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Project Title: Utilization of High-Sulfur Coal and New Fuel Derivatives in Circulating Fluidized Bed Combustors
ICCI Project Number: 86-87/2.3B-2
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ABSTRACT

In the direct utilization of Illinois high-sulfur coal and by-products of coal-processing operations, the circulating fluidized bed combustor offers definite advantages. The specific advantages of the circulating fluidized bed combustor, such as nearly complete combustion, low limestone requirements, and lower potential for corrosion and erosion make this type of fluidized bed boiler most suitable for the utilization of Illinois high-sulfur coal and new fuels derived from it. However, most of the circulating fluidized bed boilers and the technology associated therewith have been imported from Europe and very little operational data exist for Illinois high-sulfur coals. With the objective of demonstrating that Illinois high-sulfur coal and new fuel forms derived from it can be successfully utilized in circulating fluidized bed combustors and to provide technical and operational data with these fuels, a bench-scale circulating FBC unit has been designed and built at Southern Illinois University at Carbondale with ICDB support. In addition, tests have been conducted with a reference coal from the Illinois Basin Coal Sample Program. The results show that the circulating fluidized bed combustor can burn Illinois coals with high combustion efficiencies, on the order of 96% or better. Both sulfur dioxide emissions with limestone addition and oxides of nitrogen emissions have been measured, and supporting data are presented to show that the results from the bench-scale combustor at SIUC are in agreement with literature values reported from larger units. Additional work is continuing in the utilization of gob wastes, devolatilized char, and coal-water slurries, and in the optimization of limestone requirements with the circulating fluidized bed combustor.

EXECUTIVE SUMMARY

The research conducted on this project aims to provide a basis and an impetus to the direct utilization of Illinois high-sulfur coal and new fuel forms derived from it. Since direct combustion of coal for power generation is currently the major end use of Illinois coal, this effort should promote a healthier economic climate for coal utilization in the state. This is done by demonstrating that both the original high-sulfur coal as well as low-grade rejects and by-products of coal processing operations can be efficiently burned in the circulating fluidized bed combustor.

With the aim of demonstrating that Illinois high-sulfur coal and new fuel forms can be much better utilized in terms of combustion efficiency, fuel tolerance, environmental quality, etc., with the circulating fluidized bed combustor than with the atmospheric fluidized bed combustors currently in use, a 4-in. internal diameter circulating fluidized bed burner has been designed and fabricated. The combustor has been assembled and shake-down tests to debug the system have been performed. In addition, reference coals have been procured from the Illinois State Geological Survey Coal Bank in Champaign-Urbana. Low-grade fuels such as gob waste and devolatilized char have been secured and their proximate and ultimate analyses have been performed.

Following initial shake-down tests, the Illinois Basin Coal Sample Program coal number 3 has been burned in the circulating fluidized bed combustor. Tests conducted examine the influence of bed temperature and superficial velocity. Since this is the first year of the project, and a large percentage of the time was utilized for equipment design and fabrication, the data presented do not reflect the full potential of the circulating fluidized bed combustor. However, comparison with literature values reported by Ahlstrom in Finland and GA Technologies in San Diego indicates that the present data agree reasonably well with previously published results.

The sample results presented show that the circulating fluidized bed combustor does indeed allow Illinois high-sulfur coal to be burned with high combustion efficiencies. Good sulfur dioxide emissions control can be realized; however, additional work with various sizes and types of Illinois limestones needs to be performed. A rationale for minimizing oxides of nitrogen emissions is presented and will be implemented during the coming year. Also during the coming year, additional fuel types such as finely ground by-products of coal cleaning operations and coal-water mixtures will be evaluated.

OBJECTIVES

The overall objective of this project is to evaluate the technical feasibility of utilizing high-sulfur Illinois coal, coal chars, and new fuels directly in a circulating fluidized bed combustor. This is to be investigated by determining the efficiency of combustion of these high-sulfur fuels which, because of the special construction of the circulating fluidized bed combustor (CFBC), is expected to be better than that realized with conventional atmospheric fluidized bed units. In addition, the limestone requirements of the circulating fluidized bed combustor for meeting emissions requirements are to be studied. Operating variables such as fluidization velocity, particle size, etc., for obtaining high combustion efficiency and good sorbent utilization are being investigated. The roles of the various sulfur forms during combustion desulfurization in the CFBC will be analyzed from the experimental data.

INTRODUCTION AND BACKGROUND

A large majority of new power plant boilers are fluidized bed boilers, either atmospheric or pressurized. These fluidized bed units have demonstrated the capability of maintaining sulfur dioxide emission levels below regulatory limits by limestone injection. Also, low-grade fuels such as gob waste and beneficiation plant rejects can be burned in fluidized bed boilers. However, with these conventional units, limestone requirements can be quite high and boiler tube erosion problems are significant. In contrast, the circulating fluidized bed boilers offer a number of potential advantages, such as higher efficiency of limestone utilization and nearly complete carbon burn-up. Because of high fluidization velocities, heat exchanger surface area is reduced, with lower potential for tube corrosion.

Thus, with these special advantages, the circulating fluidized bed combustor lends itself to the utilization of high-sulfur agglomerating type coals such as those in the Illinois Basin. Also, the overall economics of coal mining operations can be significantly increased if the large quantities of low-heating value waste gob coal and other rejects from coal processing plants can be utilized at the site itself to generate power and heat for the mining or process operation. Hence, Illinois high-sulfur coal, new fuel forms derived from coal processing plants, and waste coal of low heating value are being evaluated in the circulating fluidized bed combustor in this research, to determine performance criteria such as combustion efficiency and sulfur dioxide reduction capabilities of CFBC units.

EXPERIMENTAL PROCEDURES

A. Equipment

The circulating fluidized bed combustor in which the experiments were conducted is a 4-in. internal diameter unit lined with castable refractory, designed and fabricated in-house. Figure 1 shows a schematic of the laboratory-scale circulating fluidized bed combustor. It has approximately the same internal diameter as a conventional noncirculating unit used previously to investigate the combustion and emissions characteristics of high-sulfur bituminous coals and waste fuels (Rajan and Taylor 1986). A blower supplies fluidizing air which is split into two streams. The main stream enters the fast fluid-

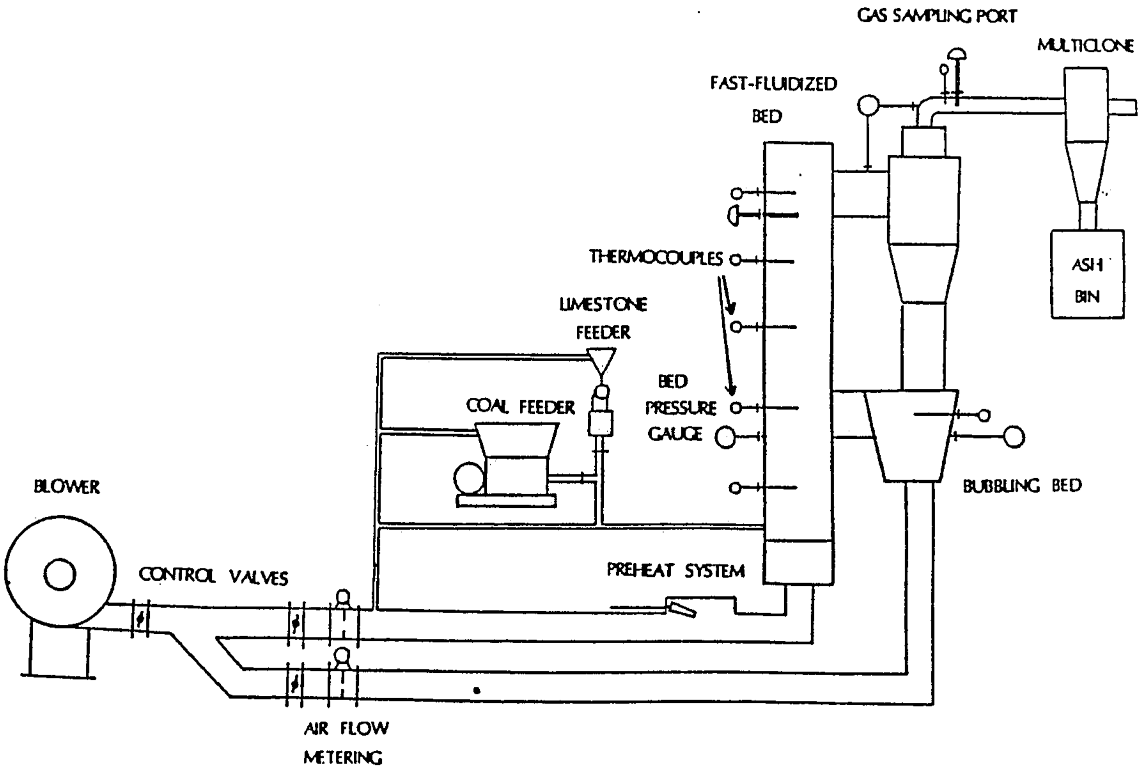

Figure 1. Schematic of bench-scale circulating fluidized bed combustor.

ized bed section of the combustor through a distributor plate specially designed to provide even fluidization. This section of the air duct also houses a propane-fired preheat system utilized to bring the bed solids up to temperatures required to ignite the main fuel. The second smaller air stream enters a bubbling bed into which the carry-over solids from the fast fluidized bed trapped by the refractory-lined hot cyclone are deposited. A non-mechanical seal ensures that these unburned fuel and smaller bed solids flow from the bubbling bed into the fast fluidized bed and not vice versa. Both air streams are metered with ASME nozzles and incorporate control valves for adjusting the flow velocities in the fast fluidizing and bubbling bed sections of the combustor. An ash removal system is also built into the bubbling bed.

Crushed coal is fed from a pressurized hopper via a screw feeder pneumatically into the dense portion of the fast fluidized bed using metered high pressure air. Sized limestone, stored in a separate hopper, is fed simultaneously into the air stream conveying the coal into the bed. Both coal and limestone feed systems have been calibrated individually.

Two quartz glass-lined observation ports, one located in the dense bed at the bottom, and the other located near the top in the dilute phase or transport section of the bed, serve for visual monitoring of the combustion process. The circulating fluidized bed combustor is instrumented with chromel-alumel thermocouples at various positions for measuring temperature. The thermocouples are connected to a selector switch and thence to a digital readout meter. Differential pressure, such as that between points below and above the distributor plate, between the dense and dilute phase section of the bed, etc., is measured using magnahelic gauges.

Solids too small to be captured by the hot cyclone are trapped in a multiclone mounted at the hot cyclone exit. The multiclone solids are later analyzed for heat content using an adiabatic calorimeter. Combustion gases are drawn off from a point at the exit of the multiclone, filtered through 2 to 5 micron particulate filters, and conveyed via heated lines to an instrument panel for determining gas composition. Carbon monoxide and carbon dioxide are measured with Beckman NDIR analyzers, oxygen with a Beckman 755 paramagnetic analyzer, oxides of nitrogen (NO_x) with a Thermoelectron 10 AR chemiluminescent analyzer, and sulfur dioxide with a Thermoelectron pulse fluorescent analyzer.

B. Sub-Assembly Description and Modification

Blower Assembly. The blower employed to supply the fluidizing air for the fast fluidizing section and the bubbling bed has been erected on a platform. PVC pipes 3.5 in. in diameter are used to convey the fluidizing air to the burner. The air stream is split up into two sections, as shown in Figure 1, feeding the fast fluidized bed and the bubbling bed. Two control valves and two ASME long radius nozzle assemblies are mounted in the lines for metering the air flow to the individual sections. The pressure drop across the nozzles are sensed by Dwyer differential pressure sensors and displayed on Dwyer digital read-out meters. During testing it was found that a by-pass valve in one of the lines was needed to control the air flow to the bubbling bed and the fast fluidized bed individually without interference from the other, and this has been installed.

Distributor Plates. Two distributor plates have been designed and fabricated, one each for the bubbling and fast fluidizing beds. Each distributor plate consists of a number of nozzles with a wire mesh screen inside the nozzle to prevent the fines in the bed from passing through the nozzle holes. Cold flow test data yielded too high a pressure drop through the distributor plates. The nozzles, which were purchased, were found to have too many layers of wire mesh in them. They were therefore modified by removing some of the wire mesh to attain an acceptable level of pressure drop in the two distributor plates.

Coal and Limestone Feeder Calibration. To ascertain the feed rates of the coal and limestone feeders, calibration runs were made at a variety of feed motor speeds. Typically this involved operating the individual feeders at a given motor speed and collecting the coal or limestone fed over a given length of time. This was repeated over the span of the motor speeds to determine the feed rate at each speed. These calibration data are then used to control the coal and limestone feed rates under actual burning conditions.

Problems encountered with the coal feeder included backing up of the coal and buckling of the coal feed auger. This has been corrected. The limestone feeder tended to clog and stop feeding under certain conditions. This problem has also been rectified.

Preheat Burner Check-Out. A propane-fired preheat burner system with a flame-out sensor is employed to bring the bed material in the fast fluidized section up to about 1100°F before injecting the coal. A flame-out sensor ensures that the propane flame is lit, or else it turns off the propane supply to the preheat system.

Testing of the preheat system showed that a stable propane flame could be maintained. However, burned gas temperatures after mixing with the air from the blower were only on the order of 500 to 600°F. Modifications were therefore carried out to bring these temperatures up to 1400°F.

Cold Flow Tests. Preparatory to burning coal in the combustor, cold flow tests were conducted to ensure that it was functioning properly. A special area of concern is the operation of the bubbling bed. To verify that the bubbling bed was actually collecting the solids from the hot cyclone and recirculating them back into the fast fluidizing section, a plastic see-through model was built and cold flow tests were conducted. Sand was used as the bed material and sawdust was blown from the fast fluidized bed section.

During the cold flow tests, pressure drops were monitored at various sections in the combustor to ensure proper flow of air and solids in the right direction. Following the cold flow tests, the bubbling bed section was lined with refractory.

Combustor Refractory Lining Conditioning. The castable refractory lining of the combustor has to be conditioned and baked before firing coal in it. The procedure, as recommended by the manufacturer, involves raising the temperature of the refractory gradually up to 500°F over a 4-hr period, holding it at 500°F for 2 hr, then raising the temperature to 700°F over a 2-hr period and holding it there for 2 hr, and so on. The full conditioning period occupied 40 hr and was accomplished over a 2-day period, day and night, without any break.

Shake-Down Tests Firing Illinois No. 6 Coal. After having performed the foregoing tests, modifications, and curing procedures, initial test runs were conducted. The bed material used in the fast fluidizing section is -14 + 35 mesh sand. The bed height used is 15 cm. The bed is brought up to a temperature of about 1100°F using the propane preheat system over a period of 4 hr. Coal is injected into the bed via the pneumatic feed system shown in Figure 1. It is allowed to burn in the bed and, once a self-sustained bed temperature of about 1400°F is reached, the propane preheat system is turned off. The circulating fluidized bed combustor was run with this coal, first in the bubbling and slugging mode and then in the circulating mode. After ascertaining the time needed to reach steady-state operation and ensuring that all the subsystems were functioning properly, the influence of bed temperature and superficial velocity was studied with the Illinois Basin Coal Sample Program coal number 3.

C. Experimental Procedure for CFBC Tests

The reference coal sample used was obtained from the Illinois Basin Coal Sample Program (IBCSP) bank at the Illinois State Geological Survey (ISGS) in Champaign, Illinois. The as-received analyses of the IBCSP No. 3 coal is shown in Table 1. The coal was ground and sieved to pass through a 14 mesh sieve in the case of the IBCSP No. 3 sample used in the circulating bed tests. This coal, therefore, contained a large percentage of fines, which were not removed, since the circulating bed combustor is adapted to digesting smaller particles through recirculation.

Table 1

Proximate and Ultimate Analysis of Coal

Analysis	Illinois No. 6	IBCSP No. 3
Proximate		
Moisture	5.4	5.36
Volatiles	35.4	39.20
Fixed Carbon	51.5	52.48
Ash	7.7	8.36
Ultimate		
C	69.72	73.82
H	5.34	4.94
N	1.53	1.68
O	13.73	8.75
S	1.95	2.27

The limestone used in the experiments was obtained from the Anna Quarries, Anna, Illinois. It is an agricultural grade limestone with a calcium carbonate equivalence of 91.3%. The limestone used in the circulating bed experiments was prepared by drying, crushing, and screening to pass through a 35 mesh sieve. The bed material used in the circulating bed tests was sand in the size range -18 +35 mesh.

The initial fixed bed height in the circulating experiments was approximately 6 in. This bed was preheated with the propane auxiliary system to about 1100°F before injecting coal, after which the preheat system was shut off. In each case, the combustor was operated until steady state was reached, which for the circulating bed combustor often took 1 to 2 days. Whenever a bed operating condition was changed, sufficient time was allowed for steady state to be reached before data were collected.

Experiments were conducted mainly to investigate the influence of bed temperature and fluidization velocity. During each test condition, bed temperature, air flow rate, coal and limestone feed rates, sulfur dioxide, NO_x, carbon monoxide, carbon dioxide, and oxygen were periodically recorded and averaged during the test period. Smaller ash particles, bed material, and unburned coal trapped by the final cyclone during the test period were collected, weighed, and their heating value determined. From these data the combustion efficiency was calculated on an energy basis.

RESULTS AND DISCUSSION

A. Comparison With Published Results

In Table 2 sample results obtained from the bench-scale circulating bed combustor at Southern Illinois University at Carbondale are compared with typical published data obtained at the 200,000 lb/hr Kauttua unit built by Ahlstrom in Finland (Oakes and Angstrom 1982), and the 2 x 10^6 Btu pilot-plant unit operated by GA Technologies at San Diego (Rickman 1984). As seen from the table, differences in fuel sulfur and nitrogen content exist among the representative fuels mentioned. The heating value for the British coal and the Ohio No. 6 and Illinois coals were on the order of 12,000 to 13,000 Btu/lb. The coal particle sizes, limestone particle sizes, operating fluidization velocity, bed temperature, calcium/sulfur mole ratio, etc., are all probably different in the cases given. Besides, there is a large difference in the diameter and height of the circulating fluidized beds, varying from the 4-in. internal diameter bench-scale unit at Southern Illinois University at Carbondale to the 200,000 lb/hr steam unit built by Ahlstrom. Despite these significant differences in scale and operating variables, there is general agreement in the measured SO_2 and NO_x emissions and the combustion efficiencies realized. The data from the SIUC unit have not been optimized for best performance and no secondary air injection was employed for NO_x control, besides the air used to reinject hot cyclone solids back into the fast fluidized bed. Hence, NO_x values did reach somewhat higher values, in the neighborhood of 400 ppm, under certain operating conditions of fuel stoichiometry, bed temperature, and superficial velocity. However, the range of NO_x values measured, viz. 150 to 450 ppm, is in agreement with results published in the literature, as seen from Table 2. The Ca/S ratio employed in the Ahlstrom tests is 2.8. The Ca/S ratios used in the present tests ranged from 2.5 to 5 and are influenced by the size of the limestone particles, superficial velocity, recycle ratio, and bed temperature. Nevertheless, the range of values reported is in agreement with previously published results.

Table 2

Comparison of Typical Test Results from Circulating Fluidized Bed Combustors

Unit	Type	Coal Used	%S	%N	SO_2 Retention (%) or SO_2 (ppm)	NO (ppm)	Combustion Efficiency (%)
Ahlstrom, Kauttua, Finland	200,000 lb/hr	British Cumberland	2.86	1.43	111 ppm	253	
GA Technologies	Pilot Plant	Ohio No. 6	5.1	-	90%	280	98.5
San Diego, California		High Ash Brazilian	3.7	-	90%	250	99.1
SIUC	Lab Bench Scale	Illinois IBCSP No. 3	2.27	1.68	70-110 ppm	150-430	93-97.5

B. Comparison of Circulating and Slugging Bed Performance

To demonstrate the advantages of the circulating fluidized bed combustor, sample results from the IBCSP No. 3 coal are compared with those obtained previously in a slugging bed combustor of approximately the same diameter (Rajan and Taylor 1986). The composition of the coal used in the slugging bed tests is also shown in Table 1. The bed material used in the slugging bed experiments was limestone of -14 + 18 mesh size.

The combustion efficiency of the slugging and circulating bed combustors are shown in Figures 2 to 4. Figures 2 and 3 show the influence of bed temperature and superficial velocity respectively on slugging bed operation combustion efficiency, while Figure 4 illustrates the effect of bed temperature on the measured combustion efficiency of the circulating bed combustor. To understand the implications of these results, the important differences in the operating variables are worth mentioning. In the slugging bed results, the coal size is in the narrow range of -18 + 30 mesh, whereas the coal used in the circulating bed tests contained all the fines that passed through a 14 mesh sieve. In Figure 2, the superficial velocity is kept constant at 4.5 ft/sec, while in Figure 4, the superficial velocity is 6.7 ft/sec, almost 50% higher. Despite these important operational differences, the circulating bed combustion efficiency is 2 to 3% higher than the slugging bed efficiency. As mentioned earlier, the performance of the circulating bed was not optimized. In addition, Figure 3 shows that at a constant bed temperature of 1500°F an increase in the fluidization velocity reduces the combustion efficiency due to higher elutriation losses in the slugging bed. These data illustrate the ability of the circulating bed combustor to handle fines and small size particles at higher superficial velocities than is recommended with bubbling and slugging bed combustors. These advantages result in decreased combustor size, higher turndown ratios, and better combustion efficiencies with the circulating fluidized bed combustor.

C. Gaseous Emissions From CFBC Tests

Figure 5 shows the sulfur dioxide emissions from the circulating bed combustor as the bed temperature is varied. The data are presented to show that the optimum temperature for best sulfur capture efficiency is the same for both conventional and circulating bed combustors and is about 1550°F. A similar figure was obtained with the slugging bed combustor, but the limestone sizes and Ca/S ratios were different. It is well recognized that in fixed bed tests the sulfur capture efficiency is increased as the limestone size decreases. In actual operation in fluidized bed combustors, decrease in limestone size results in higher elutriation losses of limestone sorbent. The circulating bed combustor reduces these elutriation losses of limestone material within the constraints of hot cyclone collection efficiency, superficial velocity, and limestone particle size. Since the limestone used in the tests of Figure 5 was sized to pass through a 35 mesh sieve, for the superficial velocity of 6.7 ft/sec, it was found that elutriation losses were still appreciable since the limestone contained a lot of fines, and Ca/S ratios of over 3 were required.

Figures 6 and 7 show the influence of operating variables on NO_x emissions, without staging of the secondary air supply. As the bed temperature is varied between 1480 to 1625°F, NO_x emissions increase from 330 to 430 ppm and then decrease. Because superficial velocity is kept approximately constant,

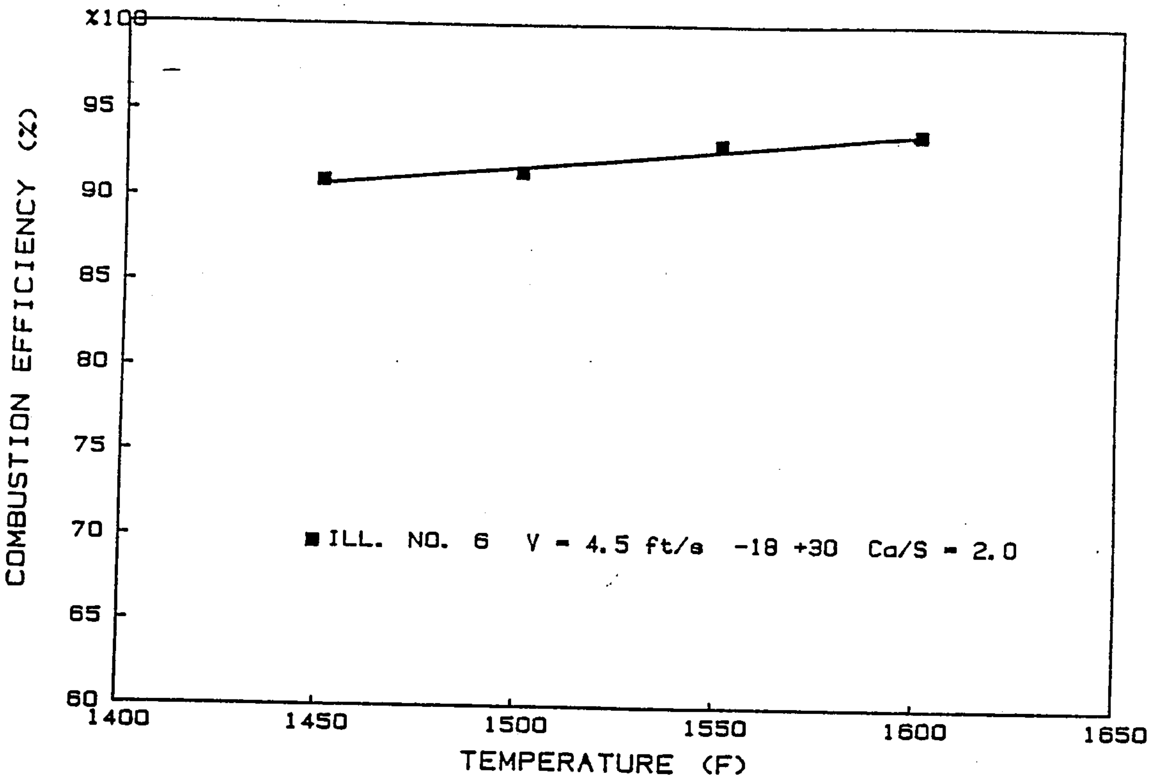

Figure 2. Combustion efficiency of FBC operating in slugging mode at various bed temperatures.

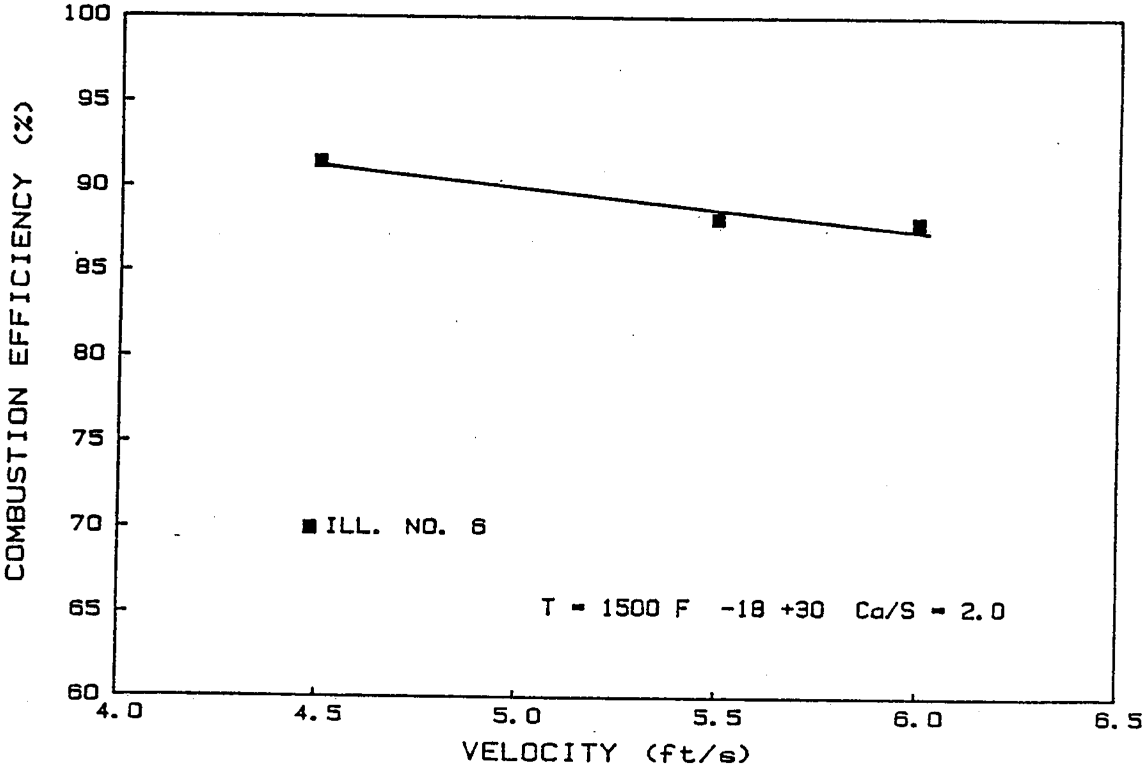

Figure 3. Combustion efficiency decrease of the slugging bed burner at high superficial velocities.

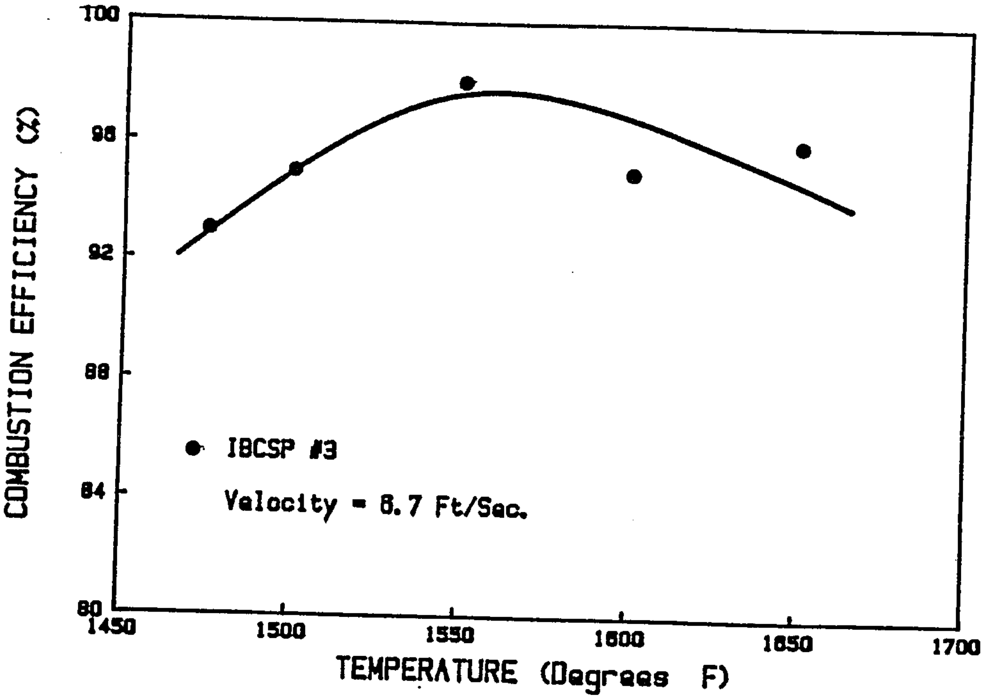

Figure 4. Combustion efficiency of circulating FBC as a function of bed temperature.

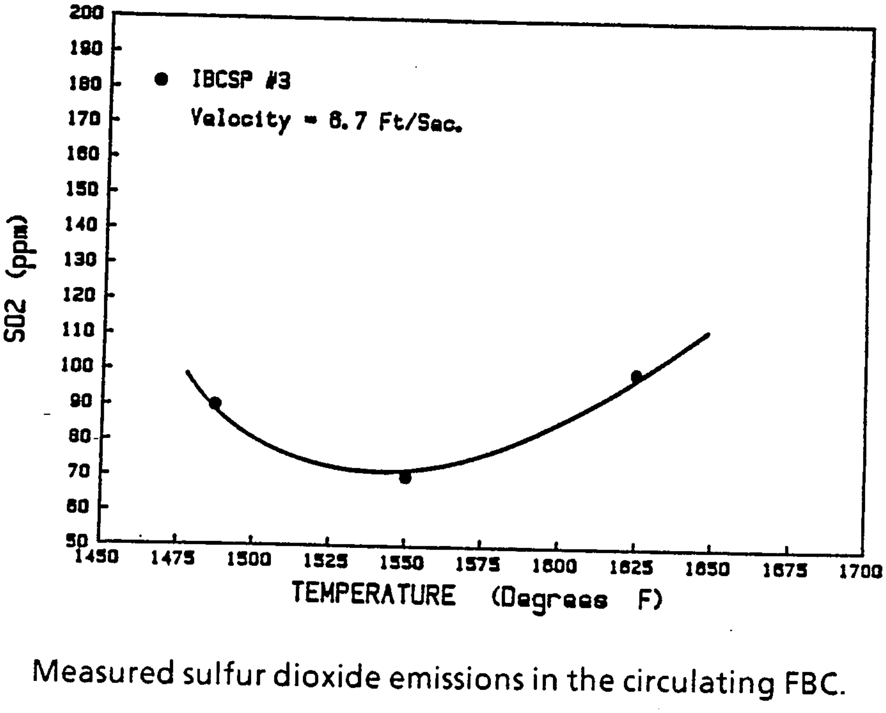

Figure 5. Measured sulfur dioxide emissions in the circulating FBC.

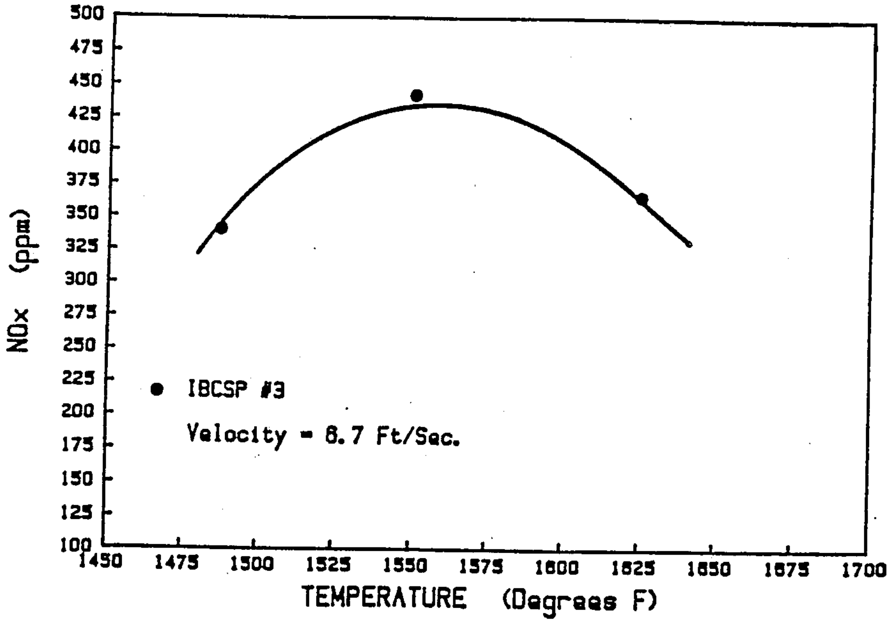

Figure 6. Influence of bed temperature on NO_x emission levels of the circulating FBC.

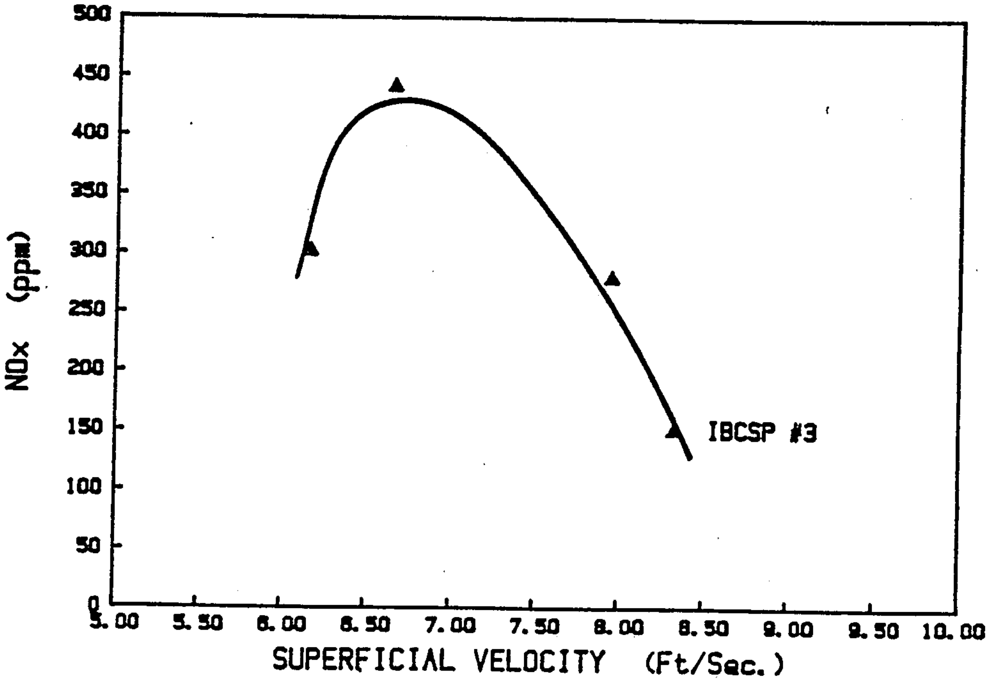

Figure 7. Sensitivity of NO_x emissions to superficial velocity in the circulating FBC.

the fuel-air ratio changes slightly as bed temperature is varied. The combined influence of bed temperature and fuel-air ratio variations result in NO_x values which are rather high compared to the published values of 250 to 280 ppm listed in Table 2. However, Figure 7 shows that NO_x levels change significantly from 300 ppm to a low of 150 ppm as the superficial velocity is varied from 6.25 to 8.3 ft/sec, at a constant bed temperature of 1550°F. The point of maximum NO_x at 6.67 ft/sec and 1550°F is the same in both Figures 6 and 7. Figure 7 shows that the changes in fuel-air ratio resulting from superficial velocity changes produce significant changes in NO_x emission levels. From this it can be concluded that NO_x emissions during coal combustion are more strongly controlled by stoichiometry than by bed temperature. With the ability to operate at higher superficial velocities, and thus leaner fuel-air ratios, the circulating bed combustor enables NO_x emissions to be reduced without sacrificing combustion efficiency. In addition, staging of the combustion air provides added capacity for fuel-air ratio control, thus further reducing NO_x levels while keeping bed temperatures at around 1550°F for optimum SO_2 control. Figures 6 and 7 show that by operating at fluidization velocities of less than 6 ft/sec or greater than 8 ft/sec, NO_x emissions in keeping with the published values of Table 2 can be realized.

Figure 8 shows typical measured profiles of carbon dioxide, oxygen, and carbon monoxide. As the carbon dioxide increases, the oxygen levels decrease, and vice versa. For the coal particle sizes used, CO_2 levels are highest at a superficial velocity of 7 ft/sec. Increasing the superficial velocity further results in a decrease in carbon dioxide levels due to decreased residence time and increased dilution of the exhaust gases. The bed temperature during the experiment was kept constant at 1550°F. Similar trends were observed when

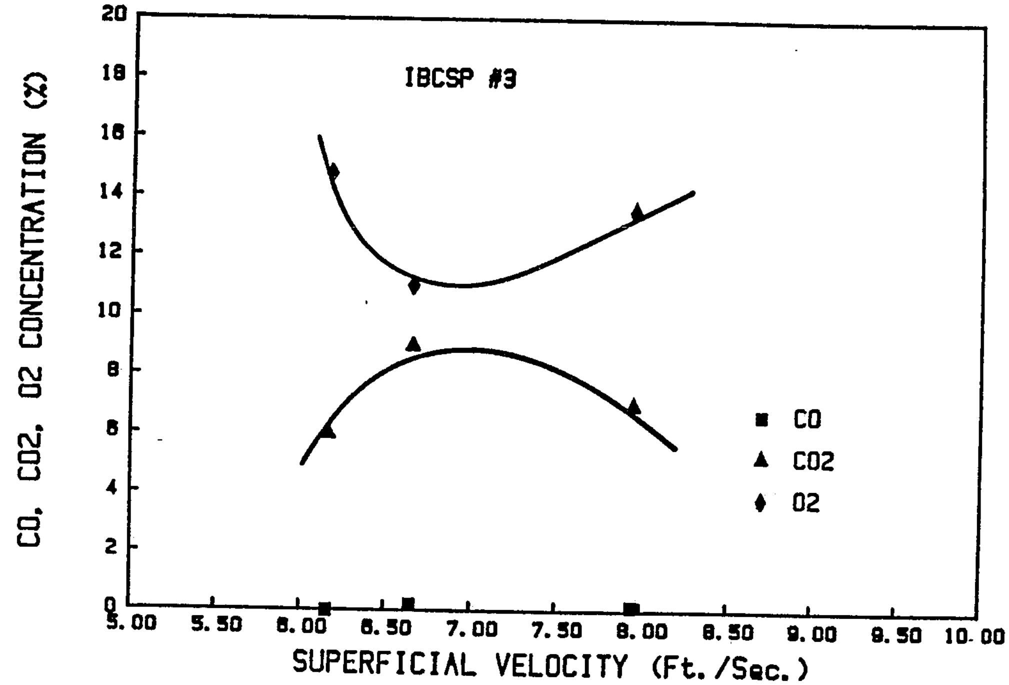

Figure 8. Effect of superficial velocity on carbon dioxide, oxygen, and carbon monoxide emissions.

the superficial velocity was kept constant and the bed temperature was varied.

CONCLUSIONS AND RECOMMENDATIONS

From the initial test results of IBCSP No. 3 coal in the circulating fluidized bed combustor, the following observations can be made:

1. Combustion is more complete and combustion efficiencies higher than slugging bed values can be obtained at higher superficial velocities.
2. The best temperature for optimum SO_2 control is about 1550°F and is similar to that for slugging bed combustors.
3. Oxides of nitrogen emissions are very sensitive to fuel/air ratios and staging effects.
4. Results from the bench-scale combustor compare favorably with pilot-scale and bigger units in terms of combustion efficiency, and SO_2 and NO_x emissions.

Additional experiments are to be conducted during the next year to evaluate the combustion characteristics of gob waste, devolatilized char, coal fines from coal cleaning operations, and coal-water mixtures. The effect of limestone size and the type of limestone is to be investigated. The tests are planned to demonstrate that both the original high-sulfur coal and waste products derived from coal cleaning and processing operations are suitable for use in circulating fluidized bed combustors employing Illinois limestones for SO_2 removal.

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