

Modeling of Effects of Volatile Matter Cloud on Heterogeneous Ignition of Single Coal Particles

HASSAN KATALAMBULA¹, JUN-ICHIRO HAYASHI¹,
KUNIHIRO KITANO² AND TADATOSHI CHIBA¹

¹Center for Advanced Research of Energy Technology,
Hokkaido University, Sapporo 060-8628, Japan

²Hokkaido National Industrial Research Institute,
Sapporo 062-8517, Japan

Keywords: Coal Ignition, Volatile Matter Cloud, Ignition Mechanism, Convection

A simple model has been developed to predict the heterogeneous ignition temperature for single coal particles under conditions of negligible, natural and forced convections. These conditions cause different sizes of the volatile matter cloud surrounding the coal particle. The model is based on the ignition of a single coal particle heated by irradiation from spot heaters in cold (ambient) surroundings. Energy from the particle surface oxidation, volatile matter combustion and physical heating from the spot heaters are all included in the particle energy balance. General ignition criterion is used to determine the ignition point. The model results agree quite well with experimental findings obtained earlier as far as the effects of particle size and volatile matter are concerned. Gas temperature emerged as the most effective model parameter influencing the ignition temperature. In the absence of volatiles in the particle vicinity, as for the forced convection case, the gas temperature remains almost constant and so does the ignition temperature. For cases where volatiles surround the particle, high gas temperatures as well as ignition temperatures are obtained. This is mainly attributed to the combustion of the volatiles contributing to the gas temperature rise, and possibly raising the particle temperature.

Introduction

Mathematical modeling of heterogeneous ignition (i.e. ignition by direct attack of oxygen on the surface of the particle) has been undertaken quite extensively by a number of researchers. Results from most of these models have shown a decreasing ignition temperature with increasing particle size. On the other hand, the effect of volatile matter on the heterogeneous ignition temperature and ignition mechanism has received less attention. In their transient model, Du and Annamalai (1994), presented the effect of a number of parameters on ignition temperature of single coal particles and showed a weak dependence of the heterogeneous ignition temperature on volatile matter. Zhang and Wall (1993) reported that the effect of volatile matter on the heterogeneous ignition temperature is reduced when the oxygen concentration is increased. At low oxygen concentrations, the contribution of volatile matter combustion to ignition is significant, and ignition seems to be in the gas phase (homogeneous). They did not, however, specify the limit of oxygen concentration above which the contribution of volatile matter ceases to be significant.

Our previous work on the effect of particle size on ignition temperature found the trend to be opposite to those generally reported in literature (Katalambula *et al.*, 1996). However, the findings were mainly due to the fact that the heating rate was maintained almost constant, something which seemed to be missing in most of the other reported works. In addition, not a single mathematical model has been made to describe these new finding, hence prompting the need to develop one for the purpose.

Since ignition is due to the interaction between chemical and physical processes occurring in a system, the onset of ignition must be defined to include not only the chemical processes but the physical ones as well (Phuoc *et al.*, 1993). A number of models have considered only the heat generated by the char surface oxidation, and do not consider the effect of volatiles combustion on the heterogeneous ignition. Generally, during volatile (gas phase) combustion, the heat from the volatile flame is transferred to the particle by conduction, thus contributing to heating up the particle (Gururajan *et al.*, 1990).

As far as the model assumptions are concerned, many authors have assumed a symmetrical distribution of volatiles around the particle and no relative motion between the particle and the gas (Du and Annamalai, 1994; Phuoc *et al.*, 1993; Yang and Wang, 1990; Gururajan *et al.*, 1990). Some have neglected

Received on April 2, 1999. Correspondence concerning this article should be addressed to T. Chiba (E-mail address: chiba@carbon.caret.hokudai.ac.jp).

the effect of radiation and natural convection (Zhang and Wall, 1993; Phuoc *et al.*, 1993). While it is a common practice to draw some assumptions in order to simplify development of the model, it is sometimes better to simplify the process/phenomenon itself so that the assumed condition is achieved. For example, for an experiment done under normal gravity conditions, no symmetry of the released volatiles can be achieved since natural convection sweeps away some of the volatiles. In so doing, the amount of volatiles taking part in the combustion reaction is affected, and consequently affecting the final results. If the experiment is performed under microgravity condition where natural convection is negligible, a good symmetry of released volatiles will be achieved and a better agreement between experimental and theoretical results can be realized.

As for the determination of the ignition point, some models have applied char weight loss as an indicator (Du and Annamalai, 1994; Yang and Wang, 1990), while some have employed Semenov's thermal explosion theory (Zhang and Wall, 1993; Wall and Gururajan, 1986; Chen, 1996; Chen *et al.*, 1994; Krishna and Berlad, 1980). Others defined the ignition point as a transition from a low temperature or kinetically controlled combustion regime to a high temperature and diffusion controlled combustion regime (Gururajan *et al.*, 1990). Phuoc *et al.* (1993) used the ratio between chemical energy and laser energy as an indicator of the ignition. Since the experiments on which this model is based (Katalambula *et al.*, 1996, 1997a, 1997b) determined the ignition temperature by a sudden jump in the particle temperature history, the theoretical part will also be based on the same principle employing the general ignition criterion.

Given the above few shortcomings, this work aims at developing a model which will address the effect of volatile matter as well as particle size on the ignition mechanism and ignition temperature. The model will also demonstrate how convection plays a part in determining the ignition mechanism.

1. Model Formulation

Considered is a problem of a single coal particle ignition in cold (ambient) surroundings. It is initially heated by infrared radiation from spot heaters, which raises the particle temperature. The heat generated by the volatiles combustion heats up the particle. The surrounding gas is then heated through the particle-gas heat transfer. The particle can also directly exchange heat with the surrounding gas by radiation. To change the size of the volatile matter cloud, three conditions are employed, namely negligible, natural and forced convections (Katalambula *et al.*, 1997b). Under negligible convection, all the volatiles released stay in the

particle vicinity thus giving the maximum volatile cloud size while under natural convection, only a portion of the released volatiles remain in the particle vicinity, the rest are swept away. Under forced convection, all the released volatiles are swept away from the particle as soon as they are released, therefore there are no volatiles left in the particle vicinity.

1.1 Assumptions

The assumptions put forward in the development of the present model are:

- 1) Heterogeneous ignition takes place soon after volatile combustion is complete;
- 2) The particle is dry, ash-free and spherical in shape;
- 3) A negligible temperature gradient exists within the particle;
- 4) Char oxidation is expressed as a first order irreversible reaction with respect to oxygen concentration and evaluated at the external surface of the particle. The product of oxidation is CO₂;
- 5) The heat of devolatilization is neglected as it is small compared to the heat of the surface oxidation and volatile matter combustion;
- 6) Boundary layer diffusion is neglected because the layer is not established until an appreciable reaction is in progress, i.e. until after the ignition.

Assumption 1 above is more of a fact than an assumption. In our previous work (Katalambula *et al.*, 1997a), it was experimentally found that char would not ignite when there is still a volatile cloud in its vicinity. The volatile cloud normally prevents the oxygen from reaching the particle surface, hence hindering the ignition. Once the volatile cloud has been removed, either by combustion or otherwise, the oxygen then is capable of reaching the particle surface and char ignition takes place.

1.2 Governing equations

Heat balance for a coal particle subjected to an external heat supply is given instantaneously by

$$m_p c_p \left(\frac{dT_p}{dt} \right) = Q = Q_{\text{gain}} - Q_{\text{loss}} \quad (1)$$

The heat gained by a particle, Q_{gain} , is made up of three sources, namely:

- a) Heat due to physical heating, Q_p , which could be from hot gases in a hot furnace, laser beam, electrical heating coil or spot heaters as in the present case;
- b) Heat due to volatile combustion, Q_v , originating from combustion of volatiles taking place in the vicinity of the particle, also referred to as heat feedback to the particle (Masami and Okazaki, 1988); and
- c) Heat due to char oxidation, Q_c .

So the total heat gained can be written as

$$Q_{\text{gain}} = Q_p + Q_v + Q_c \quad (2)$$

The physical heat from the spot heaters, Q_p , is calculated based on the light concentration principle. The spot heaters' light concentrator has a truncated cone shape shown in **Fig. 1** from which its area can be calculated. Knowing the focal area (manufacturer specified) gives the energy concentration factor. The spectral absorption efficiency, a_s , is estimated from the Mie theory and in this case is the same as that used by Zhang *et al.* (1994). Electrical to light to heat energy conversion factor, e_{cf} , is taken as 30% while n_s is the number of spot heaters and p_{pa} is the power delivered to the particle per unit particle surface area. So, the physical heat can be given by the following equation:

$$Q_p = e_{cf} a_s n_s p_{pa} \quad (3)$$

The heat due to volatile combustion, Q_v , can be calculated by

$$Q_v = H_v v_{cf} \frac{d(m_{vr})}{dt} \quad (4)$$

where H_v is the heat of reaction of the volatiles (assumed to be a one component gas) obtained by calculating the average value of the heat of reaction for individual volatile matter components released from a coal particle using the Curie Point pyrolyzer. The components included H_2 , CO , CH_4 , C_2H_4 , C_2H_6 , C_3H_6 , C_3H_8 , C_4H_8 , C_4H_{10} , and tar.

v_{cf} is the volatile concentration factor which can take a value of 1.0 if all the released volatiles are burnt in the particle vicinity, and it can be zero if none of the volatiles are burnt. The intermediate values indicate situations in between.

The last term in Eq. (4) is the rate of volatile release and is defined by

$$\frac{d(m_{vr})}{dt} = A_v (m_{vt} - m_v(T_p)) \exp\left(\frac{-E_v}{RT_p}\right) \quad (5)$$

m_{vt} is the total mass of volatiles contained in a coal particle and is obtained by the product of particle weight and volatile matter content. $m_v(T_p)$ is the amount of volatiles released until the particle reaches a temperature T_p and is estimated by Eq. (6). The parameter $m_v(T_p)$ is important in estimating the time dependent changes in the mass of char or volatiles which are not measured experimentally. This is achieved by making use of the time dependent changes in the size of the volatile cloud by assuming it to behave as a one component gas.

$$m_v(T_p) = vs(T_p) d_p w_{VM} \rho_v \quad (6)$$

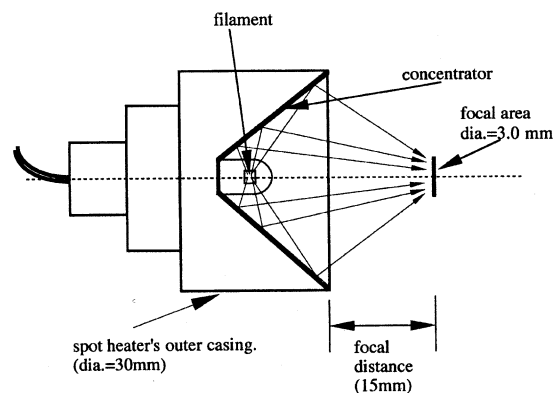


Fig. 1 Cross-section of spot heater showing shape of the light concentrator

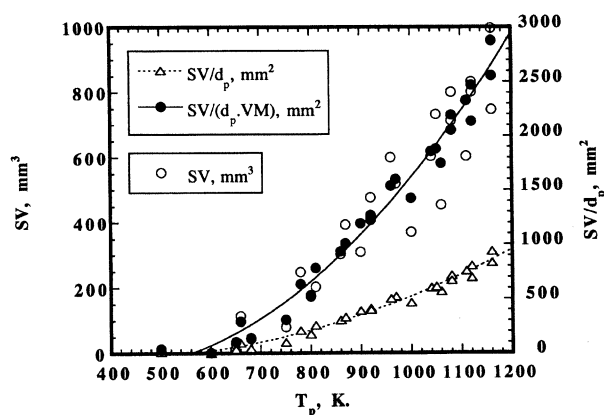


Fig. 2 Correlation for the dependence of volatile volume released on particle temperature. SV refers to volatile volume at STP

$vs(T_p)$ is the correlation for volatile volume as a function of T_p obtained from the experimental results reported previously (Katalambula *et al.*, 1997a). The observed volatile volumes are first converted to standard temperature and pressure (STP) to give the standard volume, SV. The standard volume is then divided by the particle size, SV/d_p and then by volatile matter content, $SV/(d_p \cdot w_{VM})$. The obtained results are shown in **Fig. 2**. The correlation for this is given in Eq. (7) and it represents the volume of volatiles released from a particle of unit size and unit volatile matter content:

$$vs(T_p) = 576 - 3.65T_p + 0.0047T_p^2 \quad (7)$$

Heat due to char oxidation, Q_c , is given by

$$Q_c = S_p H_c Y_{O_2}^N \left. \frac{dC}{dt} \right|_{T_p} \quad (8)$$

where

Table 1 Model parameters and values

Parameter	Description	Value	Units
A_c	pre-exponential factor for char oxidation	5.41×10^3	kg/m ² s
A_v	pre-exponential factor for devolatilization	6.74×10^7	s ⁻¹
E_c	activation energy for char oxidation	150.0	MJ/Kmol
E_v	activation energy of devolatilization	113.0	MJ/Kmol
H_c	heat of reaction for char oxidation	32790	kJ/kg
H_v	heat of reaction for volatiles	22000	kJ/kg
N	order of reaction	1.0	—
R	universal gas constant	8.314×10^{-3}	kJ/mol·K
Y_{O_2}	O ₂ mole fraction at particle surface	0.23	—
ε	emmissivity of coal	0.8	—
σ	stefan-Boltzmann constant	5.67×10^{-8}	W/m ² K ⁴
ρ_{coal}	density of coal particle	1.2×10^3	kg/m ³
v_{cf}	volatiles concentration factor	1.0 for negligible convection 0.5 for natural convection 0.0 for forced convection	— — —

$$\left. \frac{dC}{dt} \right|_{T_p} = A_c \left(\frac{m_{\text{ct}} - m_c(T_p)}{m_{\text{ct}}} \right) \exp \left(\frac{-E_c}{RT_p} \right) \quad (9)$$

and m_{ct} is the total mass of char given by

$$m_{\text{ct}} = m_{\text{coal}} - m_v(T_p) \quad (10)$$

The heat loss sources include convection and radiation, which are written as

$$Q_{\text{loss}} = \frac{Nu\lambda}{d_p} (T_p - T_g) + \varepsilon\sigma(T_p^4 - T_g^4) \quad (11a)$$

where Nu is the Nusselt number given by:

$$Nu = 2.0 + 0.6 \left(\frac{d_p u_g \rho_g}{\mu_g} \right)^{1/2} \left(\frac{c_g \mu_g}{\lambda_g} \right)^{1/3} \quad (11b)$$

In a short time interval, a linear increase of the particle temperature with time can be assumed. This assumption refers to the increase in particle temperature prior to ignition. The experimental work in this regard has been done and can be found in our previous work where temperature histories for particles ignited under different conditions are presented (Katalambula *et al.*, 1997b). It is clear from these temperature histories that a linear approximation is valid below ignition point and exponential approximation may be valid thereafter.

The particle temperature can then be expressed as a function of time as shown below:

$$T_p = T_{p0} + \frac{dT_p}{dt} t \quad (12)$$

For the estimation of gas temperature, T_g , two heat sources are considered, namely heat due to combustion of volatiles taking place around the particle, Q_v , and that due to the radiation from the particle to the volatiles Q_{lr} . Substitution of T_p in the respective equation gives Q_v as a function of time, t , and Q_{lr} as a function of both t and T_g . Thus the heat balance for the volatiles yields

$$m_v(t) c_{pv} \frac{dT_g}{dt} = Q_v + Q_{\text{lr}} \quad (13)$$

A numerical solution for the above equation by the Runge Kutta-Gill method gives T_g as a function of t and hence as a function of T_p for a given particle heating rate.

Based on the general ignition criterion (Wong *et al.*, 1995; Essenhigh *et al.*, 1989), ignition occurs when:

$$Q_{\text{gain}} \geq Q_{\text{loss}} \quad (14)$$

Equation (1) is then solved for T_p which gives the particle temperature at ignition.

1.3 Kinetic parameters

Kinetic parameters were determined stagewise employing different conditions. The first stage involved determining the parameters under forced convection. Under this condition, T_g remains constant since all volatiles were blown away as soon as they were released and hence they did not ignite in the particle's vicinity. The volatile concentration factor, v_{cf} , in this

Table 2 Sensitivity Check: Percentage change in ignition temperature due to $\pm 10\%$ change in a given parameter

Parameter	Forced convection		Natural convection		Negligible convection	
	+10%	-10%	+10%	-10%	+10%	-10%
H_v, A_v	0.0	0.0	0.0	-0.1	0.1	0.0
E_v	0.0	0.0	-0.3	0.8	-0.3	0.9
H_c, A_c	0.0	0.0	0.0	0.0	0.0	0.0
E_c	0.0	0.2	-0.1	0.4	-0.2	1.2
Q_p	0.8	-0.7	0.6	-0.7	0.7	-0.5

case is zero and the pre-exponential factor A_c was determined, while H_c and E_c are obtained from literature (Du and Annamalai, 1994). Determination of the pre-exponential factor was done by varying the A_c value until a reasonable fit of the curve to the experimental data was obtained. The second stage was under negligible convection. In this case all the volatiles accumulated around the particle, hence $v_{cf} = 1.0$. For volatiles combustion, A_v was then determined and H_v and E_v were obtained from literature (Du and Annamalai, 1994; Phuoc *et al.*, 1993). The third stage involved fitting theoretical to experimental results employing parameters established above. The v_{cf} was adjusted so as to obtain the best fit. The value of v_{cf} indicates the proportion of the released volatiles taking part in the combustion reaction. Other model parameters and their values are listed in **Table 1** and a sensitivity check for these parameters is presented in **Table 2**. It can be seen that with a change of $\pm 10\%$ of the value of a given parameter (when all other parameters are held constant), the resulting change in the heterogeneous ignition temperature is negligibly small, implying that small variations in these parameters will not affect the model results.

2. Results and Discussion

The experimental results used for validation of this model are previously reported (Katalambula *et al.*, 1996, 1997a, 1997b), and all the ignition temperatures refer to heterogeneous ignition temperatures.

2.1 Effect of volatile matter content on ignition

Under forced convection, the ignition temperature, $T_{c(F)}$, as well as the gas temperature, T_g , remained unchanged with a change in the volatile matter content, w_{VM} , (coal type) as depicted in **Fig. 3**. This shows that under forced convection, the volatiles have no effect at all since they are all swept away as soon as they are released, and hence they do not have time to burn and cause any temperature change on either the surrounding gases or the particle itself. The gas temperature, T_g , in this case remained constant and about the same as that of the hot air blown to the particle for forced convection. This implies that T_g depends to a large extent on the volatiles combustion.

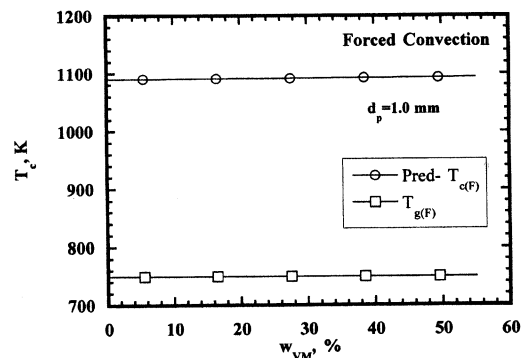


Fig. 3 Variation of gas temperature and ignition temperature with volatile matter content under forced convection

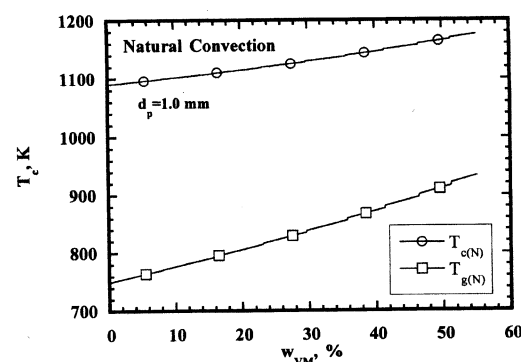


Fig. 4 Variation of gas temperature and ignition temperature with volatile matter content under natural convection

Figure 4 shows the variation of T_g and T_c with w_{VM} under natural convection. In this case, as opposed to the forced convection, it is seen that both T_g and T_c increases with w_{VM} , but T_g increases much faster than T_c . The increase of T_g is attributed to the presence of volatile matter in the particles vicinity, the combustion of these volatiles in the gas phase causes T_g to rise. A similar explanation can be given for the case of negligible convection shown in **Fig. 5**. Both T_g and T_c increase with increasing w_{VM} . In this case, all the volatiles released stay in the particle vicinity, and upon

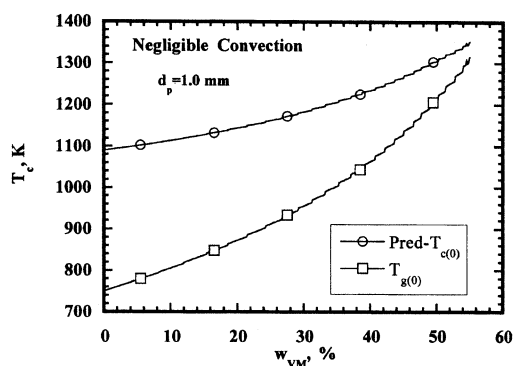


Fig. 5 Variation of gas temperature and ignition temperature with volatile matter content under negligible convection

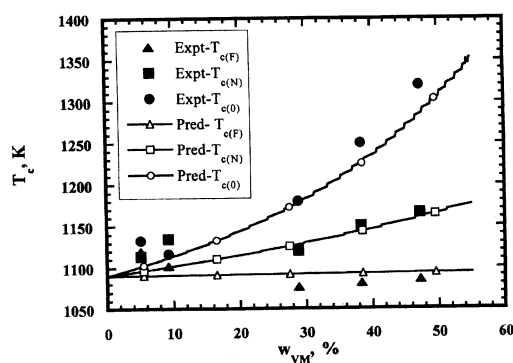


Fig. 6 Comparison of experimental and predicted results on the variation of ignition temperature with volatile matter content under negligible, natural and forced convection

ignition and combustion, they contribute significantly to the rise in T_g . At higher values of w_{VM} , T_g exceeds the particle temperature. At this point, the gas heats up the particle. Masami and Okazaki (1988) have reported that when the evolving flux of volatile matter from the particle surface in the stage of volatile matter combustion is larger than the equivalent oxygen flux to the particle from the surrounding air, the reaction/flame zone is pushed away from the particle surface. The feedback rate of the heat released in this flame zone to the particle depends on how far the flame zone is away from the particle. Hence, it can generally be said that, as volatile evolution decreases, the flame zone comes closer and closer and finally touches the particle, hence giving a maximum heat feedback.

Figure 6 puts together the above cases and shows the variation of the heterogeneous ignition temperature, T_c , with volatile matter content, w_{VM} , under the different experimental conditions. Both the experimental and calculated results are presented for comparison. For the natural convection case, the calculated results are fitted to the experimental ones by fixing the value of v_{cf} at 0.4 to 0.5. This indicates that less

Table 3 Standard and experimental volatile matter content values

Coal name	Standard VM values [%]	Experimental VM values [%]
Pennsylvania	4.4	5.1
Mt. Klappan	8.0	9.2
Datong	26.0	28.9
Coal Valley	32.5	38.3
Taiheiyō	40.2	47.2

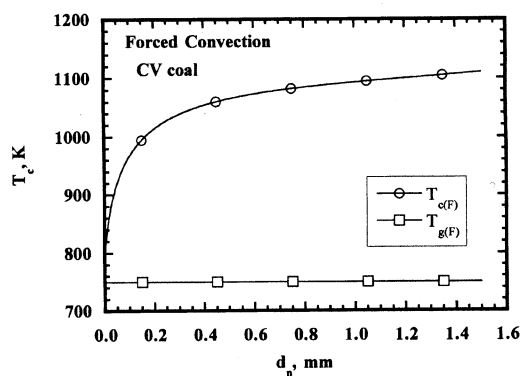


Fig. 7 Variation of gas temperature and ignition temperature with particle size under forced convection

than a half of the released volatiles are combusted, while the rest are swept away by natural convection. The volatile matter content values used are the ones which were obtained experimentally using the current experimental setup. These values are used because volatile yield increases with heating rates. The standard w_{VM} values and the experimentally obtained ones are presented in Table 3. It can be seen that the model can predict quite well the variation of T_c with w_{VM} under different conditions as exhibited by the good agreement between experimental and model results. The difference in ignition temperatures between different conditions decreases with decreasing w_{VM} of the coal. As far as ignition mechanism is concerned, the model shows that for lower volatile matter contents, the effect of convection becomes insignificant, suggesting a transfer of ignition phase (TIP) at volatile matter contents below 10%. The transfer of ignition phase means a change from homogeneous to heterogeneous ignition and vice versa.

2.2 Effect of particle size

For the case of forced convection, the variation of T_g and $T_{c(F)}$ with particle size, d_p , is presented in Fig. 7. As in the case of variation with the volatile matter, T_g remains unchanged when d_p is varied. Generally, when d_p is varied, the absolute amount of volatiles in the particle vicinity also changes, but this change does not cause any gas temperature increase because all the volatiles are swept away before they ignite. T_c , how-

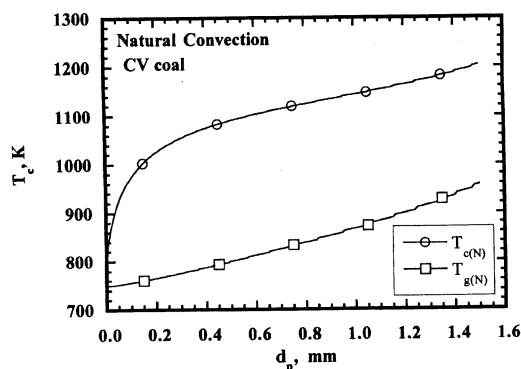


Fig. 8 Dependence of gas temperature and ignition temperature on particle size under natural convection

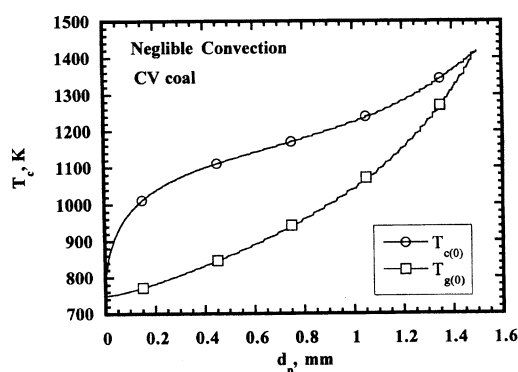


Fig. 9 Variation of gas temperature and ignition temperature with particle size under negligible convection

ever, rises quite sharply at first, but it then gradually slows down with increasing d_p . From the exhibited trend, it seems that for d_p above $400 \mu\text{m}$, an increase in d_p does not have a significant effect on $T_{c(F)}$, although it is not negligible. Figure 8 also shows the variation of T_g and $T_{c(N)}$ with d_p . Here, T_g as well as T_c are seen to increase with d_p . The increase of T_g can be attributed to the availability of volatiles in the particle vicinity which upon combustion contributes to an increase in T_g . Figure 9 presents the negligible convection case where T_g increases until it exceeds $T_{c(0)}$ at d_p of about 1.4 mm. This is due to the fact that the absolute amount of volatiles increases with particle size. Accumulation of these volatiles around the particle under negligible convection condition leads to higher T_g after the volatiles ignition and combustion.

The experimental and predicted results for the effect of particle size, d_p , on T_c are shown in Fig. 10. The model shows an increasing T_c with increasing d_p under all the three conditions as previously reported (Katalambula *et al.*, 1997a). The agreement between the predicted and experimental results is quite reasonable. On the other hand, the model shows that convec-

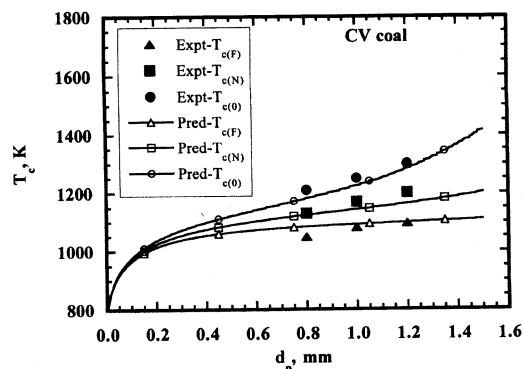


Fig. 10 Effect of particle size on ignition temperature under negligible, natural and forced convection: Comparison of experimental and predicted results

tion has no effect on small particles (below $200 \mu\text{m}$), implying a transition of the ignition phase from homogeneous to heterogeneous ignition. Whereas $T_{c(F)}$ and $T_{c(N)}$ seem to increase almost linearly after the initial sharp rise, $T_{c(0)}$ forms a sigmoid shaped curve exhibiting a second sharp rise as d_p increases. This could be due to the increasing amount of volatiles in the particle vicinity as the particle size increases, hence resulting into higher gas temperature, and consequently the heterogeneous ignition temperature.

2.3 General observation

In the present model, gas temperature, T_g , has emerged as a very strong parameter in influencing ignition temperature. In the absence of volatiles in the particle vicinity, as for the forced convection case, T_g has remained almost constant and so has $T_{c(F)}$. For the cases where the volatiles surrounded the particle, T_g as well as T_c increased simultaneously, mainly being due to the combustion of the volatiles which contributed to the gas temperature rise and possibly raising the particle temperature.

Conclusion

A model for predicting the effect of convection on heterogeneous ignition of single coal particles has been developed. The predicted results on the effects of volatile matter, particle size and heating rate on the heterogeneous ignition temperature show a good agreement with the experimental ones. Within the limits of the current model, the followings are concluded:

- 1) The amount of volatiles surrounding a coal particle significantly influences the ignition mechanism and ignition temperature;
- 2) The gas temperature is a very strong parameter in influencing the ignition temperature under any conditions. At the same time, gas temperature strongly depends on the amount of the volatiles in the particle vicinity;

- 3) Under forced convection, ignition characteristics are independent of coal type;
- 4) Under normal gravity, only 40–50% of the released volatiles is combusted, the rest is swept away by natural convection;
- 5) Both the volatile matter content and the particle size have an appreciable influence on the ignition mechanism.

Nomenclature

A_c	=	pre-exponential factor for char oxidation	[kg·m ⁻² s]
A_v	=	pre-exponential factor for volatile release	[s ⁻¹]
a_s	=	spectral absorption efficiency	[—]
c_p	=	specific heat	[J·kg ⁻¹ K]
d_p	=	particle diameter	[m]
E_c	=	activation energy for char oxidation	[MJ·Kmol ⁻¹]
E_v	=	activation energy of devolatilization	[MJ·Kmol ⁻¹]
e_{cf}	=	energy conversion factor	[—]
H_c	=	heat of reaction for char oxidation	[kJ·kg ⁻¹]
H_v	=	heat of reaction for volatiles	[kJ·kg ⁻¹]
m	=	mass	[kg]
m_{vt}	=	total mass of volatiles contained in a coal particle	[kg]
$m_v(T_p)$	=	amount of volatiles released until temperature T_p	[kg]
N	=	order of reaction	[—]
n_s	=	number of spot heaters	[—]
P_{pa}	=	power delivered to the particle	[kJ·s ⁻¹]
Q	=	net heat supply rate	[kJ·s ⁻¹]
Q_c	=	heat due to char oxidation	[kJ·s ⁻¹]
Q_g	=	rate of heat generation/gain	[kJ·s ⁻¹]
Q_l	=	rate of heat loss	[kJ·s ⁻¹]
Q_p	=	heat due to physical heating	[kJ·s ⁻¹]
Q_v	=	heat due to volatile combustion	[kJ·s ⁻¹]
R	=	universal gas constant	[kJ·mol ⁻¹ K ⁻¹]
S_p	=	particle surface area	[m ²]
T	=	temperature	[K]
T_c	=	particle temperature at char ignition	[K]
t	=	time	[s]
t_c	=	time taken for char ignition	[s]
U	=	gas velocity	[m·s ⁻¹]
v	=	volume	[m ³]
v_{cf}	=	volatiles concentration factor	[—]
v_s	=	specific volatile volume per unit particle size	[m ³ /m]
w_{vm}	=	volatile matter content of coal	[wt%]
Y_{O_2}	=	oxygen mole fraction	[—]
ϵ	=	emmissivity of coal	[—]
λ	=	thermal conductivity of gas	[W·m ⁻¹ K ⁻¹]
μ	=	viscosity	[kg·m ⁻¹ s ⁻¹]
ρ	=	density	[kg·m ⁻³]
σ	=	Stefan-Boltzmann constant	[W·m ⁻² K ⁻⁴]

<Subscript>

c	=	char
g	=	gas
p	=	particle
v	=	volatiles
(F)	=	Forced convection
(N)	=	Natural convection
(O)	=	Negligible convection

Literature Cited

- Chen, J. C.; "Distributed Activation Energy Model of Heterogeneous Coal Ignition," *Combust. Flame*, **107**, 291–298 (1996)
- Chen, J. C., M. Taniguchi, K. Narato and K. Ito; "Laser Ignition of Pulverized Coals," *Combust. Flame*, **97**, 107–117 (1994)
- Du, X. and K. Annamalai; "The Transient Ignition of Isolated Coal Particle," *Combust. Flame*, **97**, 339–354 (1994)
- Essenhugh, R. H., M. K. Misra and D. W. Shaw; "Ignition of Coal Particles: A Review," *Combust. Flame*, **77**, 3–30 (1989)
- Gururajan, V. S., T. F. Wall, R. P. Gupta and J. S. Truelove; "Mechanism for the Ignition of Pulverized Coal Particles," *Combust. Flame*, **81**, 119–132 (1990)
- Katalambula, H., K. Kitano, K. Ikeda and T. Chiba; "Mechanism of Ignition of Single Coal Particle: Effect of Heating Rate on Particle-Size Dependence of Ignition Temperature," *J. Chem. Eng. Japan*, **29**, 523–530 (1996)
- Katalambula, H., K. Kitano, K. Ikeda, J.-i. Hayashi and T. Chiba; "Mechanism of Single Coal Particle Ignition under Microgravity Condition," *J. Chem. Eng. Japan*, **30**, 146–153 (1997a)
- Katalambula, H., K. Kitano, K. Ikeda, J.-i. Hayashi and T. Chiba; "Dependence of Single Coal Particle Ignition Mechanism on the Surrounding Volatile Matter Cloud," *Energy and Fuels*, **11**, 1033–1039 (1997b)
- Krishna, C. R. and A. L. Berlad; "A Model for Dust Cloud Autoignition," *Combust. Flame*, **37**, 207–210 (1980)
- Masami, T. and K. Okazaki; "Temperature History of Burning Particles with Scattering, Absorbing, and Emitting in Pulverized-Coal Combustion," *Coal Combustion Science and Technology of Industrial and Utility Applications*, J. Feng, ed., p. 139–146, Hemisphere Publishing Corp., New York, USA (1988)
- Phuoc, T. X., M. P. Mathur and J. M. Ekmann; "High Energy Nd-Yag Laser Ignition of Coals; Experimental Observations," *Combust. Flame*, **93**, 19–30 (1993)
- Wall, T. F. and V.S. Gururajan; "Combustion Kinetics and the Heterogeneous Ignition of Pulverized Coal," *Combust. Flame*, **66**, 151–157 (1986)
- Wong, B. A., G. R. Gavalas and R. C. Flagan; "Laser Ignition of Levitated Char Particles," *Energy and Fuels*, **9**, 484–492 (1995)
- Yang, J.-T. and G. G. Wang; "The Effect of Heat Transfer on Coal Devolatilization," *J. Heat Transfer*, **112**, 192–200 (1990)
- Zhang, D. K. and T. F. Wall; "An Analysis of the Ignition of Coal Dust Clouds," *Combust. Flame*, **92**, 475–480 (1993)
- Zhang, D., T. F. Wall and P. C. Hills; "Ignition of Coal Particles: The Influence of Experimental Technique," *Fuel*, **73**, 647–655 (1994)