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Observation of Coal Fragmentation in Early Stages of Combustion

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Measurements of coal fragmentation in the early stages of combustion were undertaken in the size range of crushed coals for Chinese Dongjin and Indonesian Roto coals. A flat flame burner fed with a premixed mixture of methane, air and partly hydrogen was used for the burning of a single coal particles. A high speed video camera system was used for the observation of coal fragmentation during approximately 80 msec. Fragmentation is consistently observed in the controlled combustion environment over a gas flame temperature range of 1220 K ~ 1320 K. The data indicate that a single coal particle often disintegrates into two, three, and sometimes more fragments. The dominant mechanisim of fragmentation is that producing two fragments in primary fragmentation. The Dongjin coal breaks up more extensively than the Roto coal with the frequency of fragmentation exhibiting a strong particle size dependence and a weaker gas flame temperature dependence. The mean time of primary fragmentation for the Dongjin coal falls to between 10 msec and 20 msec and does not remarkably vary with particle size and gas flame temperature. The mean time of primary fragmentation for the Roto coal is strongly dependent on the particle size, whilst shows less gas flame temperature dependence.

Key Words: Coal Fragmentation, Primary Fragmentation, Fragmentation Frequency, Mean Fragmentation Time, High Speed Motion Analysis System

1. Introduction

Cyclone combustors used centrifugal forces to suspend burning fuel particles according to their size in equilibrium against the drag of inwardly spiralling air, thus increasing their residence time relative to that of the gas. Large particles may, however, be flung to the walls before being completely burnt. On the other hand, some fine particles may be convected out of the system very rapidly(Gupta et al., 1984; Lawn, 1987). The size of fuel particle is, therefore, one of important parameters in designing cyclone combustors. Data in the literature for the development and analysis of non-slagging cyclone combustors show that best performance in terms of carbon burnout and ash retention is obtained with crushed coals in the size range of $d_m = 200 \sim 400$ μm with 90% < 1 mm(Morgan et al., 1988). Study of the fundamental processes has shown the crucial importance of particle fragmentation in predicting pollutant emission, ash retention and carbon burnout in non-slagging units(No and Syred, 1990). The crushed coals were, therefore, selected for the observation of coal fragmentation in this study.

The previous fragmentation studies can be classified as in the fluidised bed combustion and in the pulverised combustion during devolatilisation and char combustion. The fragmentation of coal particle has been mostly recognized in the context of fluidised bed combustor and a review is available (Beer, 1988). Numerous experimental observation and theoretical analysis for char fragmentation can be found in the literature and reviews are available(No, 1990; Baxter, 1992). Fragmentation behaviour in coal combustion

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depends basically on coal type, ash distribution and chemical composition, and also on physical properties and combustion conditions. In addition, fragmentation behaviour in char combustion significantly affects the formation of fly ash and affects both the mean and variance of char burning time.

Several studies have experimentally quantified the processes which take place during the early stages of single coal particle combustion(McLean et al., 1981, Choi, et al., 1991, 1992). Little attention has been, however, paid to the fragmentation during the coal particle heat up and devolatalisation processes. Experiments in this study were, therefore, carried out to quantify the fragmentation in the early stages of coal combustion during which coal particles heat up and devolatilise. The purpose of this study is to investigate the mode of fragmentation, fragmentation frequency and its time as a function of coal type and gas flame temperature. In this paper, the term fragmentation encompasses all phenomena that produce more than a single flame from a coal particle through the direct observation of visual images. The distiction between the apparent volatile flame and the particle flame was based on the assumption of short burning time of volatile flame(McLean et al. 1981).

2. Experiments

A flat flame burner with a syringe type coal feeder and a high speed video camera system were used in this study, Fig. 1. The experiments were undertaken at atmospheric pressure in oxidizing environment provided by a burner fed with premixed mixture of methane, air and partly hydrogen. This burner is a similar type one described by McLean et al.(1981) and Choi et al. (1991). The flame is formed immediately downstream of a 45 mm diameter brass plate. Approximately 350 holes of 1 mm diameter were drilled with 2 mm spacing on the plate. Coal particles are injected into the reactor in a dilute single stream on the centerline of the reactor through a 3 mm diameter capillary tube which partially protrudes through the burner grid. Crushed size-graded coal particles were supplied to the capillary tube by a syringe type coal feeder. To provide uniform particle feeding into the reactor, the tube was regularly stuck by a rod driven by a motor.

The axial and radial temperature distributions in the burner without coal supply were measured. The axial temperature gradient is approximately −500 K/100 mm due to heat loss to the surroundings. Within the first 150 mm of the burner surface the raidial temperature profile is, however, nearly flat within ±75 mm of the centerline.

Two different coals, called Dongjin(China) and Roto(Indonesia) coals following the name of supplier, were tested in this study. The proximate analysis of coals including the heating value is shown in Table 1. The coals were prepared for these experiments by grinding and impact milling. The sample coals were classified as four size bands of sieve mesh number of 140~70(106~212 μm), 70~45(212~355 μm), 45~35(355~500 μm), and 35~25(500~710 μm).

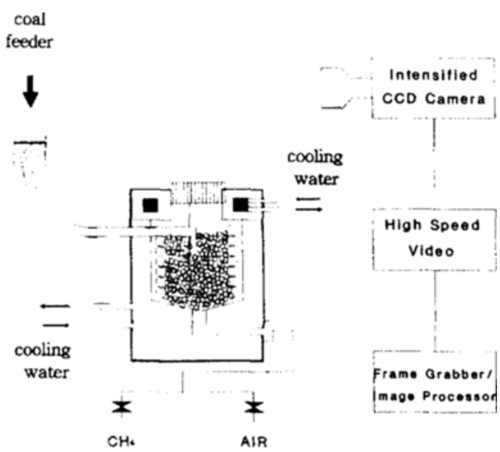

Fig. 1 Schematic diagram of experimental apparatus

Table 1 Typical properties of coals used

		Dongjin	Roto
Proximate analysis	Moisture	3.99	11.83
	Volatile matter	25.68	46.83
	Fixed carbon	58.55	39.80
	Ash	11.78	1.54
Heating value (kJ/kg)		24989	22038

A high speed video camera system was used for the observation of coal fragmentation during coal particle heat up and early stages of combustion. A high speed motion analysis system(KODAK Ektapro 1000) enabled to record visual images at a rate up to 1000 frames per second. The overall experimental technique for high speed motion analysis system is described more fully in the literature(Choi et al., 1991, 1992). In this experiment, a typical particle could be observed for approximately 80 msec. The experiment was duplicated 50 times for the different coals and gas flame temperatures of 1220 K, 1270 K and 1320 K with oxygen concentration of 14.3%, 12.1% and 2.6% respectively. It should be noted that the selected temperatures and oxygen concentrations were measured by the gas analyzer(IRM gas analyzing computer 3000P) at the first 5 mm above the burner surface and in the centerline. The gas flame temperature was selected here to simulate the rapid heat up and devolatilisation processes which occur during crushed coal combustion in the upper part of vertical non-slagging cyclone combustor(Morgan, 1990).

3. Results and Discussions

The single flame of the selected coals have been tested in the flat flame burner. Processes which occur during early phase of coal combustion have been directly observed and recorded by high speed motion analysis system. Various physical phenomena related to coal fragmentation have been identified.

Figure 2 shows the edited photographs of typical mode of fragmentation for different coal particle sizes and gas flame temperatures. When a single coal particle enters the post flame region, is heated and is ignited, bright luminous flames are observed around the particle. Fragmentaton is consistently observed in the controlled combustion environment in the experimental conditions. From (a) it is found that fragmentation producing two fragments occurs at 10 msec for the Roto coal at 1220 K. Two particle flames are visible until about 30 msec and eventually they make a single flame as reaction is progressed. This is probably due to the slip velocity between the particle and the gas. This kind of framentation mode can be classified as percolative fragmentation(Beer, 1988). The different type of fragmentation for the Roto coal at 1320 K is shown in Fig. 2(b). It is found from the figure that flames of volatile cloud around the particle is formed immediately after ignition of coal particle due to evolution of volatiles. The size of the apparent volatile flame is gradually increased as reaction is progressed and then decreased in later stages. Two fragments were produced at 21 msec in the central part of flame.

The typical modes of fragmentation for the Dongjin coal are shown in Figs. 2(c) and (d). In Fig. 2(c) the single particle flame is elongated along the direction of the particle path and then ultimately volatile flame, lifted off from the particle, is formed. Volatile flame lifted off from particles was occasionally observed. This is probably due to the buoyancy effect of the volatile cloud or the slip velocity between the particle and the gas(Choi et al., 1992). When two flames were formed, the separated flame may include the jetting of combustibles from individual pores, and the condensed material formed by volatile matter which eventually separate from the particles. In this study the separted flame which does not persist for more than 3 msec is treated as the volatile flame under the assumption of short burning time of volatile flames(McLean et al., 1981). The volatile flames lifted off from particles were, therefore, not counted as a particle fragmentation owing to the overprediction of the extent of coal fragmentation. In this case, small two fragments seperated from the main particle which may contain char or ash particle is found at 42 msec by the precise observation and thus this kind of data were included in the fragmentation. More than three fragments are produced at 5 msec around the particle for the Dongjin coal at 1320 K, as shown in Fig. 2(d). This is probably due to the thermal stresses or internal pressure generated within a coal particle in the initial heating period of coal combustion.

Figure 3 shows the distributions of number of fragments with the variation of gas flame tempera-

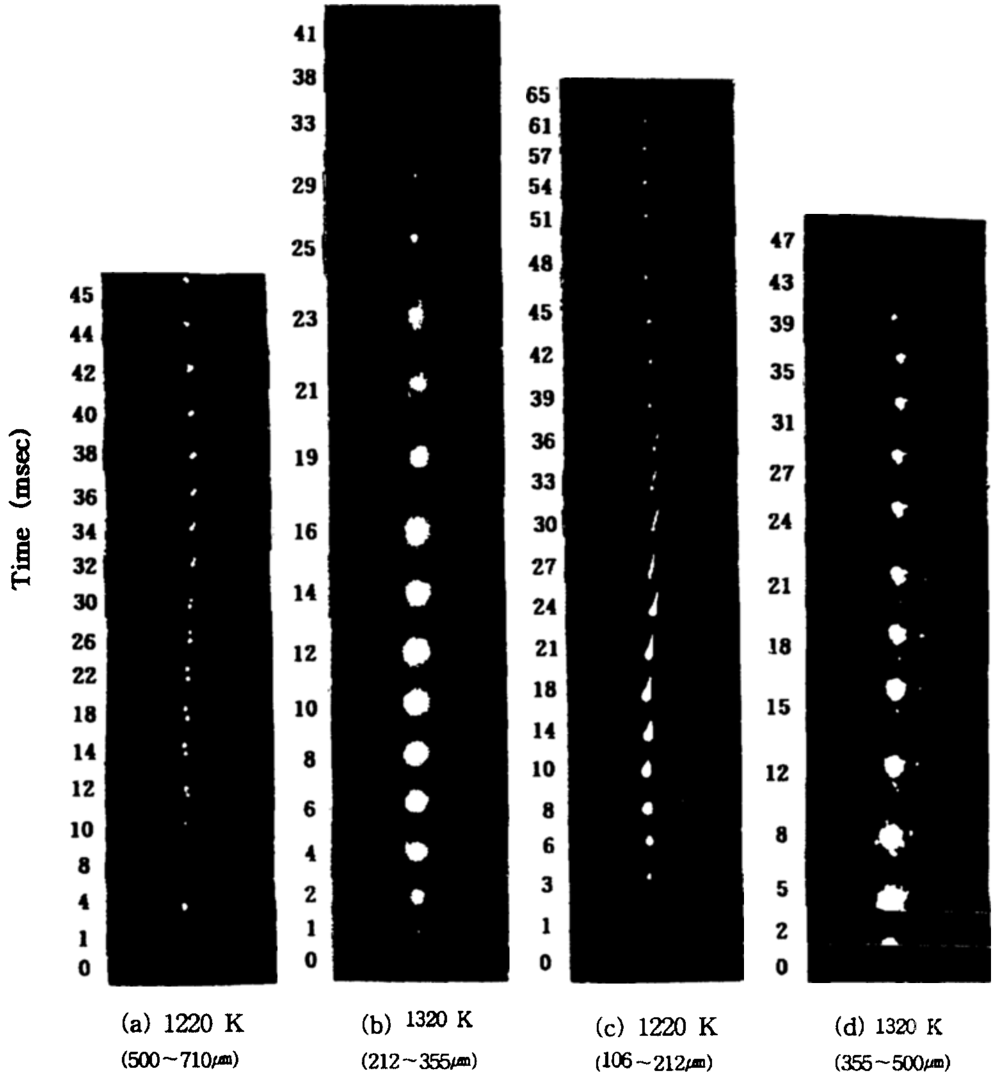

Fig. 2 Typical mode of coal fragmentation(a, b : Roto, c,d : Dongjin)

ture and particle sizes for the Dongjin coal. It is found from this figure that a single coal particle often disintegrates into two, three and sometimes more fragments. All particle size bands considered here show a secondary fragmentation even though the frequency of such fragmentation is not significant. The frequency of secondary fragmentation is increased with the increase of gas flame temperature and with the decrease of particle size. The dominant mechanism of fragmentation is that producing two fragments in primary fragmentation, indicating that frequency of it is increased with the decrease of particle size.

The distributions of fragment numbers and frequency of primary and secondary fragmentation for the Roto coal are shown in Fig. 4. The distributions of two fragments in primary fragmentation for all particle sizes considered are similar to those of bituminous coal. A secondary fragmentation is rarely found. The data from Fig. 3 and Fig. 4 indicate that two fragments are mostly produced in primary fragmentation and the increase of gas flame temperature affect on the increase of fragmentation frequency for both coals

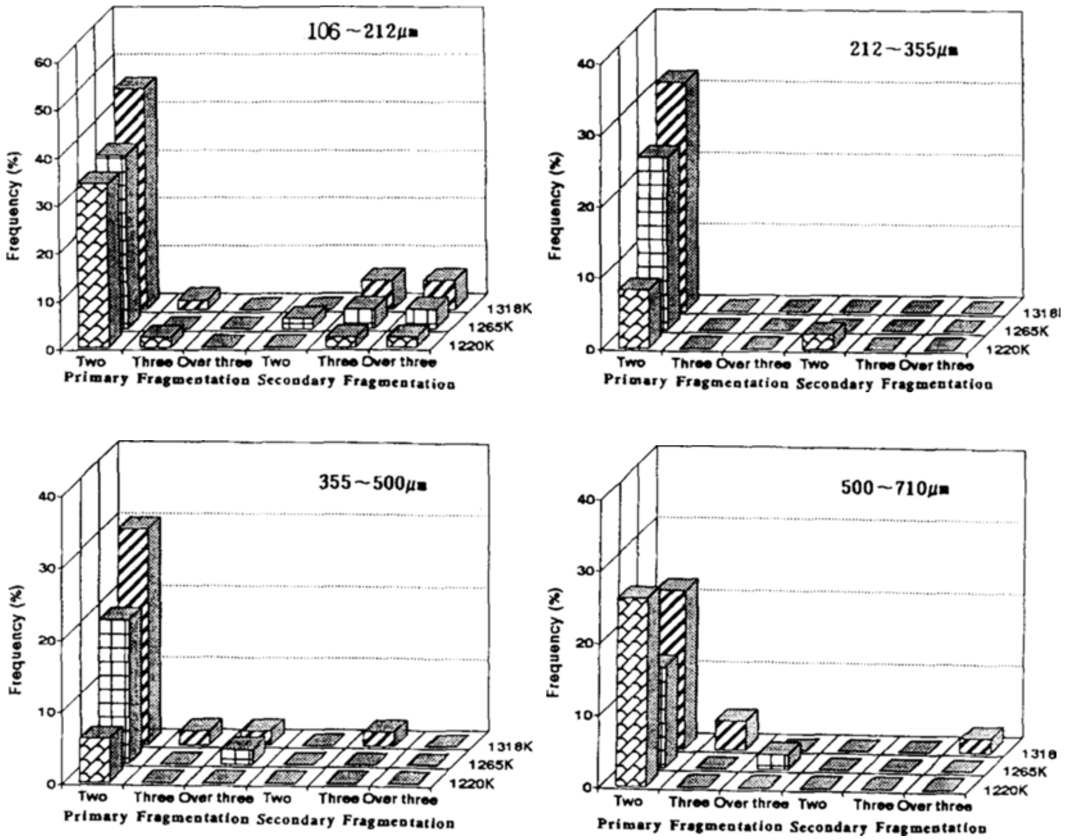

Fig. 3 Distributions of number of fragments and fragmentation frequency for different particle sizes(Dongjin coal)

considered.

Figure 5 illustrates the resulting cumulative frequency in primary fragmentation for the selected coals at the gas flame temperature of 1320 K. The cumulative fragmentation frequencies in primary fragmentation are remarkably similar in slope for both coals, indicating that frequencies for the Dongjin coal exceed that for the Roto coal over the particle size range considered. The frequencies for larger than 300 μm particles for both coals show little variance due to relatively short observation time comparing with the burning time of larger particles. The data for both coals were obtained in which 10~50% of a single coal particle breaks up within 80 msec after ignition.

Figure 6 shows the effect of particle size on the mean fragmentaton time for the Roto coal. In this article, the mean fragmentaton time was defined as the arithmetic mean time in primary fragmentaton. The measurements of primary and secondary fragmentaton time showed considerable scatter. The mean time of primary fragmentaton, however, is not varied remarkably with the variation of gas flame temperature in a given particle size, as shown in Fig. 6. The particle size strongly affects on mean fragmentaton time, indicating that mean fragmentaton time is considerably decreased with an increase in particle size for larger than 300 μm diameter. This is due to the observation of fragmentation only during early stages of combustion, i.e. within 80 msec residence time obtained from the present rig.

Figure 7 illustrates the effect of particle size on the mean fragmentation time for the Dongjin coal. Variation in the mean fragmentaton time is not significant with the increase of gas flame temperature and the particle size. It is found that the mean fragmentaton time falls to between 10

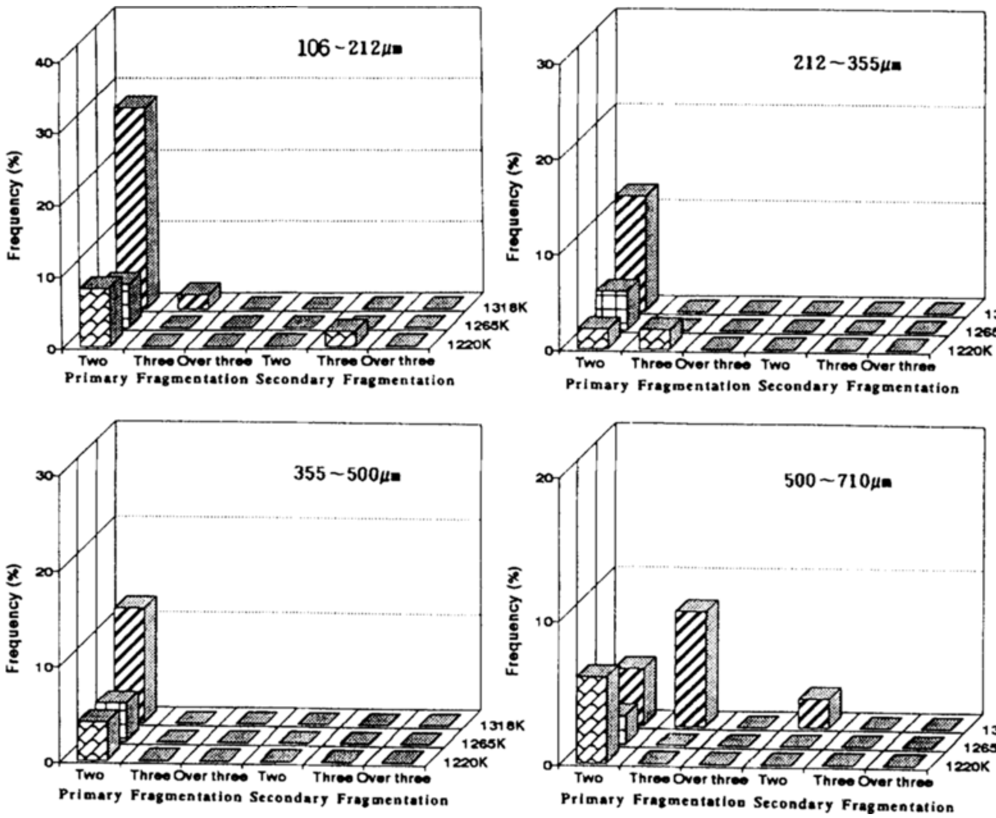

Fig. 4 Distributions of number of fragments and fragmentation frequency for different particle sizes(Roto coal)

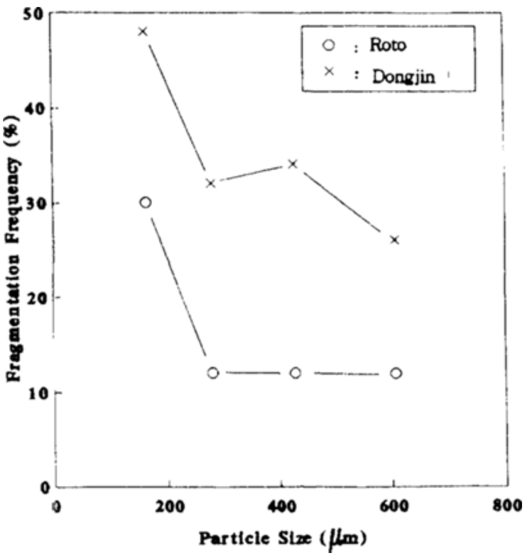

Fig. 5 Effect of particle size on cumulative fragmentation frequency for different coals(1320 K)

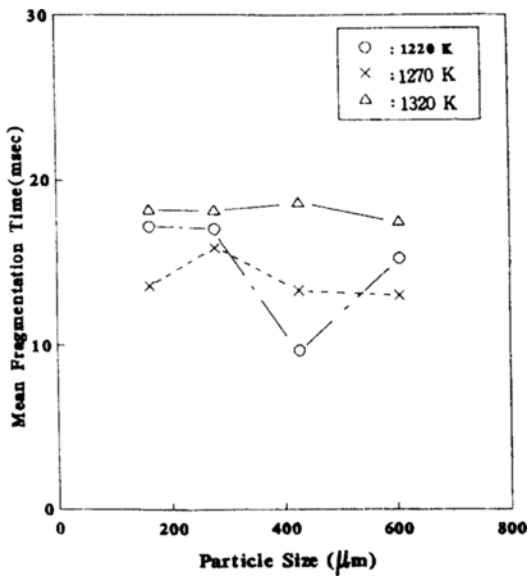

Fig. 6 Effect of particle size on mean fragmentation time(Dongjin coal)

msec and 20 msec after ignition for a given gas flame temperature and particle size range. According to the theoretical analysis, devolatilisation of a 250 μm particle starts at about 90~100 msec (No and Syred, 1990). The data, therefore, indicate that fragmentation occurs early on in the devolatisation process.

As noted above, it is clear that the gas temperature and oxygen concentration varies with the axial direction and there may be the slip velocity between the particle and the gas. Those factots may affect the results obtained in this study. The present observation of coal fragmentation during coal heat up and early stages of combustion is, however, the first quantitative study of this phenomenon, although previous studies provided the possibility of it(Choi et al., 1992; McLean et al., 1981). This study is still useful to analyse the devolatilisation process of coal combustion.

Those who have reported extensive fragmentation have almost exclusively investigated with large particles in devolatilisation process in the context of fluidised bed combustor or with small particles in char combustion process in relation to the fly ash formation and pulverised coal combustion. The results obtained in this work, therefore,

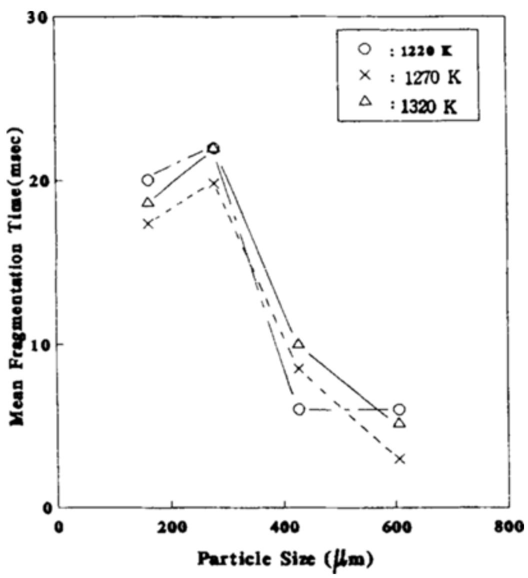

Fig. 7 Effect of particle size on mean fragmentation time(Roto coal)

can be used to create a model of fragmentation in the early stages of crushed coal combustion and estimate the burning time of coal particles in a given conditions. The data in this study indicate that fragmentation in the early stages of small particles is crucial and should be taken into account in the engineering analysis of coal combustion.

Clearly further study on the measurement of flame size, the variation of it, and particle temperature is required, including the coal fragmentation as a function of oxygen concentration.

4. Conclusions

Experiments for the measurement of coal fragmentation in the early stages of combustion were undertaken for the crushed coal in Chinese Dongjin and Indonesian Roto coals. A small laboratory-scale flat flame burner fed with a premixed mixture of methane, air and partly hydrogen was used for the burning of a single coal particles. A high speed motion analysis system was used for the observation of coal fragmentation for approximately 80 msec.

Important conclusions to emerge from this study of observation of fragmentation during the early stages of crushed coal combustion are :

1. The dominant mechanism of fragmentation for both coals is that producing two fragments in primary fragmentation for a given surrounding gas temperature and particle size range.
2. Coal particle sizes considered here for both coals show a secondary fragmentation phenomenon accompanied by secondary ignition although the frequency of such fragmentation is low, especially for lignite.
3. The Dongjin coal disintegrates more extensively than the Roto coal with the frequency of fragmentation exhibiting a strong surrounding gas temperature dependence and a weaker paritcle size dependence.
4. The mean time of primary fragmentation for the Dongjin coal falls to between 10 msec and 20 msec and does not remarkably vary with particle size and surrounding gas temperature.
5. The mean time of primary fragmentation for

the Roto coal is strongly dependent on the particle size, whilst shows less surrounding gas temperature dependence.

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References

Baxter, L. L., 1992, "Char Fragmentation and Fly Ash Formation During Pulverized-Coal Combustion," *Combust. Flame*, Vol. 90, No. 2, pp. 174~184.

Beer, J. M., 1988, "Recent Trends in Coal Combustion : Research And Application," *Coal Combustion Science and Technology of Industrial and Utility Applications* (Feng, J. ed.), Hemisphere, pp. 1~19.

Choi, S., Hong, S. E., Kim, J. S. and Kim, J. J., 1991, Observation of Single Coal Particle Flames, *Combust. Sci. and Tech.*, Vol. 78, pp. 117~216.

Choi, S., Shin, Y. S. and Kim, J. S., 1992, "Characterization of Coal Properties Through Observation of Single Particle Flames," *Proc. of the 2nd JSME-KSME Thermal Engineering Conference*, Oct. 19-21, pp I-247~I-252.

Gupta, A. K., Lilley, D. J. and Syred, N., 1984, *Swirl Flows*, Abacus Press, U.K..

Lawn, C. J. ed., 1987, *Principles of Combustion Engineering for Boilers*, Academic Press.

Mclean, W. J., Hardesty, D. R. and Pohl, J. H., 1981, "Direct Observations of Devolatilizing Purlverized Coal Particles in a Combustion Environment," *Eighteenth Symposium(Int'l) on Combustion*, The Combustion Institute, pp. 1239~1245.

Morgan, D., Biffin, M., No, S. Y. and Syred, N., 1988, "An Analysis of the Behaviour of Non-Slagging, Coal Fired, Cyclone Combustors Using a Phenomenological Model," *Twenty-Second Symposium(Int'l) on Combustion*, The Combustion Institute, pp. 175~182.

Morgan, D. J., 1990, Characteristics of Non-Slagging Cyclone Combustors for Solid Fuels, Ph.D. Thesis, School of Engineering, Univ. of Wales, Cardiff, U.K..

No, S. Y., 1990, Processes Involved in Coal Combustion in Non-Slagging Cyclone Combustion, Ph.D. Thesis, School of Engineering, Univ. of Wales, Cardiff, U.K..

No, S. Y. and Syred, N., 1990, "Thermal Stress and Pressure Effects on Coal-Particle Fragmentation and Burning Behaviour in a Cyclone Combustor," *J. Inst. Energy*, Vol. 63, No. 457, pp. 195~202.