한국에너지공학회지(1993), 제2권 제3호
Energy Engg. J (1993), Vol. 2, No. 3 pp. 285~292

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

Hyung Taek Kim
Energy Department, 5 Wonchon-dong, Suwon, Korea,
441-749 Ajou University

Abstract—A cylindrical-shape, horizontal furnace was used to investigate the effect of particle size on the pulverized coal combustion behavior. Theree differently-sized fractions (5, 30, and 44 microns in average diameter) of high-volatile bituminous coal, were burned in the test furnace. Ignition characteristics of pulverized coal flame were determined through the amount of methane in the carrier gas for the self-sustaining flame. Easiest ignition occured with the immediately-sized coal particles. Ignition of coal jet flame appeared to occur through a gas-phase homogeneous process for particles larger than 30 microns. Below this limiting size, heterogenous process probably dominated ignition of coal flame. Oxygen concentration of combustion air was varied up to 50% to determine the oxygen-enrichment effect on the coal ignition behavior. Oxygen enrichment of primary air assisted ignition behavior of pulverized coal flame. However, enrichment of secondary air didn't produce any effect on the ignition behavior.

1. Introduction

Growth of the electricity generation in the twentieth century is expected to continue in order to satisfy energy demand in Korea. Given the near-term finite outlook for petroleum and natural gas resources, along with the restricted construction of nuclear power plant, electric power generation utilities will 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 have only a minor impact on power generation practice from now until the end of the century. In contrast, any improvements in 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, developments of pulverized coal combustion technology are required to satisfy growing energy demand.

In the pulverized coal (p. c.) combustion process, lumps of coal are first pulverized and then transported into a hot combustion chamber with the stream of air, 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 their ignition temperature. Particles then burn during their passage through the 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 occuring 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.

Coal-air 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

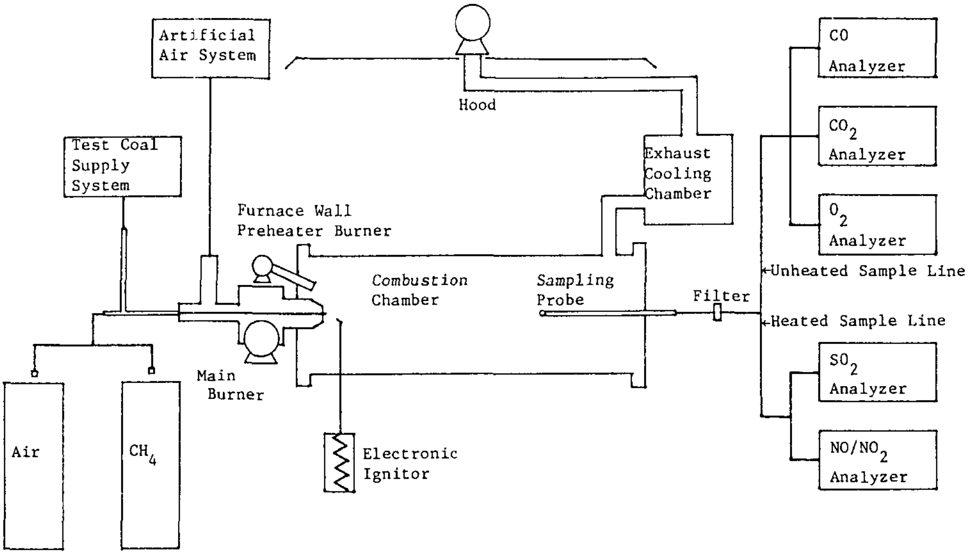

Fig. 1. Schematic of the Overall Combustion Facility.

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 ignition characteristics was a major concern in this study.

2. Experimental

Experiments are conducted firing coal of three different particle size in the test facility as shown in Figure 1. The combustion chamber consisted of a 0.69 m long by 0.38 m diameter cylindrical carbon steel housing and a 0.75 m long by 0.54 m diameter carbon steel drum so that the entire length of combustor is 1.44 m. The first stage combustor was positioned horizontally with the two largest (0.38 m in diameter) ports located at opposite ends, parallel to the burner and the flame axis. One of these larger ports permitted burner access into the chamber, while the other allowed the attachment of the second stage. Exhaust gases exited the second stage through a 0.127 m diameter carbon steel duct located at the top. High-temperature refractory insulation (Babcock and Wilcox, Kaowool Ceramic Fiber Insulation), 25.4 mm thick, was used to line the internal furnace chamber walls to withstand temperature up to 1500 K. Incoming hot products from the combustion chamber were passed through carbon steel duct-work and introduced in the cooling system with a fine water mist before being exhausted into the laboratory's hood system. An exhaust flow was developed by using a 7000 l/min blower evacuating through a hood. A butterfly damper was installed into the duct-work in order to allow the adjustment of furnace draft. Another butterfly damper was also installed in the duct-work between the combustion chamber and the cooling chamber. The combustor was normally operated under a slightly negative pressure.

The burner system consisted of three main components with individual functions : 1) preheating gas burner to heat the combustor wall, 2) pilot flame to ignite the incoming coal/air mixture, and 3) pulverized coal burner to produce a test flame. A gas burner (Cadillac Quick-Heat, Model-H3, Clements MFG. Co.) was attached into the front flange of the combustion chamber, as shown in Figure 1. This burner utilized compressed methane as a fuel; its air requirements were satisfied by a blower that was an original component of the gas burner package. The burner was capable of raising the furnace wall temperature from ambient to about 1000 K in about 10 minutes and its firing rate was about 8.8 KW (30,000 Btu/hr). For the pilot flame, a mixture of methane and air was first introduced through horizontal stainless steel tubing into the combustion chamber. The range of premixtures that could be fired was determined through ignitibility experiment which is explained in the following chapter. An electronic discharge system was used to ignite the premixed methane/air pilot flame. After the methane/air pilot flame was ignited, pulverized coal was transported to the combustor. Coal-burning system is the modified version of liquid fuel burner (INTERBURNER Mark 1, Sloan Valve Company) which is capable of coal particle-transport. Stainless steel tubing (1.27 cm O.D. and 0.79 cm I.D.) was inserted through the center of the original burner's swirl vane. The swirl vane was snuggly-fit inside an air draft tube which was fastened to the front flange of the combustor.

Air supply to the combustor was divided into primary air and secondary air. Secondary air requirements was met by either the conventional package burner blower, if the oxidant were to be normal air, or an 'artificial' air. Artificial air preparation and delivery system is capable of producing oxygen-enriched air. After the secondary air introduction in the furnace, establishment of a pulverized coal flame was visually verified through the window. It typically had a yellowish-orange color. The pilot flame was burned continuously throughout an experimental test because its termination almost always resulted in the extinguishment of the pulverized coal flame. Methane and air flows to the pilot flame burner were controlled using a critical flow orifice system[2], and were supplied by compressed gas cylinders. The pilot flame was normally fired at 3.6~5.4 KW (12,000~18,000 Btu/hr). The firing rate of coal burner was fixed at 5.4 KW (18,000 Btu/hr) so that total firing rate was 9.0~10.8 KW (30,000~36,000 Btu/hr).

The pulverized coal delivery system consisted of a venturi and a screw feeder system. The venturi ejector was designed such that the pressure at its throat was sub-atmospheric. Coal was metered with the variable-rate screw feeder (SCR-20 Feeder, Vibra Screw Incorporated). Pulverized coal was first loaded into the cone-shaped hopper. The hopper was then vibrated to keep the screw covered with pulverized coal. Normal feed rates were reproducible within ± 2 percent. A high-velocity (about 5 m/sec) methane/air stream was injected into the horizontal feed line, upstream to the venturi. This flow transported pulverized coal particles from the inlet of the venturi to the combustion chamber. Pulverized coal particles from the feeder fell downward toward the venturi and then passed to the combustion chamber. Once set, the system operated with little attention unless the coal feed or primary methane/air flow rate had to be changed. The feeder/entrainer system worked well with all the variously sized coals tested. Deposition of pulverized coal particles within the horizontal feed line will occur unless the velocity of the primary gas mixture is above some critical value. In shakedown tests, an air volume flow rate of about 2.36×10^{-4} m^3/s was found to transport the pulverized coal with no fallout of particles

Table 1. 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
Ash	16.5	16.1	14.2
CALORIFIC VALUE (Btu/1b)	12,424	12,474	12,954
MOISTURE**	1.5	1.5	1.2

* Percent, dry basis

** Percent

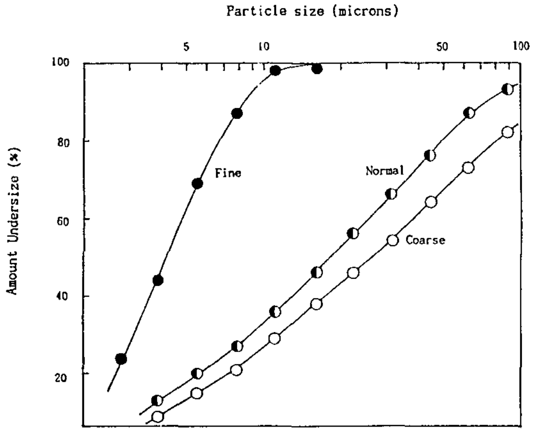

Fig. 2. Particle Size Distribution of the Coals As Determined by MICROTRAC Analysis.

within the transport tube.

The experimental procedure consisted of first lighting the furnace preheating burner with the electric spark. The cooling system was then turned on. 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, 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.

3. Results and Discussions

Ultimate and proximate analyses of the test coal samples were determined as shown in Table 1. The coal selected for the experiments was a high-volatile bituminous coal. The size distribution of the pulverized coal particles were determined using a commercial analyzer (Leeds & Northrup MICROTRAC Model 7991-01). The three particle size distributions, labelled 'coarse', 'normal', and 'fine', had mean volume diameters of 43.7, 30.2 and 4.9 microns, respectively. The particle size distributions of each are illustrated in Figure 2.

Ignition temperature is defined as the minimum temperature necessary to produce self-sustained combustion. In a pulverized coal/air flame, it is difficult to isolate ignition phenomena because of the great number of particles associated with the flame. When individual pulverized coal particles are subjected to heat, they generate volatiles that can ignite before the solid residue does. Such a process would be called homogeneous ignition. As the heating rate of the particle increases, however, the finite time required to release volatiles becomes comparable to the time required to heat the particle to its ignition temperature. Under the latter conditions, it is conceivable that the particles could ignite and burn by direct oxygen attack on the solid surface before devolatilization This phenomenon is called heterogeneous ignition, and is probably the manner by which pulverized coal particles ignite when subjected to rapid heating rate of 104 K/s 3).

A century-long held notion was that ignition in a pulverized coal/air flame occurred in the gas phase4). Howard and Essenhigh5−7) were the first to provide experimental evidence concerning the particle size effect on the coal ignition behavior. The results represented that for the Pittsburgh high-volatile bituminous coal, 100 micron-sized coal particle ignited most probably on the surface, i. e., heterogeneously. Later, Thomas et al.8) showed, by exposing brown coal particles to a hot flowing air stream, that such a heterogenous ignition occurred even for 1000 micron-sized brown coal particles.

A comprehensive treatment of the effect of particle size on pulverized coal ignition behavior has been published by Beer9) by applying a dimensionless analysis of ignition time, particle size, and excess air. The study defined two distinct particle sizes, one for the 'best ignition' and the other for the 'worst ignition'. Statements from the results illustrated as : (a) time to ignition will increase in both the regions of small and large particles and (b) there will be a region of medium-sized particles in which time to ignition will minimize. It will be the limit of this latter size range where a minimum "time to ignition", i. e., a "best ignition", occurs.

The effect of particle size on ignition temperature was experimentally studied by Weight10) by injecting small quantities of British high-volatile bituminous coal into preheated air-flue gas mixtures. The gas stream flowed down a heated silica tube maintained at a constant temperature. Decreasing the particle size from the 152~211 micron range to the 53~89 micron

Table 2. Ignition Characteristics of the Three Different Particle Size Distributions of Pulvered Coal Studied.

Carries Gas Composition	Energy Contribution of Each Fuel	Coarse Size	Normal Size	Fine Size
100% CH_4 + 0% air	37.5% coal + 62.5% CH_4	O	O	O
75% CH_4 + 25% air	44.4% coal + 55.6% CH_4	O	O	O
60% CH_4 + 40% air	50% coal + 50% CH_4	O	O	O
40% CH_4 + 60% air	60% coal + 40% CH_4	X	O	X
20% CH_4 + 80% air	75% coal + 25% CH_4	X	O	X

Where : O = ignition
X = no ignition

decreased the ignition temperature by as much as 100 K. Removing coal fines (particles less than 40 microns in diameter) from the original pulverized coal size distribution (1~200 microns) appeared not to have any adverse effect on ignition temperature. This experimental investigation proposed that ignition of coal particle be enhanced with smaller size to a certain limit. Below the limited size, particle size has no effect on the iginition behavior.

However, the characterization of ignition in actual pulverized coal flames is complicated by the three-dimensional nature of the fluid flow involved. This geometry complicates the problem of defining where ignition occurs. In the case of the jet flames produced in this study, flow (heat and gas) is dominated by recirculation and backmixing. This backmixing flow can supply 60~95% of the heat required for ignition[11]. Because the point of ignition could not be well defined specially, the investigation focussed only on whether ignition occurred or not, and what influenced such behavior.

Three different size distributions were used for the investigation of ignition characteristics of high-volatile bituminous coal. In early attempts to establish a standardized ignition test procedure, the combustor's walls were first heated to 1000 K with a stoichiometric methane/air preheat flame. Upon achieving a uniform wall temperature of 1000 K, primary air was introduced through the horizontal feed line and the screw feeder energized so that coal particles would begin to be transported into the combustor. After firing at this condition for about 30 minutes, during which time thermal performance reach a steady-state, the auxiliary methane/air flame was turned off. For all three sizes of the coal examined, the pre-ignited coal flames did not continue burning, that is, they were not self-sustaining. Such behavior may be explained by the fact that pulverized coal particles are known not to ignite spontaneously below furnace wall temperatures of 1300 K[6,7].

Second attempts to achieve self-sustaining coal ignition consisted of replacing the primary carrier air with methane/air premixtures. The methane content of the primary gas stream was varied from 0~100 vol% in

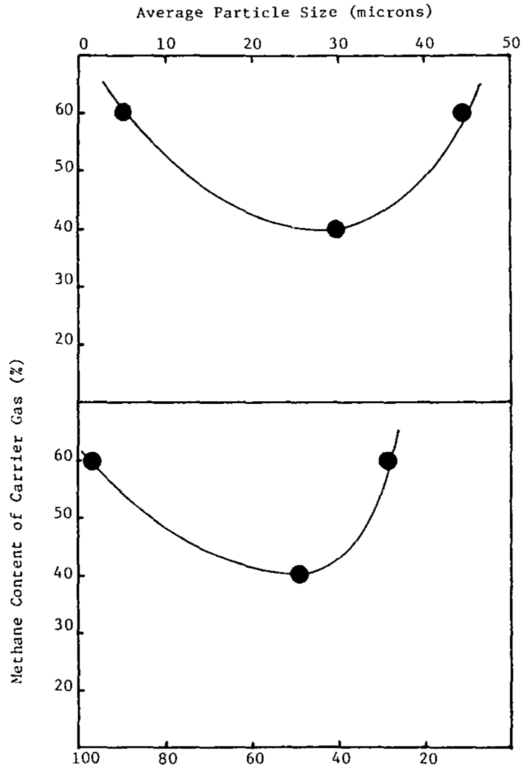

Fig. 3. Ignition Characteristics of Coarse, Normal, and Fine-Sized Coals Burned.

order to find the lower limit required to produce a self-sustaining coal flame. An equal mixture of coal and methane produced the greatest number of self-sustaining coal flames. The results of these tests are presented in Table 2 for all three coal particle size distributions. Figure 3 is the plot of the ease of ignition, as defined by the methane content of the carrier mixture, as a function of mean particle size and the amount of fines. In the Figure 3, data points are the average values of several experiment and the fines are defined as those particles with diameters less than 20 microns. It was surprising that the normal distribution of pulverized coal required the minimum amount of methane in the primary carrier gas for self-sustaining ignition, whereas the coarser and finer sizes required more methane. It has been expected that the smaller the particle size, the less methane would be required for self-sustaining ignition. However, the experimental finding was in accordance with a statement of Beer's review paper[9], which proposed that 'best

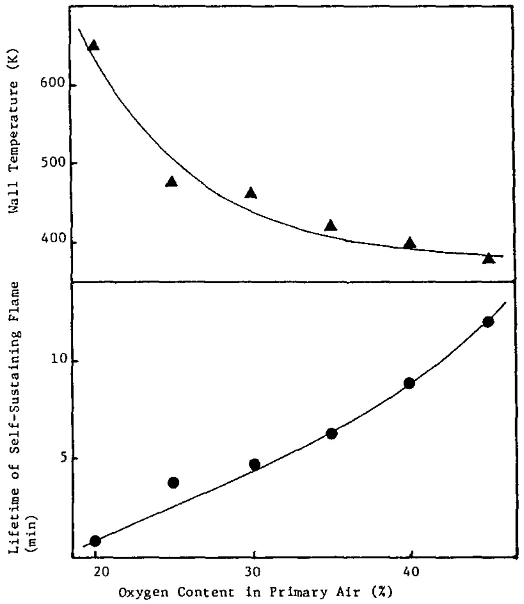

Fig. 4. Effect of Oxygen Enrichment of 40% Methane+60% Primary Air on Ignition Characteristics of Coarse Coal.

ignition' was expected to occur in the range of medium particles.

Figure 3 also illustrates that addition of fines into 'normal' distribution has a adverse effect on the ignition behavior. Whereas, tubular reactor experiment by Weight[10] didn't show any influence on ignition of coal particle with addition of fines. With the consideration of the different experimental condition of current investigation and Weight's (jet flame vs. heated tube) and different size of fines (>20 micron vs. >40 micron), general statement can be made as addition of fine didn't represent enhancing effect on the ignition of pulverized coal flame.

Ignition phenomena may be explained as some critical temperature exists at which the rate of heat loss to the surroundings equals the rate of heat generated by chemical reaction. At this point of adiabaticity, the temperature of the particle rises sharply, and can reuslt in heterogeneous ignition. The study of Seeker et al.[12] determined that the heterogeneous ignition theory failed to predict the behavior of particles larger than 10 microns. With this finding in mind, fine-sized coal may ignite heterogeneously while the normal- and coarse-sized coal may ignite differently, i. e., homogeneously. With the independent confirmation of differing ignition behavior, it is not surprising to find that the intermediate-size sample had the best ignition characteristic.

The data in Figure 3 indicate that a minimum exists in the ease of ignition as a function of particle size and that there is an accompanying change in the ignition mechanism. An inspection of ignition temperature data[13] reveals that ignition temperature for a 75-micron, high-volatile bituminous coal particle is several hundred degrees less than that for coal volatiles (methane, carbon monoxide, and hydrogen). It could be assumed, therefore, that because the ignition of the 30-micron coal particle was easiest, its ignition mechanism was dominated by heterogeneous process. What could change to make ignition worse as particle size got smaller or larger? Two simple explanations are offered. First of all, as they get smaller, particles heat more rapidly and more of their mass is generated into volatiles. The more mass of coal volatiles, the higher the apparent ignition temperature. Secondly, as coal particle diameter increases, mass transport of oxygen to the particle surface becomes limited, impeding ignition. Hence, the interesting effect of particle size on ease of ignition can be logically justified.

The effect of furnace wall temperature (300, 500, 750, 1000 K) on pulverized coal particle ignition was also investigated for a 50/50 mixture of coal/methane and a normal-sized distribution of coal. The results showed that pulverized coal flames of all three coal sizes were self-sustaining even with room temperature walls. This finding implies that the pulverized coal particles were being thermally and/or chemically ignited with the aid of methane combustion, rather than physically ignited with the aid of hot walls. If methane combustion solely raise local temperature, thereby stimulating ignition physically, an estimate could be made of the heat provided to the flame by the walls in assistance of ignition. The amount of heat provided by methane combustion is only half that introduced through the auxiliary gas burner and is not enough to increase the wall temperature to a thermal ignition condition. It can be concluded that methane combustion assisted coal flame ignition by a chemical, rather than a physical, mechamism.

The effect of the oxygen partial pressure of the primary methane/oxidant carrier gas mixture on the ignition behavior of differently-sized coal particles was also investigated. Particular carrier gas premixture (40% methane + 60% air) was enriched in oxygen from 20% to 50%. The length of time that the flame would self-sustain without auxiliary methane/air flame was measured, as was the wall temperature at the time of extinguishment. Both parameters are plotted as a function of oxygen concentration in Figure 4, which illustrated that higher oxygen concentration enhanced the ease of pulverized coal ignition. Such behavior is in accordance with the theoretical considerations[4,14] as well as experimental results[15,16]. The effect of oxygen enrichment of the secondary air was also investigated. Experimental results showed that oxygen enrichment of the primary carrier gas enhanced ignitibility, whereas enrichment of secondary air had very little or no effect on the pulverized coal ignition.

4. Conclusions

Three differently-sized fractions of pulverized coal were test-fired in the cylidrical-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 ignition characteristics. The following conclusions were made from the experimemtal data.

1. Within the given particle size range, normal-sized pulverized coal particle was easier to ignite than either fine- or coarse-sized ones.
   Ignition appeared to occur via a homogeneous process for particles larger than 30 microns. However, below this limit diameter, heterogeneous process probably dominate ignition phenomena.
2. Coal flames were not self-sustaining because of relatively low furnace wall temperature. A mixture of coal and methane allowed coal flames to be burned continuously. Methane aided coal ignition in a chemical, rather than a physical, manner.
3. Oxygen enrichment of the primary air enhanced the ease of pulverized coal ignition. However, enrichment of secondary air didn't show any effect on the coal ignition behavior.

References

1. Field, M., Gill, D., Morgan, B. and Hawksley, P.: Combustion of Pulverized Coal, Bulletin of the British Coal Utilization Research Association, **30, 31**, 1966~1967.

2. Kim, H.: M. S. Thesis in Fuel Science, The Pennsylvania State University, University Park, PA, U.S.A. (1983).
3. Howard, J. and Essenhigh, R.: Combust. Flame **9**, 337 (1965).
4. Annamalai, K. and Durbetaki, P.: Combust. Flame **29**, 193 (1977).
5. Howard, J. and Essenhigh R.: Ind. Eng. Chem. Process Design and Development **6**, 74 (1967).
6. Howard, J. and Essenhigh R.: Eleventh Symposium (Int.) on Combustion, Academic Press, New York, NY, U.S.A, p. 399 (1967).
7. Howard, J.: M. S. Thesis in Fuel Science, The Pennsylvania State University, University Park, PA, U.S.A. (1965).
8. Thomas, G, Harris, I. and Evans, D.: Proc. Roy. Soc. Lond. A, 300, 62 (1967).
9. Beer, J.: Fuel Society Journal **12**, 29 (1961).
10. Weight, R.: J. Inst. Energy **54**, 176 (1981).
11. Beer, J.: Proc. 2nd Symp. Flames and Industry, Institute of Fuel (London), p. C1 (1962).
12. Seeker, W., Wegener, D., Lester, T. and Merklin, J.: Seventeenth Symp. (Int.) on Combustion, The Combustion Institute, Pittsburgh, PA, p. 155 (1979).
13. Steam : Its Generation and Use, 39th ed., published by Babcock and Wilcox, NY, p. 33 (1978).
14. Peskin, R., Polymerpoulos, C. and Yeh, P.: American Institute of Astronautics and Aeronautics Journal **5**, 2173 (1967).
15. Ghosh, B. and Orning, A.: Ind. Eng. Chem. **47**, 117 (1955).
16. Smoot, L., Horton, M. and Williams G.: Sixteenth Symp. (Int.) on Combustion, The Combustion Institute, Pittsburgh, PA, p. 375 (1976).