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The Effect of Particle Size on Combustion Characteristics of Pulverized High-Volatile Bituminous Coal

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Abstract — The particle size effect on the combustion characteristics of pulverized coal was investigated in the cylindrical-shape, horizontal furnace, fired in the range of 8.8~10.6 kw. Three differently-sized fractions (5, 30, and 44 microns in average diameter) of high-volatile bituminous coal, were burned in the test furnace. Burnout behavior of pulverized coal flame were determined through the measurement of stable species concentrations (CO_2 and H_2O). Concentrations of CO_2 were compared with the theoretical values and the result showed good agreement. Thermal behavior of pulverized coal flame were determined as maximum flame temperatures occurred at fuel-rich conditions in every case. Flame lengths were also determined by decreasing with the particle size decrease. The flame length of the fine sized coal sample was comparable to that produced by distillate oil. The color of the coal flames ranged from orange to yellow, with the flame of the fine size fraction being brighter and yellower than the others.

1. Introduction

Electricity generation in Korea is expected to increase in the twentieth century in order to meet ever-growing energy demand. With the near-term finite outlook for petroleum and natural gas resources and the restricted construction of nuclear power plant, electricity generation utilities have to largely depend upon coal to supply the bulk of their primary energy needs in the future. Although research and development on new coal utilization systems, e. g., fluidized bed combustor, magnetohydrodynamic power generation system, and gas turbine-combined cycle system, are currently underway, these advanced technologies are expected to give only a minor impact on power generation practice from now until the end of the century. In contrast, any improvements of current technologies, especially the direct firing of pulverized coal, could have a major and immediate impact on power generation capacity and efficiency. For this to be the case, pollutant generation behavior of pulverized coal combustion flame is required to understand the combustion characteristics which is the guideline of producing high-efficient, pollution-free electric power. Because characteristics of coal flame such as flame length, flame temperature, flame shape are largely dependent on the particle size of feeding coal, the objective of this study is to investigate the effect of particle size distribution on pulverized coal combustion behavior in the laboratory-scale combustor.

Largely developed as an empirical art, progress of pulverized coal firing has been marked by the efforts of devoted engineers whose success may be attributed to persistence despite of many discouraging obstacles. In the pulverized coal (p. c.) combustion process, lumps of coal are first pulverized and then transported into a hot combustion chamber with the air flow, known as primary air. Primary air typically constitutes 15~20% of the air required for complete combustion. As the coal particles enter the combustion chamber, they absorb heat from coal flame. This heating process brings the particles to the ignition temperature. Particles then burn during the passage through the combustion chamber. Combustion provides both the heat for ignition and for the maintenance of system temperature. Burning carbonaceous particles, non-burning ash ones, and gases constitute the make-up of a pulverized coal flame.

Several processes are occurring during the p. c. combustion. Heat transfer from the flame to the incoming particles, heat transfer from furnace walls to the incoming particles, evolution of volatile matter, ignition/combustion of gaseous and solid material, and transport of oxidant to gaseous and solid combustion zones, are major processes to be concerned. Each of these processes is dependent, to varying degrees, upon the others, so that the p. c. flame as a whole is a very complex two-phase reacting system.

The development of pulverized coal combustion processes requires the simultaneous prediction of ignition and burning rates, pollutant formation, and heat transfer properties of the materials present in the combustion region. Coal flames contain polydisperse mixtures of particles, with sizes extending from the submicron range to over 200 microns. The initial size distribution of the coal will most likely change along the length of the flame as the smaller particles burn out first. Furthermore, there is evidence that the propagation rate through a pulverized coal flame is controlled primarily by the smaller particles, i. e., the fines[1)]. Larger particles may pass through the flame unreacted or partially reacted, although they would have release volatiles as they were heated. As particle size is an important rate-determining parameter, the effect of particle size distribution on pulverized coal combustion behavior was a major concern in this study.

Beeston and Essenhigh[2)] published a combined experimental/theoretical analysis of single coal particle combustion. The theory was assumed that rate-controlling process was the oxygen diffusion into the particle surface. Reaction at the surface was assumed to be instantaneous and first order with respect to the oxygen partial pressure. The relationship between burnout time (t_b) and particle diameter (d_0) was given by Eq. (1).

$$t_b = [(C_f/100)/f]\, k\, d_0^2/\ln(1-P_0) \qquad (1)$$

In Eq. (1), k equals $\rho/3\rho_0 D_0(T/T_0)^{0.75}$ and C_f represents fixed carbon % of coal, f is swelling factor, P_0 is oxygen concentration, ρ is coal density, ρ_0 is air density, D_0 is diffusion coefficient of oxygen. The results showed well agreement between calculated and experimental values as burnout time increased with increasing particle diameter.

Experimentally, combustion behavior of pulverized coal have usually been studied by burning velocity[3-8)] or flame temperature[9-13)] as the determined parameter. Hattori[3)] measured the burning velocity of high-volatile bituminous coal combustion using inverted conical flames. Pulverized coal/air mixtures were first discharged from a Bunsen-type burner with the ignition source of concentric acetylene flame. Flame velocity was observed to increase markedly as the grain size of the coal decreased. Ghosh and Roy[4)] showed same trend when firing bituminous coal in an isothermal furnace. With these findings, it was suggested that the presence of finer particles in the flame would reduce the distance between successive layers of particles, and therefore, increase the rate of flame propagation.

Six different size of high-volatile bituminous coal were used in the experiments of Burgoyne and coworkers[5)], having mean diameter of 11, 22, 33, 45, 62 and 120 microns. The pulverized coal/air mixtures were burnt on a downward, water-cooled burner. The ignition source was an annular premixed coal gas/air flame formed at the periphery of the coal/air stream. The mean burning velocity was determined by a 'total area' method, i. e., the ratio of the volumetric air flow and the flame surface area. Increased particle size resulted in a decreased burning velocity.

Marshall and coworkers[6)] also attempted to clarify the relationship between particle size and burning velocity. They employed a modified Bunsen burner in that ring was used for the flame stabilization. The mass-median particle sizes of high-volatile bituminous coal used are 4.9 and 6.2 microns. Experimental and calculated results generally indicated that burning velocity increased with decreasing particle size. Other types of laminar pulverized coal flame experiments[7,8)] also resulted in the same general results.

Flame temperatures have been measured in industrial-type pulverized coal combustors as a function of particle size[9,10]. Hubbard[9] suggested that when the size of the high-volatile bituminous coal particles was small, volatiles would be evolved more rapidly, combustion would be faster, and the flame temperature hotter. In his experiment, a change from 70% to 93% less than 74 microns resulted in the axial gas temperature becoming 140 K higher and the position of the maximum temperature moving nearer to the burner. Beer's experiments[10] have shown a similar type of burning behavior with changing particle size. In his research, anthracite coal fines definitely affected mixing along the jet axis. The explanation was that fine particles followed the gas streamlines more closely and caused better mixing and more rapid and hotter combustion while coarser particles were more liable to stay on the jet axis. Flat flame burners have also been used to measure the temperatures of pulverized coal/air flames[11-13]. However, particle size effects have not been investigated with this type of apparatus thus far.

From the just-concluded review, it appears that the general combustion tendencies of pulverized coal flames are that burning velocity and flame temperature are inversely proportional to particle size.

2. Experimental

Experiments are conducted in the horizontal, cylindrical-shape combustion test facility. The detailed description of test unit is presented in the author's previous paper[14]. The investigation of combustion behavior of p. c. flame was conducted according to experimental matrix of Table 1. Three different particle sizes of coal were fired with varying excess air and O_2 enrichment. Profiles of temperature and product of combustion were acquired to explain the behavior of p. c. flame.

Furnace wall temperatures were measured along the horizontally-mounted cylindrical combustor. Temperature measurements were conducted using sheathed thermocouples. No attempts were made to correct the temperature indicated by the sheathed thermocouples for conduction and radiation losses. So that all temperatures reported herein will be denoted as apparent flame or wall temperatures.

Extractive sampling technique was used to monitor the concentration of products of combustion. Gas samples were withdrawn by means of the water-cooled stainless steel probe, which was operated at a constant sampling rate. Sample gases were first passed through glass fiber filters to remove particulates and then conveyed to the various analyzers via two different pathways. One sample line was for nitrogen oxides and sulfur oxide analysis; the other was for the analysis of carbon dioxide, carbon monoxide and oxygen. The first line was heat-traced above 373 K to ensure that any water present in the exhaust did not condense. A manually activated

Table 1. Matrix of the experimental study.

VARIABLES						DATA AQUISITION			
Flame System	Particle Size Distribution		Excess Air	Oxygen Enrichment		Profiles		Ignition Behavior	Burnout Behavior
	(Fine %)	(Coarse %)	(%)	(%)		product	pollutants		
Bituminous Coal + Air	100	0 (Fine)	0	21~30	:	x	x	x	x
			15	〃	:	x	x	x	x
			30	〃	:	x	x	x	x
	50	50 (Normal)	0	21~30	:	x	x	x	x
			15	〃	:	x	x	x	x
			30	〃	:	x	x	x	x
	30	70 (Coarse)	0	21~30	:	x	x	x	x
			15	〃	:	x	x	x	x
			30	〃	:	x	x	x	x

Fine: less than 20 microns. Coarse: 20~200 microns.

valve-switching system permitted the periodical checking of instrument calibration during the experiment.

The experimental procedure consisted of first lighting the furnace preheating burner with the electric spark. Upon heating the near-field furnace wall temperature to about 1000 K, a predetermined composition of methane/air mixture was ignited on the pilot burner, the screw feeder energized so that coal start to feeding, the primary carrier gas flow started, and the preheater burner turned off. The furnace was then allowed to fire coal until a steady-state thermal condition was reached, i. e, until a constant wall temperature profile was attained. Data were then collected at the initial firing conditions. When any combustion parameter was changed, the furnace was allowed to re-equilibrate before any new data were taken. Temperatures were typically reproducible to within about ± 25 K for any given furnace condition. Burnout, or complete carbon conversion, was determined by first calculating the maximum possible CO_2 concentration that could be produced at each test condition and then comparing it with the measured concentration in the exhaust line. Stable gas concentrations for flames of all stoichiometric conditions were typically reproducible to within a few percent. The reproducibility of NO_x and SO_2 measurements was always $\pm 10\%$, or lower.

3. Results and Discussions

Ultimate and proximate analyses of the test coal samples were determined as shown in Table 2. The coal selected for the experiments was a high-volatile bituminous coal. The three particle size distributions, labelled 'coarse', 'normal', and 'fine', have mean volume diameters of 43.7, 30.2 and 4.9 microns, respectively.

To characterize the extent of combustion at the furnace outlet, the actual concentrations of O_2 and CO_2 in the dry exhaust were measured at varying levels of excess air. Fig. 1 displays a comparison between experimentally measured CO_2 and O_2 concentrations and their theoretically calculated values under different stoichiometric conditions for the 50/50 mixture of coal and methane. As shown in Fig. 1, combustion was near complete (about $\pm 90\%$) in the furnace within experimental uncertainty.

Specific physical combustion characteristics of

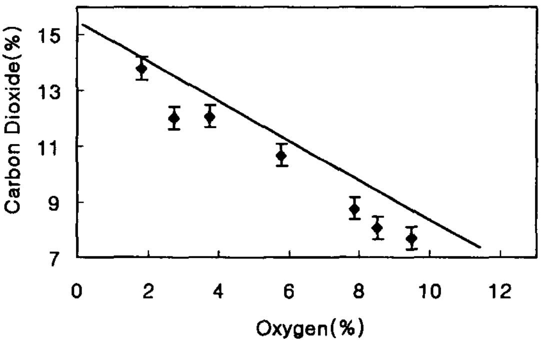

Fig. 1. Concentrations of CO_2 and O_2 in the exhaust gas in a 50/50 mixture of coal/methane flame.

Table 2. Analyses of high-volatile bituminous coals burned.

	Fine-Sized Coal (Weight %)	Normal-Sized Coal (Weight %)	Coarse-Sized Coal (Weight %)
PROXIMATE ANALYSIS*			
Volatile Matter	28.4	29.4	30.4
Ash	16.5	16.1	14.2
Fixed Carbon	55.1	54.5	55.4
ULTIMATE ANALYSIS*			
Nitrogen	1.5	1.5	1.5
Carbon	69.3	70.2	74.4
Hydrogen	4.5	4.8	4.7
Sulfur	1.6	1.6	1.7
Oxygen	6.7	5.9	3.5
CALORIFIC VALUE (Btu/lb)	12,424	12,474	12,954

*Percent, dry basis.

the coal flames (length, shape, and color) were evaluated at normal operating conditions for each of three different particle size. Flame lengths were defined as the distance from the burner nozzle to the end of visible emission. The results of flame length data are shown in Table 3, along with similar data from Briceland and coworkers[15]. In general, flame length is increased with particle size. However, the increment portions are quite different between two sets of experiment because of their different experimental hardware. Fig. 2 is the plot of flame length and normalized flame length, which is determined by multiplying the ratio of combustor length, versus average particle diameter for each size. The flame lengths of the different particle size of coal determined in the two studies correlated very well considering the differences in experimental hardwares. Essenhigh[16] reports that the burning time of single particles has close relationship with the particle diameter. The data in Fig. 2, which are not for single particle combustion, exhibit similar particle size dependencies on flame length.

Table 3. flame lengths for different particle sizes.

Average Particle Size (microns)	Flame Length Determined Visually (centimeters)	Flame Legnth Determined Chemically (centimeters)	References
43.7	35	36	This Study
30.2	30	34	〃
4.87	23	27	〃
41.0	140		15
18.1	90		15
6.6	60		15

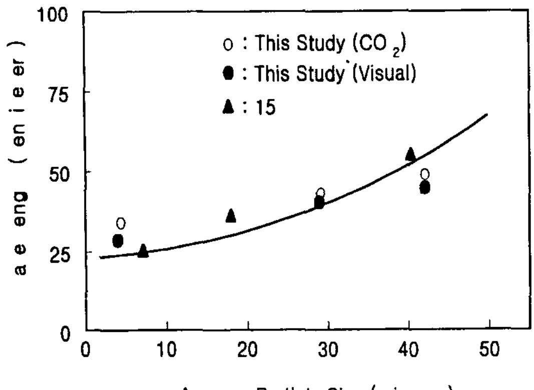

Fig. 2. Various flame length measurements with particle size.

Coal flames of smaller particle size had a shorter flame length because the burning time for smaller particles is generally shorter than that for bigger ones, assuming fluid-dynamic behavior is similar in either case. More accurate flame length measurements were determined by the use of CO_2 concentration profiles as in Fig. 3. The distance from the burner nozzle to the position of nearly-constant, maximum CO_2 concentrations was defined as the flame length. The flame length determined chemically with CO_2 concentration profiles agreed to within $\pm 15\%$ of those determined visually. Both values are given in Table 3 and Fig. 2. Flame lengths of pulverized coal flame show close relationship with particle size.

The pulverized coal flame appeared as a rapidly pulsating, conically shaped fireball, with sparklers flickering out from its tail. The color of the flames ranged orange to yellow, with the flame of smaller size being brighter and yellower than others. Visible radiation was greatest for flames of small particles, as has been seen elsewhere[7]. The flame of

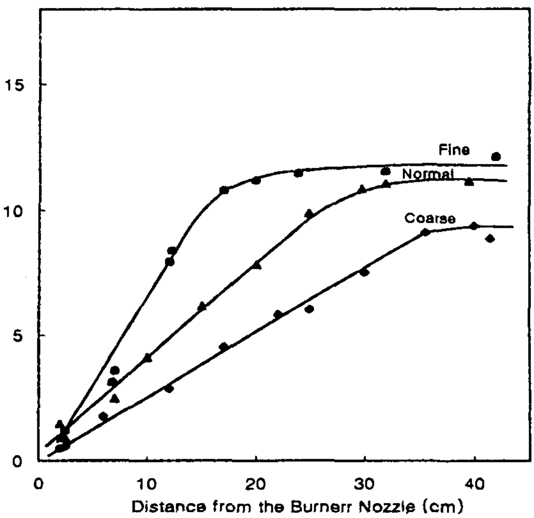

Fig. 3. CO_2 concentration with distance from the burner nozzle as a function of particle size.

the fine size looked more like a gaseous flame than the p. c. flame. Whereas, flames of coarse size showed more and larger glowing incandescent particles than smaller size fraction.

The coal flame temperature profiles were uniform over the entire length of the combustor. The apparent maximum temperature was about 1150 K, occurring first at about 20 cm from the burner nozzle and continuing throughout entire combustor length. The exhaust temperature measured at the end of the combustor was about 800±50 K. Measured temperature values are 100~200 K lower than actual flame temperature because of utilization of sheathed thermocouple.

The flame temperatures of different size fraction are plotted as a function of coal concentration in Fig. 4. Table 4 provides information on the flow rates and coal/air concentrations used in the experiment. As shown in Fig. 4, the fine size distribution generated the maximum flame temperature at 0.25 *g/l*, the normal size distribution at 0.45 *g/l*, and the coarse size distribution at 0.6 *g/l* of coal concentration, respectively. The values of maximum flame temperature is not compared with different particle size because of their experimental error, however, coal concentration of maximum flame temperature is important in describing coal combustion behavior.

Smoot and coworkers[7] experimentally and theoretically investigated the effect of particle size on the maximum flame velocity while varying coal concentration. They used standing flame to evenly distribute the unburned coal particles and results showed theoretical calculations compared favorably with measured data, and that the maximum flame temperature occurred at the maximum flame velocity[8]. A high-volatile bituminous coal, which had a mean diameter of 10 microns, showed a maximum velocity at a coal concentration of 0.3 *g/l*. Medium particles (33 micron average diameter) had a maximum flame velocity at a coal concentration of 0.5 *g/l*.

Fig. 5 shows a plot of particle size and coal concentration at the maximum flame temperature using the data of Smoot and coworkers[7] and those obtained in the study. Because many differences exist between the experimental conditions of two studies,

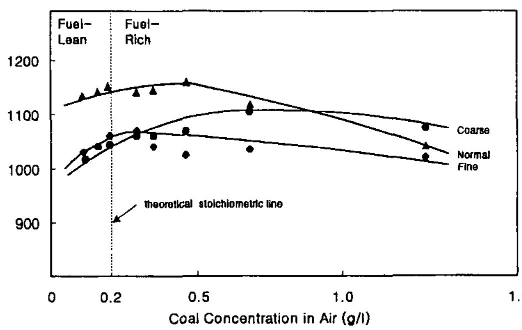

Fig. 4. Maximum flame temperatures with coal concentration as a function of particle size.

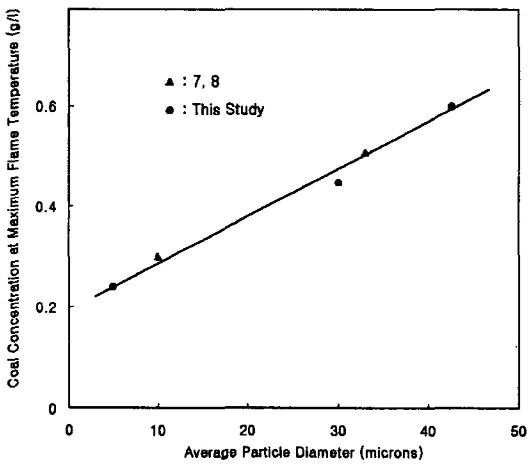

Fig. 5. Coal concentration at maximum flame temperature as a function of particle size.

Table 4. Selected calculated values of coal/air concentrations and volume flow rates.

Equivalence Ratio (Φ)	Excess Air (%)	Coal Concentration (*g/l*)	Total Air Flow Rate (*l*/min)	Secondary Air Flow Rate (*l*/min)	Primary Air Flow Rate (*l*/min)
1.0	0	0.20	160	154	6
0.85	15	0.18	180	174	6
0.7	30	0.15	200	194	6

i. e., diffusion vs. premixed, turbulent vs. laminar, three-dimensional vs. one-dimensional, and 'Keystone' vs. 'Pittsburgh' coal, it is clear that particle size distribution is the single most important variable determining the rate of coal combustion.

The effect of oxygen enrichment of the secondary air was investigated for the normal size fraction of coal under fuel-lean conditions. Fig. 6 shows that the CO_2 concentration and wall temperature remained constant as the oxygen partial pressure of the secondary air was increased 20% to 30%. However, the exhaust oxygen concentration increased and the flame appeared brighter upon oxygen enrichment. The usual consequences of oxygen enrichment in coal flames are the acceleration of burning velocity and the increase in adiabatic temperature. Flame temperatures may actually have been increased with oxygen enrichment. Evidence for this is the increased brightness in the flame upon addition of oxygen. Carbon dioxide concentrations remained constant because the coal already had sufficient oxygen to be completely consumed at fuel-lean condition; the measured oxygen concentration was the sum of that before oxygen enrichment and the fractional increase resulting from oxygen enrichment.

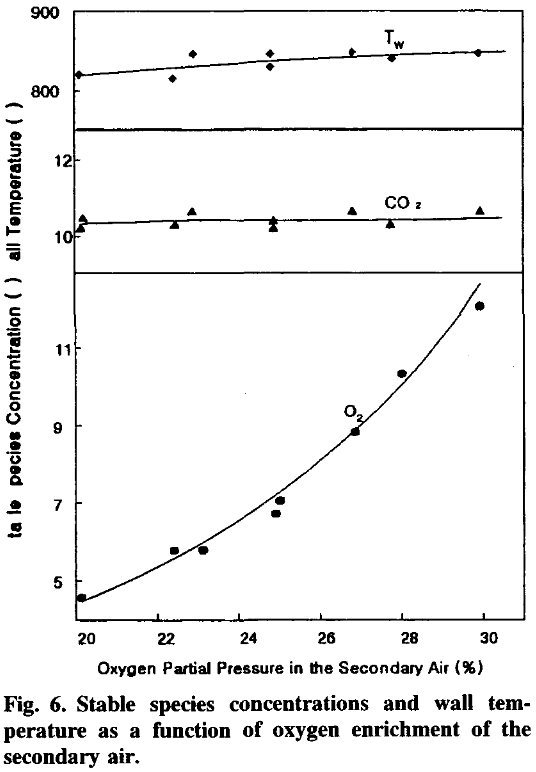

Fig. 6. Stable species concentrations and wall temperature as a function of oxygen enrichment of the secondary air.

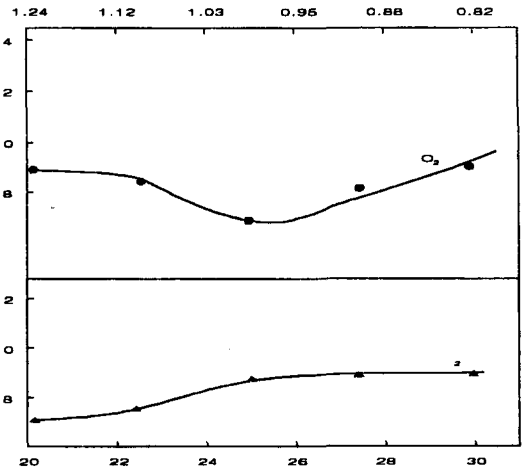

Fig. 7. Stable species concentrations as a function of oxygen enrichment of the secondary air for fuel-rich flames.

The effect of oxygen enrichment on pulverized coal flames of different stoichiometries was also investigated. Concentrations of CO_2 and O_2 at the exhaust of fuel-rich flames as in Fig. 7 were different from those of fuel-lean flames upon oxygen enrichmennt as similar to other studies[17,18]. Actually, the curves of CO_2 and O_2 for the fuel-rich condition exhibited different behavior starting at about 25% oxygen partial pressure, which is the turning point from fuel-rich to fuel-lean. In the fuel-rich flame, the added oxygen was consumed to complete the burning of fuel; as a result, the exhaust oxygen content first decreased and then increased. The CO_2 data behaved similarly, that is, first CO_2 increased and then it stayed constant after the stoichiometric concentration had been reached.

4. Conclusions

Three differently-sized fractions of pulverized coal were test-fired in the cylindrical-shape, horizontal combustor. The purpose of the investigation was to survey different experimental conditions for pulverized coal combustion and study the effect of particle size on coal flame characteristics. The following conclusions were made from the experimental data.

1) As the particle size of coal combustion is increased, flame lengths show increasing tendency with particle size.

2) The particle size distribution had a major influence on the rate of coal flame propagation. Two different sets of experiments indicated that a combination of coal concentration and particle size determined maximum flame temperature and flame length.

3) The maximum flame temperature of a coal particle distribution occurred at fuel-rich conditions.

4) Oxygen enrichment of the secondary air had a different effect on fuel-rich flames than it had on fuel-lean ones.

References

1. Field, M., Gill, D., Morgan, B. and Hawksley, P.: Combustion of Pulverized Coal, Bulletin of the British Coal Utilization Research Association, Vols. 30-31, (1966-1967).
2. Beeston, G. and Essenhigh, R.: "Kinetics of Coal Combustion: The Influence of Oxygen Concentration on the Burning-out Times of Single Particles", *J. Phys. Chem.*, **67**, 1349 (1963).
3. Hattori, H.: "Flame Propagation in Pulverized Coal-Air Mixtures", Sixth Symposium (Int.) on Combustion, Reinhold, New york, NY, 590 (1956).
4. Ghosh, B., Basu, D. and Roy, N.: "Studies of Pulverized Coal Flames", Sixth Symposium (Int.) on Combustion, Reinhold, New york, NY, 595 (1956).
5. Burgoyne, J. and Long, V.: "Some Measurements of the Burning Velocity of Coal-in Air Suspension", Paper No. 28 at the Conference on Science in the Use of Coal, Institute of Fuel, London, D16 (1958).
6. Marshall, W., Palmer, H. and Seery, D.: "Particle Size Effects and Flame Propagation Rate Control in Laminar Coal Dust Flames", *J. Inst. Fuel*, **37**, 342 (1964).
7. Smoot, L., Horton, M. and Williams G.: "Propagation of Laminar Pulverized Coal-Air Flames", Sixteenth Symposium (Int.) on Combustion, The Combustion Institute, Pittsburgh, PA, 375 (1976).
8. Horton, M., Goodson, F. and Smoot, L.: "Characteristics of Flat, Laminar Coal Dust Flames", *Combust. Flame*, **28**, 187 (1977).
9. Hubbard, E.: "The First Performance Trial and First Combustion Mechanism Trial with Pulverized Coal", *J. Inst. Fuel*, **33**, 386 (1960).
10. Beer, J.: "The Effect of Fineness and Recirculation on the Combustion of Low Volatile Pulverized Coal", *J. Inst. Fuel*, **37**, 286 (1969).
11. Milne, T. and Beachey, J.: "The Microstructure of Pulverized Coal-Air Flames. II. Gaseous Species, Particulates and Temperature Profiles", *Combust. Sci. & Technol.*, **16**, 139 (1977).
12. McLean, W., Hardesty, D. and Pohl, J.: "Direct Observation of Pulverized Coal Particles in a Combustion Environment", Central States Section Combustion Institute, CSS-CI-80-11, (1980).
13. Mitchell, R. and McLean, W.: "On the Temperature and Reaction Rate of Burning Pulverized Fuels", Eighteenth Symposium (Int.) on Combustion, The Combustion Institute, Pittsburgh, PA, 1113 (1982).
14. Kim, H.: "The Effect of Particle Size on Ignition Characteristics of Pulverized High-Volatile Bituminous Coal", *Energy Engg*, **3**, 285 (1993).
15. Briceland, C., Khinkis, M. and Waibel, R.: "Combustion Characteristics of Fine-Ground Coal", American Flame Research Committee, AFRC-83-10, (1983).
16. Essenhigh, R.: "Coal Combustion", Coal Combustion Technology, C. Y. Wen and E. Stanley Lee Eds., Addison-Wesley, Reading, MA, 171 (1971).
17. Lima, J.: "Effect of Oxygen-Enrichment on NOx from Distillate Petroleum Flames in a 25 Kilowatt Combustor", M.S. Thesis in Fuel Science, The Pennsylvania State University, (1983).
18. Smouse, S.: "Effect of Oxygen-Enrichment on Nitrogeneous Emissions from Flames of Petroleum, Coal-Derived Distillate Fuels", M.S. Thesis in Fuel Science, The Pennsylvania State University, (1984).