustion systems. The former⁷⁾ tested two different coals (types A and B) and measured the gas temperatures in the blowpipe combustion region in relation to the distance from the injection position (shown in Figs. 3 and 4). The latter⁸⁾ tested three kinds of medium to high volatile coal (types C, D and E). They sampled the burning coal particles with a solid sampling probe and analysed the ash content to evaluate the degree of burn-out. Figure 5 shows a typical example of the results relating the degree of burn-out to the coal injection rate. The characteristics of the coals and the experimental conditions employed by both researchers are given in Tables 1 and 2, respectively.

In the calculation, the ignition temperature, T_{ig} for the coals is assumed to be 1 000 K (see Nomura and Callcott⁹⁾). Further, the emissivity of blowpipe wall, E_w is assumed to be 0.9 since the effect of E_w in the range from 0.5 to 1 is only 2 or 3 % on the value of X_p and its value seems to be between 0.7 and 1.¹⁰⁾ Other constant values needed for calculation are listed in Table 3.

Since no specific values of K_{do} , the burning constant, are available for these coals, they are estimated from the experimental data. Then, using these values of K_{do} , the sensitivity of the theory is tested and compared with the trends obtained in the experiments.

Firstly, for coals A and B, the values of K_{do} have been calculated which give a best fit to the measured gas temperatures for $F = 1.4 \times 10^{-3}$ kg/s for coal A and for $F = 1.1 \times 10^{-3}$ kg/s for coal B. These have been 3×10^7 s/m² for both A and B. Using the obtained values of K_{do} , further calculations have been made on

Fig. 3. Blast gas temperature in relation to distance from injection position for coal A.

Fig. 4. Blast gas temperature in relation to distance from injection position for coal B.

Fig. 5. Degree of burn out in relation to coal injection rate.

the gas temperatures in terms of X at other coal injection rates employed in the test, which are shown as the full lines in the corresponding figures 3 and 4. Judging from comparison with the experiments, the theoretical estimate seems reasonable.

Next, the values of K_{do} for coals C, D and E have been re-calculated by substituting data of degree of burnout and the employed experimental condition.⁸⁾ For each coal the average is adopted as the value of K_{do} . These are 2.15×10^7 s/m² for coal C, 2.88×10^7 s/m² for coal D and 5.14×10^7 s/m² for coal E. Using these values and the experimental conditions, the degrees of burnout are calculated and compared

Table 1. Coal compositions. (wt%)

Component		Coal Type				
		A	B	C	D	E
Proximate	Volatile matter	35.9	33.3	36.0	33.9	17.1
	Ash	4.0	10.0	3.8	12.5	9.9
	Moisture	1.0	—	6.2	3.1	1.7
	Fixed carbon	59.1	56.7	54.0	50.5	71.3
Ultimate (on dmmf basis)	C	79.38	75.3	80.0	77.2	80.4
	H	5.13	4.9	4.9	5.0	4.3
	O	8.41	7.8	12.8	15.5	12.9
	S	0.38	0.3	0.34	0.43	0.61
	Heat of combustion $Q_s[\times 10^6 \text{ J/kg}]$	31.6	29.2	31.6	30.3	30.8

Table 2. Experimental conditions for coal combustion experiments.

Coal	Coal Type			
	Blast temp. (K)	Blast flow ($\times 10^{-3}$ m ³ /s)	Blowpipe diameter (m)	Mean particle diameter ($\times 10^{-6}$ m)
A	1 243	32.1	0.05	40.0
B	1 203	32.1	0.05	37.0
C-1	1 273, 1 373	42.9	0.07	48.5
C-2	1 473, 1 573	42.9	0.07	46.9
D-1	1 273	42.9	0.07	43.0
D-2	1 373	42.9	0.07	45.0
E-1	1 373	42.9	0.07	42.9
E-2	1 473, 1 573	42.9	0.07	44.3

Table 3. Constant values for calculation.

$\mu = 3.4328 \times 10^{-7} T_A^{0.6996} \text{ kg/ms}$	
$C_p = (0.9526 \times 10^3 + 2.1458 \times 10^{-1} T_A - 3.1206 \times 10^{-5} T_A^2) \text{ J/kgK}$	
$K_e = \mu(C_p + 0.3603) \text{ J/mKs}$	
$\rho_s = 1\,200 \text{ kg/m}^3$	$C_{ps} = 1.463 \times 10^3 \text{ J/kgK}$
$A_p = E_p = 0.8$	$E_w = 0.9$
$\sigma = 5.669 \times 10^{-8} \text{ J/m}^2\text{K}^4\text{s}$	$Q_v = 5.015 \times 10^7 \text{ J/kg}$
$X_i = 0.5 \text{ m}$	$T_{s0} = 298 \text{ K}$
$V_{p0} = 13 \text{ m/s}$ (from Ref. 7))	$T_{ig} = 1\,000 \text{ K}$
Assume coal as $C_{m1}H_{m2}O_{m3}$	
$C_{m1}H_{m2}O_{m3} + M_p\alpha O_2 \longrightarrow m_1CO_2 + 0.5m_2H_2O$	
$M_p = 12m_1 + m_2 + 16m_3$	
$\alpha = (m_1 + m_2/4 - m_3/2)/M_p$	

with the experimental values in Fig. 6. Although some dispersion is observed, the trend of the plots seems to be along the full line with unity slope.

In Fig. 5, the experiment indicates the degree of burnout decreases with increasing coal injection rate, F . The theory shows the same trend which is depicted by the full lines. The reason for this trend is explained by using Eq. (24) and Fig. 7. The gas temperature, T_A increases with increasing F , which enhances the combustion rate or the degree of burn-

Fig. 6. Comparison of calculated degree of burn out with experimental one.

Fig. 7. Effect of coal injection rate on T_A , C_A , and R_A .

Fig. 8. Relation between $K_{d0}/(1-C_{ash})$ and volatile matter content.

out. On the other hand, the oxygen content, C_A in the blast gas decreases for greater F , which reduces the combustion rate. The effect of oxygen content on K_d is greater than that of blast gas temperature, which is shown in Fig. 7 by the line of R_A , the ratio of K_d at T_0 and C_0 to that at T_A and C_A . This causes a slightly decreasing trend of the degree of burnout with increasing coal injection rate.

Figure 8 shows the relationship between the calcu-

lated K_{do} value divided by $(1-C_{ash})$ and the volatile matter. Although only a few points have been plotted, a reasonable trend can be seen that K_{do} decreases (or the combustion rate increases) with increasing volatile matter.

V. Conclusion

A theoretical study has been conducted on the combustion of pulverized coal injected into the blast furnace blowpipe region. In this work, a simplified model of the coal combustion has been used in order to derive simple equations. The derived results have explained qualitatively the combustion characteristics occurring in the blowpipe-tuyere region and have been confirmed with reported experiments in reasonable agreement.

The combustion model has used the burning constant, K_{do} which is a material constant affected by the volatile matter and ash content of the coal. The present work has assumed the values of the burning constant to correspond with reported combustion data. Although the number of the combustion data point is limited, a reasonable correlation has been obtained (Fig. 8) between the burning constant and the volatile matter content. This correlation should be useful in other research areas such as predictions of coal dust explosion phenomena.¹¹⁾

Finally, the objective of the present work is to provide preliminary information for the optimization of blast furnace operations with pulverized coal injection. For this optimization, further research is needed on the raceway zone combustion of injected coals, which should be combined with the present theoretical work.

Nomenclature

- A : projected area defined in Fig. A-1 (b) [m^2]
 A_1 : $6/(D_{p0}\rho_s C_{ps})$ [m^2K/J]
 A_2 : $N\pi D_{p0}^2/(\rho_0 V_{a0} C_p)$ [m^2K/J]
 A_i : area of wall inside blowpipe effective for radiation [m^2]
 A_o : frequency factor [kg/m^2s]
 A_p : absorptivity of particle [—]
 A_s : projected area of a particle [m^2]
 B_1 : $7.5 (\rho_0 \mu)^{0.5}/(\rho_s D_{p0}^{1.5})$ [m^{-1}]
 $b = (T_r/T_0) - 1$ [—]
 C : mole fraction of oxygen in gas phase at $X=X$ [—]
 C_A : mean value of mole fraction of oxygen in the burning zone [—]
 C_{ash} : mass fraction of ash in original coal [—]
 C_d : degree of burn-out [—]
 C_f : resistance coefficient [—]
 C_g : oxygen concentration at $X=X$ [mol/m^3]
 C_{g0} : oxygen concentration at $X=0$ [mol/m^3]
 C_0 : mole fraction of oxygen in gas phase at $X=0$ [—]
 C_p : specific heat of gas per unit mass at constant pressure [J/kgK]
 C_{ps} : specific heat of particle per unit mass [J/kgK]
 C_r : mole fraction of oxygen in blast gas at

- tuyere nose [—]
 D : inside diameter of blowpipe [m]
 D_{ff} : diffusion coefficient at temperature, T_g and pressure, P_0 [m^2/s]
 D_o : diffusion coefficient at 298 K and 101 kPa [m^2/s]
 $D_p(t)$: diameter of unburnt fuel core of particle [m]
 D_{pe} : apparent diameter of a burning particle at $t=t$ [m]
 D_{p0} : initial diameter of particles [m]
 E : activation energy [J/mol]
 E_w : emissivity of inside wall of blowpipe [—]
 F : mass injection rate of pulverized coal [kg/s]
 F_p : modified view factor [—]
 F_r : friction force of gas acting on a unit surface area of inside wall [kgm/s^2]
 f : friction coefficient [—]
 $G = X/X_b$ [—]
 G_c : conversion factor = 980 [$kg/mkPa s^2$]
 $G_i = X_i/X_b$ [—]
 $G_m = F_p A_p E_w \sigma T_0^4$ [$J/m^2 s$]
 G_q : conversion factor = 1 [$kgm^2/J s^2$]
 H : enthalpy per unit mass of gas [J/kg]
 h : heat transfer coefficient [$J/m^2 K s$]
 K_c : thermal conductivity of gas [$J/mK s$]
 K_{dA} : burning constant at temperature T_A and oxygen content C_A [s/m^2]
 K_{do} : burning constant at 298 K and 0.21 oxygen content [s/m^2]
 k_o : mass transfer coefficient [m/s]
 L : distance defined in Fig. A-1(a) [m]
 $M(t)$: mass of unburnt fuel of a particle at time t [kg]
 $M_d(\theta) = M(t)/M_0(1-C_{ash})$ [—]
 M_e : mass of a particle at time t [kg]
 M_0 : initial mass of a particle [kg]
 M_p : molecular weight of particle [kg/mol]
 N : number injection rate of coal particles per unit cross sectional area of blowpipe [$m^{-2} s^{-1}$]
 P : pressure of blast gas at $X=X$ [kPa]
 P_0 : pressure of blast gas at $X=0$ [kPa]
 Pr : Prandtl number [—]
 Q_r : rate of heat transferred by radiation [J/s]
 Q_s : heat of combustion of particle [J/kg]
 Q_v : oxidation heat per unit mass of volatile matter [J/kg]
 R : gas constant 8.288×10^{-3} [$m^3 kPa/molK$] or 8.314 [$J/molK$]
 $R_A = (T_A/T_0)^{0.75} (C_A/C_0)$ [—]
 R_f : mole flow rate of gaseous oxygen at $X=X_b$ [mol/s]
 $R_1 = 2r/D$ [—]
 Re : Reynolds number with respect to a particle [—]
 Re' : Reynolds number with respect to blowpipe [—]
 r : distance of a particle from the axis of cylinder [m]
 T_A : mean value of gas temperature in the burning zone [K]

- T_g : temperature of gas at $X=X$ [K]
 T_{ig} : ignition temperature of coal particles [K]
 T_0 : temperature of blast gas at $X=0$ [K]
 T_r : temperature of blast gas at tuyere nose [K]
 T_s : temperature of particles at $X=X$ [K]
 T_{s0} : temperature of particles at $X=0$ [K]
 T_w : temperature of wall inside blowpipe [K]
 t : time variable [s]
 t_1 : time for injected coal particles to be ignited [s]
 t_s : time for injected particles to reach tuyere nose [s]
 $U = V_a - V_p$ [m/s]
 V : volatile matter content [—]
 V_a : velocity of blast gas at $X=X$ [m/s]
 V_{a0} : velocity of blast gas at $X=0$ [m/s]
 V_p : velocity of particles at $X=X$ [m/s]
 V_{p0} : velocity of particles at $X=0$ [m/s]
 X : distance from injection point in blowpipe [m]
 X_b : distance between injection point and tuyere nose [m]
 X_t : length of blowpipe upstream of injection point effective to radiation [m]
 X_p : length of warm-up zone [m]
 $Y(\theta) = NM_0(1 - C_{ash})/(\rho_0 V_{a0})\{1 - M_a(\theta)\}$ [—]
 $Y_a = G_q C_p T_0 / V_{a0}^2$ [—]
 $Y_b = G_q Q_s / V_{a0}^2$ [—]
 $Z = \{D/(2X_b)\}^2$ [—]
 $Z_a = 1 + R_1^2 - 2R_1 \cos \phi$ [—]
 α : moles of oxygen consumed by combustion of unit mass of coal [mol/kg]
 β : angle defined in Fig. A-1 [—]
 θ : $t - t_1$ [s]
 θ_s : $t_s - t_1$ [s]
 μ : gas viscosity [kg/ms]
 ρ : density of blast gas at $X=X$ [kg/m³]
 ρ_0 : density of blast gas at $X=0$ [kg/m³]
 ρ_s : density of particles [kg/m³]
 σ : Stefan-Boltzmann constant [J/m²K⁴s]
 τ_A : time required for complete combustion of a particle under the conditions of $T_g = T_A$ and $C = C_A$ [s]
 τ_0 : time required for complete combustion of a particle under the conditions of $T_g = T_0$ and $C = C_0$ [s]
 ϕ : angle defined in Fig. A-1(a) [—]

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Appendix A

Figure A-1 shows the geometrical relation for radiation between the inside wall of pipe with a diameter D and a particle of a diameter D_{p0} placed in the pipe at $X=0$. The radiant heat, dQ_r transferred from a small area, dA_i of the inside wall of the pipe to the particle can be represented by the following equations.

$$dQ_r = A_p E_w \sigma T_w^4 (A/\pi) dA_i$$

$$A = \frac{\pi D_{p0}^2 \sin \beta}{4L^2}, \quad \sin \beta = \frac{D/2 - r \cos \phi}{L}$$

.....(A-1)

where, T_w : the temperature of the wall at $X=X$

A : the projected area as shown in Fig. A-1(b).

For simplicity, it is assumed that T_w is equal to that of the adjacent gas and that the gas temperature is constant for $X < 0$ and has a linear relationship with the distance, X for $X > 0$, that is,

$$OH = \frac{D}{2} - r \cos \phi$$

$$SH = \sqrt{X^2 + r^2 \sin^2 \phi}$$

Fig. A-1. View factor geometry.

$$\begin{aligned} T_w &= T_0 & (X < 0) \\ T_w &= (T_r - T_0)(X/X_b) + T_0 & (X > 0) \dots\dots(A-2) \end{aligned}$$

where, T_r : the gas temperature at the tuyere nose ($X = X_b$).

Integration of Eq. (A-1) gives the total radiant heat, Q_r from the inside wall to the particle as follows.

$$Q_r = \pi D_{p0}^2 A_p E_w \sigma T_0^4 F_p \dots\dots\dots(A-3)$$

where,

$$\begin{aligned} F_p &= \frac{Z}{2\pi} \left[\int_{-G_i}^0 \int_0^\pi \{ (1 - R_1 \cos \phi) (G^2 + Z Z_a)^{-1.5} \} \right. \\ &\quad \times d\phi dG + \int_0^1 \int_0^\pi \{ (1 - R_1 \cos \phi) (bG + 1)^4 \\ &\quad \times (G^2 + Z Z_a)^{-1.5} \} d\phi dG \left. \right] \dots\dots\dots(A-4) \end{aligned}$$

$$Z = \{ D / (2X_b) \}^2$$

$$R_1 = 2r/D$$

$$Z_a = 1 + R_1^2 - 2R_1 \cos \phi$$

$$G = X/X_b$$

$$G_i = X_i/X_b$$

$$b = (T_r/T_0) - 1$$

X_i : the length of blowpipe upstream of the injection point effective to the radiation

F_p is a modified view factor and depends not only on the blowpipe geometry but also on the value of (T_r/T_0). The variation of F_p with the dimensionless pipe length, X_b/D is shown in Fig. A-2. Since the effect of R_1 on F_p is very small, the value of F_p at $R_1=0$ (the case that a particle is on the axis of blowpipe) is assumed. Then,

$$\begin{aligned} F_p &= \frac{b^4 Z}{4} \left\{ \frac{1+3Z}{(1+Z)^{1/2}} + 3Z \ln \frac{Z^{1/2}}{1+(1+Z)^{1/2}} \right\} \\ &\quad + \frac{2b^3 Z}{(1+Z)^{1/2}} - 3b^2 Z \left\{ (1+Z)^{-1/2} \right. \\ &\quad \left. + \ln \frac{Z^{1/2}}{1+(1+Z)^{1/2}} \right\} + 2b \left\{ Z^{1/2} - \frac{Z}{(1+Z)^{1/2}} \right\} \\ &\quad + 0.5 \left\{ (1+Z)^{-1/2} - \frac{G_i}{(G_i^2 + Z)^{1/2}} \right\} \dots\dots\dots(A-5) \end{aligned}$$

Fig. A-2. Modified view factor in relation to dimensionless pipe length.

Additionally, when the values of X_b and X_i become greater, the value of F_p is converged to unity for a given b .

Appendix B

When coal particles are exposed to a hot air, the evolution of volatile matter takes place from the particle surface. The rate of the evolution can be expressed by the following formula.

$$M_0 \left(-\frac{dV}{dt} \right) = \pi D_{p0}^2 A_0 V \exp \left(-\frac{E}{RT_s} \right) \dots\dots(B-1)$$

where, V : the volatile matter content at time t

A_0 : the frequency factor

E : the activation energy

R : the gas constant.

It is assumed that the volatile matter is oxidized as soon as it is evolved from the particle surface and the resultant heat of oxidation contributes to the temperature rise of the particle. Then, a heat balance around the particle in place of Eq. (9) is given by,

$$\begin{aligned} \frac{dT_s}{dt} &= A_1 \left\{ h(T_g - T_s) + G_m \right. \\ &\quad \left. + Q_v A_0 V \exp \left(-\frac{E}{RT_s} \right) \right\} \dots\dots(B-2) \end{aligned}$$

where, Q_v : the heat of oxidation per unit mass of volatile matter.

Next, in the warm-up zone, the equation of continuity, the ideal gas law and a heat balance of the gas phase are represented by,

$$\rho V_a = \rho_0 V_{a0} \quad (\text{continuity}) \dots\dots\dots(B-3)$$

$$T_g \rho = T_0 \rho_0 \quad (\text{ideal gas law}) \dots\dots\dots(B-4)$$

$$\begin{aligned} \frac{d}{dX} (\rho V_a C_p T_g) &= \left(\frac{N}{V_p} \right) \pi D_{p0}^2 h (T_s - T_g) \\ &\quad (\text{heat balance}) \end{aligned}$$

or

$$\frac{dT_g}{dt} = A_2 h (T_s - T_g) \dots\dots\dots(B-5)$$

where, $A_2 = N \pi D_{p0}^2 / (\rho_0 V_{a0} C_p)$.

Equations (2) to (4) and (B-1) to (B-5) are solved numerically with respect to time t and give the length of the warm up zone, X_p at which the temperature of the particle, T_s becomes the ignition temperature, T_{ig} . The numerical computations use the following initial conditions (at $t=0$ and $X=0$),

$$\begin{aligned} T_s &= T_{s0} = 298 \text{ K}, \quad T_g = T_0 = 1200 \text{ K}, \\ V_p &= V_{p0} = 0, \quad V_a = V_{a0}, \quad \rho = \rho_0, \quad V = 0.3 \end{aligned}$$

and the following constant values of A_0 and E which have been reported by Kobayashi⁽¹¹⁾ for bituminous coal of 60×10^{-6} m in diameter,

$$\begin{aligned} 6A_0 / (D_{p0} \rho_s) &= 6.6 \times 10^4 \text{ s}^{-1} \\ A_0 &= 792 \text{ kg/m}^2 \text{ s}, \quad E = 1.046 \times 10^5 \text{ J/mol.} \end{aligned}$$

From Fig. B-1, it is said that the variation of T_g with the distance, X is very small (assumption (6))

Fig. B-1. Gas temperature and Reynolds number along the X -direction in the warm-up zone.

Fig. B-2. Warm-up zone distance in relation to blast velocity.

and that the value of Re is in the Allen region ($2 < Re < 500$) (assumption (7)).

Figure B-2 shows the length of the warm up zone, X_p in relation to the blast velocity, V_{a0} where the full line is the approximate one and the dotted line is the numerical one. From this comparison, the effect of volatile matter on the length of the warm-up zone seems to be very small (assumption (5)).

Appendix C

Assumptions (8) and (9) are examined by the numerical solution derived below. In order to calculate the variation of pressure, P along X -direction, the equation of motion is also used.

$$-\frac{d}{dX}(\rho V_a V_a) - \frac{d(PG_c)}{dX} - \frac{4}{D}F_r = 0 \quad \text{.....(C-1)}$$

The first term in Eq. (C-1) is the momentum flux per unit cross sectional area and the second term is the pressure force. Fanning's equation is used to determine F_r , the friction force acting on the inside wall,

$$F_r = f(\rho V_a^2/2) \quad \text{.....(C-2)}$$

where, $f = 0.0791/Re'^{0.25}$ ($2.1 \times 10^3 < Re' < 10^5$)

Fig. C-1. Blast gas temperature along the X -direction in the burning zone.

Fig. C-2. Distance between injection position and position where particles burn out in relation to blast velocity.

$$Re' = \rho D V_a / \mu.$$

Therefore, the simultaneous solution of Eqs. (2) to (4), (11) to (13) and (C-1) gives the variation of V_a , T_g and the other factors such as P and U with the distance, X . The initial conditions ($t=t_1$ or $\theta=0$) are:

$$V_a = V_{a0}, \quad \rho = \rho_0, \quad M_d(\theta) = 1, \quad P = P_0, \\ V_p = V_p(t_1), \quad X = X_p(t_1), \quad T_g = T_0$$

The numerical results are compared with those calculated from Eqs. (15) and (16). Figures C-1 and C-2 show the variation of T_g with the distance, X and the warm-up plus burning zone distance, X_b with V_{a0} , respectively. The numerical results are given by the dotted line and the approximate ones are the full line. In this numerical calculation, the variation of P/P_0 with X has been in the range 0.99 to 1 and that of U/V_{a0} has been between 0 and 0.1 in the burning zone. Consequently, assumptions (8) and (9) and the approximate solutions given by Eqs. (14) to (16) are considered to be reasonable.