COMBUSTION OF A SINGLE LARGE LIGNITE PARTICLE

S. Tia, P. Pravalpruk, and S. Suriyapradilok

Combustion Research Laboratory
Department of Chemical Engineering
King Mongkut's Institute of Technology Thonburi
Bangkok 10140, Thailand.

ABSTRACT

Burn-out time of a single large lignite particle (3-14 mm) was examined using the captive sample technique. Lignite samples were obtained from mines located in the northern part of Thailand. Within the conditions studied, the particle size has significant effect on both the extinction time delay of volatile-supported flame and char burn-out time, while it has little effect on ignition time delay. The extinction time delay of volatile-supported flame was well correlated with particle size by the simple power law. Theoretical analysis showed that the burn-out time of residual char is controlled by mass transfer of oxygen from ambient gas to the particle surface and through the ash layer. The burning time constants for both chemical reaction and mass transfer were also estimated and compared with theory.

INTRODUCTION

The significance of coal to the future of Thailand has been well recognized, particularly for power generation[1]. Both local lignite and imported coal are proposed as future resources to replace oil and natural gas. For the industrial sector, local lignite showed high potential for medium and large scale boilers[2]. However, the combustion of these low-grade coals can be relatively costly due to reduced boiler capacity and efficiency, and the cost incurred in controlling pollution levels. Lignite as a fuel will be more widely accepted by the industrial sector if these problems can be solved. It is, therefore, necessary to gain an understanding of the complex processes that occur during combustion of these lignites in order to improve the existing combustors and to develop new combustion techniques. To design and size a combustion chamber for a given heat release rate, basic information about the burning rate and burn-out time of these lignites should be known.

Coal particles burn in three different stages:[3] (i) heating and evolution of volatile matter, (ii) combustion of volatile products around and behind the coal particle, and (iii) combustion of the residual char which is the longest stage. The controlling mechanism and characteristic time taken by each stage are significantly effected by ambient temperature and size of the coal particles. Devolatilization and combustion of coal volatiles is not yet amenable to exact theoretical description. The theory of char combustion is now fairly well understood. Its combustion rate is controlled by chemical kinetics for small particles at low temperature, whereas large particles at high temperatures burn at a rate which is controlled by the rate of oxygen transport from bulk gas to the outer surface of char. In the intermediate case, the combustion rate is mainly controlled by a combination of pore diffusion and reaction kinetic. In practice, the combustion rate of char depends on both the conditions under which it is produced and the properties of the parent coal from which it is form. Without experimentally derived results concerning char's physical and chemical properties, the prediction of burn-out in a furnace is impossible.

The objective of this study is to measure the total burn-out time of Thai lignite under convective flow using the captive sample technique. The data obtained are compared with the theory reported in the literature. The estimation of burning time constants for both chemical reaction and mass transfer from experimental data are also shown.

EXPERIMENTAL PROCEDURE

Lignite samples having the properties as shown in Table 1 were obtained from Banpu and Lanna Lignite companies. Their origins are both in the northern part of Thailand. After grinding, the particles having nearly spherical shape were filed and weighed. The equivalent diameter of lignite particle was estimated from its weight and apparent density. A small hole about 0.8 mm diameter was drilled in each selected lignite particle, except for the sizes below 5 mm for which the hole size was 0.4 mm. This hole was used to support the lignite particle on a ceramic thread. The weight change due to hole drilling was normally below 1% and can be neglected.

The furnace used in this experiment is made from a ceramic tube of 2.54 cm ID and 35 cm length which is placed horizontally with the electrical heater wrapped on the outside surface. The furnace temperature was measured by using a K-type thermocouple and can be automatically controlled within ±5 K accuracy. The flow rate of air was measured by using a calibrated rotameter.

Table 1 Proximate analysis (ASTM D-3172) and apparent density of lignite samples

	Ban Pu	Lanna
Moisture, %	12.76	15.94
Ash, %	6.95	1.01
Volatile matter, %	42.88	41.40
Fixed carbon, %	37.40	41.55
Apparent density, g/m^3	1.281	1.203

The furnace was preheated to the desired temperature and the air flow rate was adjusted to the desired value. After reaching a steady state, a single lignite particle supported on a ceramic thread was quickly inserted into the furnace. The ignition and extinction time delay of volatile-supported diffusion flame, and burn-out time of residual char were observed visually and recorded by using stop-watches.

RESULTS AND DISCUSSION

It was observed that the combustion behaviour of these lignite samples are the same as described in our previous work.[4] After insertion into the furnace, the particle pyrolyzed with a small spot of glowing combustion at the particle surface. A second or two later a envelope of the volatile-supported flame formed. The times at which the occurrence and extinction of this flame took place were recorded as the ignition and extinction time delays, respectively. Once the volatile-supported diffusion flame disappeared the entire coal particle had a bright orange glow. The time taken from start to stop of bright glow combustion was recorded as residual char

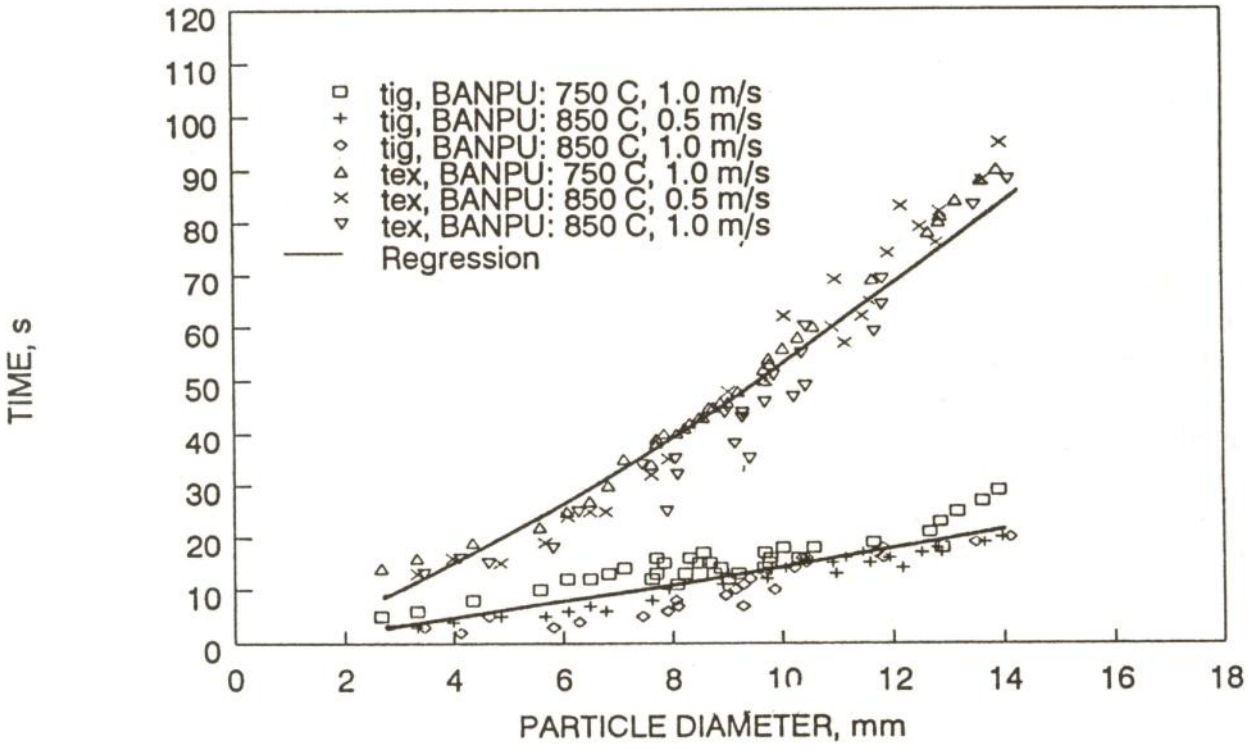

Figure 1 Ignition and extinction time delays of volatile-supported flame for Banpu lignite.

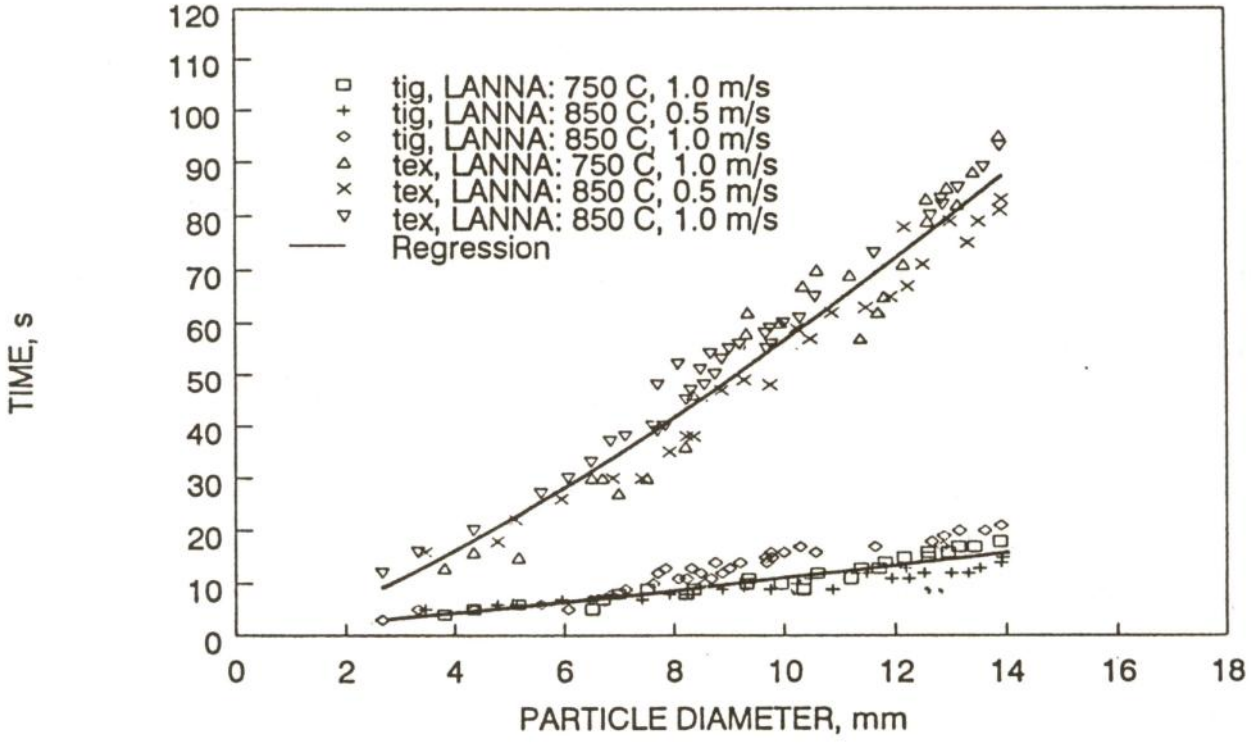

Figure 2 Ignition and extinction time delays of volatile-supported flame for Lanna lignite.

burn-out time. The build-up of ash on the particle surface was observed. For large particle sizes, it was hard to judge when the char was completely burnt by visual observation because of the thick layer of formed ash. The summation of extinction time delay and residual char burn-out time is the total burn -out time of the lignite particle.

The ignition and extinction time delays of volatile-supported diffusion flame are shown in Figs. 1 and 2 respectively, for Banpu and Lanna lignite samples at different ambient conditions. They are of the same order of magnitude as those reported in the literature[4]. Within the experimental conditions, the ignition time delays for both lignites are not sensitive to the initial particle diameter, gas temperature and gas velocity. The extinction time delay of the volatile-supported flame, in contrast, is strongly dependent on the initial particle diameter but only mildly dependent on ambient conditions. Although these time delays are much shorter than the burn-out time of residual char (Figs. 3 and 4) which therefore have less effect on the furnace sizing, the information on these time delays is useful for designing a combustion chamber near the feed point and secondary air supply system.

A theoretical model for the evolution and combustion of volatiles from a single large lignite particle in a hot oxidizing gas stream has been proposed in our previous work.[4] The prediction results are in good agreement with the experiments. However, the model is too complex for practical use. In this study, the simple power law as suggested by Essenhigh[5] was used to fit the ignition and extinction time delays of volatile-supported diffusion flame. For all conditions these time delays may be represented by:

$$t_{ig} = 0.78 d_i^{1.25} \quad \text{(Banpu)}$$
$$= 1.19 d_i \quad \text{(Lanna)} \qquad (1)$$
$$t_{ex} = 2.17 d_i^{1.38} \quad \text{(Banpu)}$$
$$= 2.53 d_i^{1.35} \quad \text{(Lanna)} \qquad (2)$$

where d_i is the initial diameter of coal particle in mm, t_{ig} and t_{ex} are the ignition and extinction time delays in seconds, respectively. Comparison between the experimental data obtained in this study and these correlations are also presented in Figs. 1 and 2. Since both samples are the same rank coal (see Table 1) the correlations of extinction time delay for Banpu and Lanna lignites are nearly the same.

The burn-out time of residual chars, which are respectively shown in Figs. 3 and 4 for Banpu and Lanna lignites, are strongly dependent on particle size but not sensitive to the ambient temperature and gas velocity. As expected, the burn-out time of residual char, about 10 times longer than the extinction time delay, is the longest stage, and thus has greater effect on furnace sizing.

Assuming that the unreacted-core model with first order reaction can be applied for residual char combustion, the theoretical burn-out time of spherical char particle can be written as[6]:

$$t_b = \frac{\rho d_i}{24 n k_c C_o} + \frac{\rho d_i^2}{288 n D_e C_o} + \frac{\rho d_i^2}{72 n Sh D_g C_o}$$
$$= K_c d_i + (K_{d1} + K_{d2}) d_i^2$$
$$= K_c d_i + K_D d_i^2 \qquad (3)$$

where ρ = char density, d_i = initial diameter of char particle, n = 1 if the combustion product is CO_2 and equals 2 if the combustion product is CO, Sh = Sherwood number, D_g = diffusivity of oxygen in ambient gas, D_e = effective diffusivity of oxygen in ash layer, k_c = combustion rate constant, and C_o = concentration of oxygen in the ambient gas. K_C and K_D are the burning time constants for chemical reaction and mass transfer (ash layer, K_{d1}, and gas film, K_{d2}), respectively.

The density of char is estimated from apparent density of parent coal (ρ_o) by:

$$\rho = \rho_o(1 - (\%\text{Volatile} + \%\text{Moisture})/100) \qquad (4)$$

Sherwood number is calculated from[7]:

$$Sh = 2 + 0.6 Re^{1/2} Sc^{1/3} \qquad (5)$$

where Re = Reynolds number and Sc = Schmidt number.

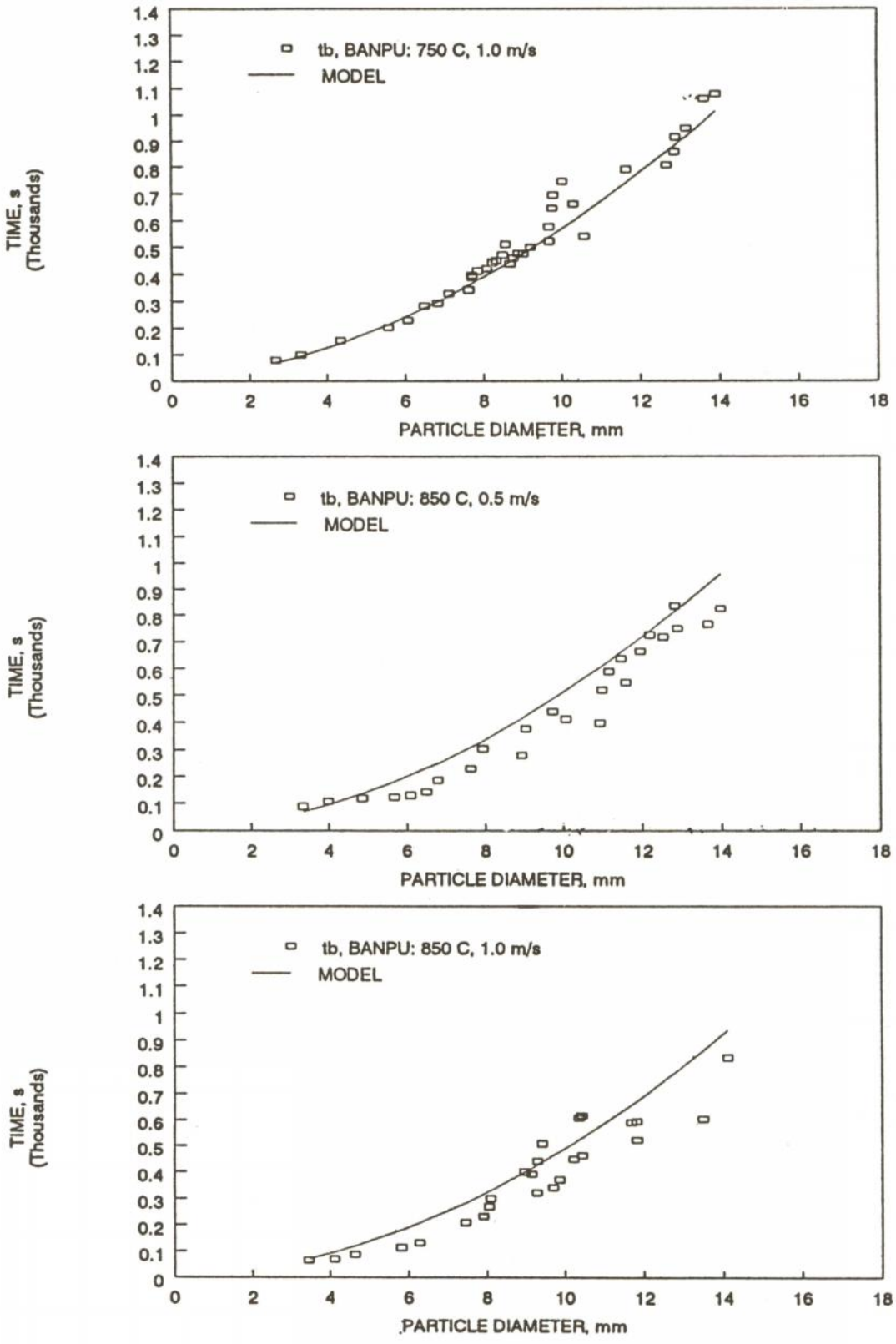

Figure 3 Experimental and predicted burn-out times of residual char from Banpu lignite combustion.

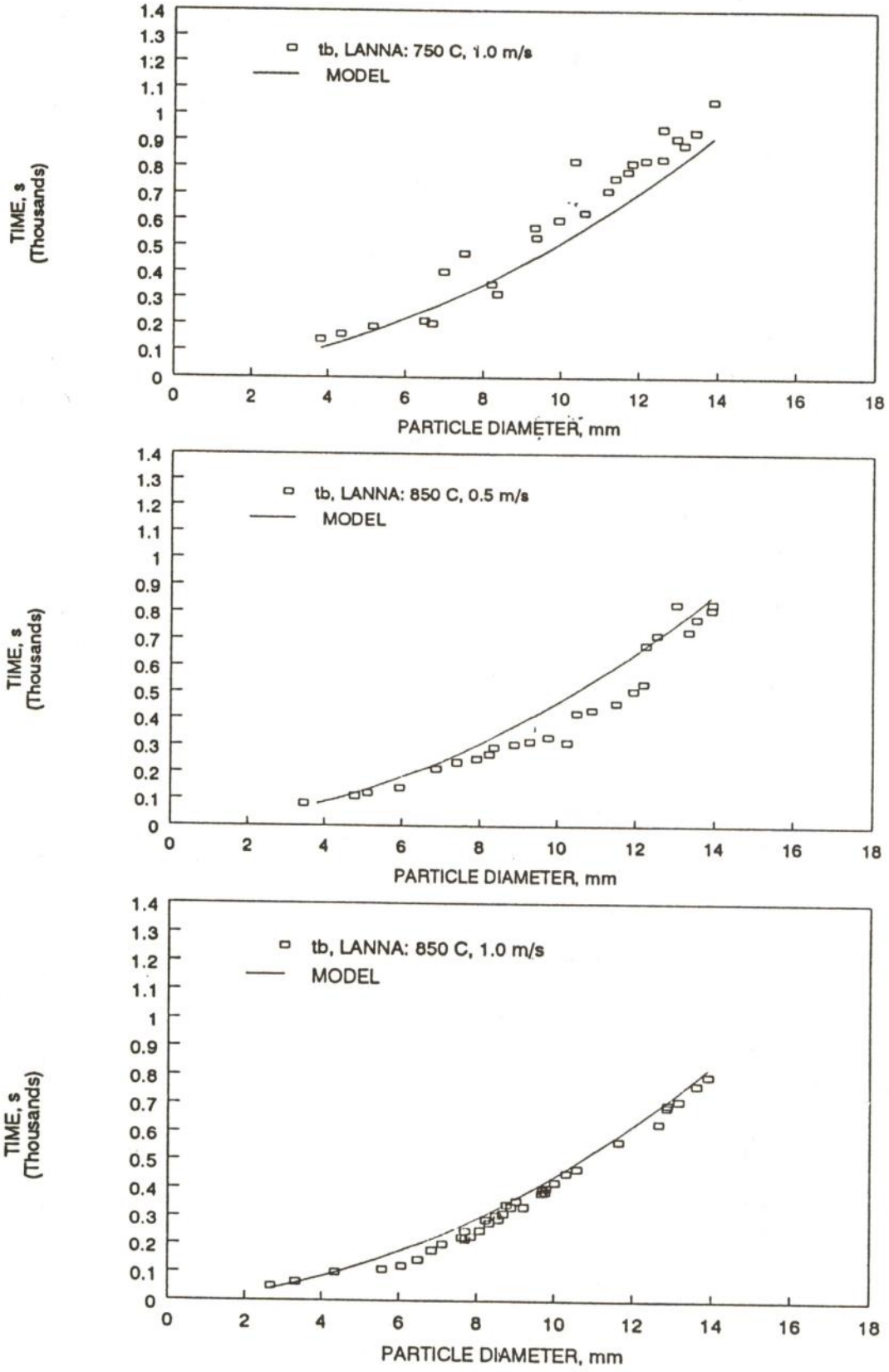

Figure 4 Experimental and predicted burn-out times of residual char from Lanna lignite combustion.

The effective diffusivity of oxygen in ash layer is estimated from[8]:

$$D_e = D_g\epsilon/2 \quad (6)$$

where ϵ = porosity of ash layer.

The combustion rate constant used in this study is [9]:

$$K_c = 59500T_p\exp(-149227/R_gT_p) \text{ cm/s} \quad (7)$$

where T_p = particle temperature (K) and R_g = universal gas constant (8.3143 J/mol.K).

The reported particle temperature during combustion is 100-275 C higher than the ambient gas temperature [4, 10-11] and the value of 100 C is used in this study. For the reaction between carbon and oxygen, it is concluded from the experimental results[12] that the main product of large particle char combustion at about 800 C is CO, and thus n equals 2. Using Eqs. (3)-(7) and the input data presented in Table 2 incorporated with air properties, the burn-out times of residual char were calculated and compared with experimental data as depicted in Figs. 3 and 4 for Banpu and Lanna lignite samples, respectively. With the ash porosity as an adjustable parameter ($\epsilon = 0.9$), the model well predicted the char burn-out time. It was noted that the high value of ash porosity corresponds to the low ash content of the lignite samples (Table 1). The experimental data were also correlated in the form of Eq. (3) using least -square method determine the experimental values of burning time constants (K_C and K_D), and the obtained results were in the same order as those obtained from the theory (Table 3). Any discrepancy can be attributed to the assumption made for particle temperature and ash porosity as well as the problem of ash layer on the recorded burn-out time. For both lignite samples, an increase in the gas temperature causes a significant reduction in K_C value, but only slightly effects K_D. From the calculated results, it is clearly seen that the combustion was controlled by the rate of oxygen transfer through gas film and ash layer when the gas temperature was increased from 750 C to 850 C (K_D/K_C changes from 3.5 to 13). In this study, the burning time constant for mass transfer through ash layer was 3-5 times greater than that across gas film.

For fixed bed combustion, Eq. (3) can be applied by selecting an appropriate Sherwood number (Eq. (5)) concerning gas flow across fixed bed. But for fluidized bed combustion, the ash layer will be peeled off by grinding action of inert particles (sand, limestone), thus internal mass transfer resistance can be neglected from Eq. (3). However, the system introduces additional mass transfer resistance between air bubble and emulsion phase, which is depended on bed properties and air flow rate. This effect should be included in the burning time equation.

CONCLUSIONS

The total burn-out time of single large lignite particle (3-14 mm) was examined by using captive sample technique and was found to be in the order of 100-1,100 seconds. The extinction time delay (10-90 seconds) was much shorter than the char burn-out time and it is well correlated with particle diameter by using a simple power law. The unreacted -core model predicted the char burn-out time excellently. Both experiment and theory indicated that the char burn-out time is controlled by the rate of oxygen transfer through the gas film and ash layer, especially at high temperature. The burning time constants for chemical reaction and mass transfer obtained from experiment are in line with those derived from theory.

REFERENCES

1. Mantajit, N., "Coal Supply in Thailand", Seminar on **the Significance of Coal to Thailand Future,** Nov. 25-26, Bangkok, Thailand, 1993.
2. Chullabodhi, C., Tia, W. and Sasiwimol, S., "Potential of Lignite for Fuel Oil Substitution in Industrial Boilers", **Thailand Engng. Soc. Magazine,** Vol. 43, p. 73, 1990.
3. Essenhigh, R. H., "Coal combustion", in **Chemistry of Coal Utilization,** Ed. Elliott, M. A., 2nd Suppl. Vol., Wiley, New York, 1981.

Table 2 Values of parameters used in Eq. (3).

	750 C	850 C
C_o, mol/cm^3	1.19×10^{-5}	1.08×10^{-5}
D_g, cm^2/s	0.502	0.537
	Banpu	Lanna
ρ, g/cm^3	0.568	0.513
ε	0.90	0.90

Table 3 Burning time constants for chemical reaction and mass transfer.

Śample	Gas Temp. (C)	Gas Vel. cm/s	Experiment		Theory	
			K_C s/cm	K_D s/cm^2	K_C s/cm	K_D s/cm^2
Banpu	750	100	164.6	432.1	129.8	429.1-481.6
	850	50	23.8	417.7	35.6	465.6-519.4
	850	100	13.5	416.6	35.6	444.7-490.5
Lanna	750	100	161.1	428.6	117.3	387.7-423.4
	850	50	22.1	384.5	32.2	420.8-467.8
	850	100	11.3	398.6	32.2	402.2-452.1

4. Tia, S., Bhattacharya, S. C. and Wibulswas, P., "Pyrolysis and Volatile Combustion of a Single Large Lignite Particle", **Energy**, Vol. 16, No. 8, pp 1131-1146, 1991.
5. Essenhigh, R. H., "The Influence of Coal Rank on the Burning Times of Single Captive Particles", **J. Engng. Power**, Vol. 85, p. 183, 1963.
6. Levenspiel, O., "Chemical Reaction Engineering", 2nd ed., Wiley, New York, 1972.
7. Ranz, W.E. and Marshall, Jr., W.R., "Evaporation from Drop, Parts I and II", **Chem. Eng. Prog.**, Vol. 48, pp. 141, 173, 1952.
8. Satterfield, C. N., "Mass Transfer in Heterogeneous Catalysis", MIT Press, Cambridge, MA, 1970.
9. Field, M.A., "Combustion of Pulverized Fuel", BCURA, Leatherhead, England, 1967.
10. Basu, P., "Burning Rate of Carbon in Fluidized Beds", **Fuel**, Vol. 56, p.390, 1977.
11. Chakraborty, R. K. and Howard, J. R., "Burning Rates and Temperatures of Carbon Particles in a Shallow Fluidized -Bed Combustor, **J. Inst. Fuel**, Vol. 51, p. 220, 1978.
12. Arthur, J.R., "Reaction between Carbon and Oxygen", **Trans. Faraday Soc.**, Vol. 47, p. 146, 1951.