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ADVANCED TWO-STAGE COMBUSTOR

by

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IGT

ADVANCED TWO-STAGE COMBUSTOR

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ABSTRACT

The Institute of Gas Technology's (IGT) two-stage combustor promises increased combustion efficiency, greatly reduced formation of NO_x, significantly lower CO, THC, SO_x, and HCl emissions, lower particulate emission, and production of environmentally benign residue (ash, spent sorbent). The first stage of the combustor is a turbulent fluidized bed, which operates under substoichiometric conditions so that the fuel-bound nitrogen is prevented from producing NO_x. Sorbent is injected to promote the capture of sulfur and/or chlorine in solid form. The cyclonic combustor constitutes the second stage of the two-stage combustor. High-intensity, high-efficiency combustion of the reducing gases from the first stage takes place in this cyclonic combustor under conditions that minimize the formation of NO_x while providing low CO and THC emissions.

INTRODUCTION

The major challenges facing coal and waste combustion today are to find more cost-effective ways to reduce the air pollutants generated [NO_x, SO_x, CHl, CO, total hydrocarbons (THC), etc.] while producing environmentally benign residue (ash, spent sorbent, etc.). The state-of-the-art combustion technology for achieving some of these goals is fluidized-bed combustion (FBC), namely, bubbling fluidized-bed combustion (BFBC) and circulating fluidized-bed combustion (CFBC). Although the FBC is more efficient in reducing air emissions than conventional coal combustion, it is necessary to develop an advanced generation combustion system that will enable cleaner, more effective combustion of coal, particularly high-sulfur coal and wastes.

A commercial FBC has an inert fluidizing media within the bed. The FBC is operated to ensure complete combustion of coal and wastes. To reduce the sulfur and/or chlorine emissions, limestone is added to the FBC. However, operating with limestone does not suppress the formation of NO_x. Attempts to reduce NO_x by air staging combustion results in deterioration in SO_x removal or generation of significant amounts of leachable sulfur compounds in the ash. The FBC is also designed so that a significant amount of ash exits the top of the vessel with the gas. This ash must then be removed mechanically (cyclones, baghouse, or electrostatic precipitator). Because of low operating temperatures, removed ash (both bottom and fly) is leachable. The limitation of operating temperatures of lower than 1600°F also results in relatively large equipment sizes.

IGT's two-stage combustion system is based on the sloped-grid fluidized-bed (SGFB) concept and the cyclonic incineration concept, both of which have been tested extensively over a decade. The primary objective of this development is to produce an advanced combustion system that will result in increased combustion efficiency, greatly reduced formation of NO_x, significantly lower in CO, THC, SO_x and HCl emissions, lower particulate emissions, and production of environmentally benign residue (ash, spent sorbent).

The first stage of the combustor, the agglomerating fluidized-bed reactor, has already demonstrated its wide application with gasification of coal and other carbonaceous fuels, reclamation of foundry sands, and destruction of organic contaminants present in spent blast grits.[2,6] The agglomerated ash produced from coal was in compliance with EPA toxicity standards for leachability; the foundry sand as well as blast grits were freed from organic contaminants with destruction and removal efficiencies of up to 99.999%.

Similarly, the second stage of the combustor, the cyclonic combustor, has already demonstrated its capability with a wide variety of gaseous and liquid wastes.[1,4]

Process Description

The two-stage combustion process is shown in Figure 1.

The process utilizes ash agglomerating type density/size selective solids withdrawal from the fluidized bed. The carbonaceous feed material, such as coal, is fed to the fluidized bed by means of any suitable feed system. Within the fluidized bed, these carbonaceous materials are combusted under substoichiometric conditions to produce an ash and gas mixture comprising CO, H_2, CH_4, H_2O, N_2, and H_2S in a reducing region existing in the major portion of the fluidized bed. The combustion is carried out at temperatures that maintain non-slagging conditions for

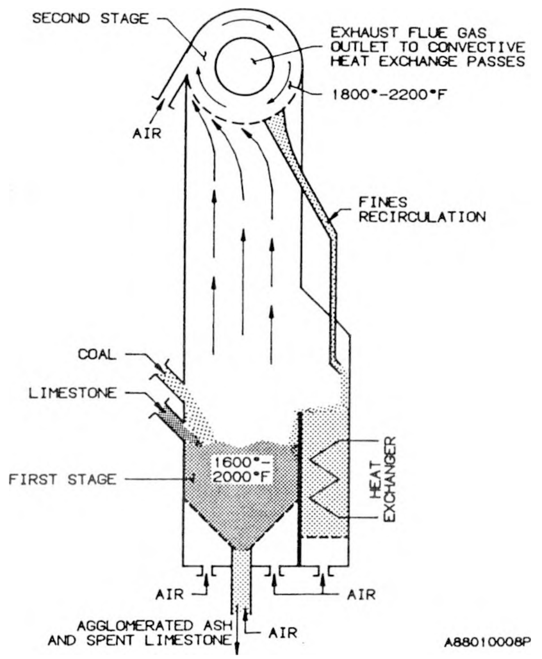

Figure 1. Advanced two-stage fluidized-bed combustor with ash agglomeration.

ash and provide conversion of fuel-bound nitrogen to molecular nitrogen, generally about 1600° to 2000°F. The combustor may be operated from atmospheric pressure to 1000 psig. As a result of reducing conditions, nearly all the sulfur present in the carbonaceous feed material is converted to gaseous hydrogen sulfide and carbonyl sulfide, and practically all of the nitrogen present in the feed material is converted to molecular nitrogen. The ratio of hydrogen sulfide to carbonyl sulfide is typically about 20:1.

Fluidizing gas consisting of air or enriched air is introduced into the fluidized-bed combustor through a perforated sloping gas distributor plate as well as through the ash discharge conduit. The concentration of oxygen in these two streams may differ considerably, depending upon agglomerating and classification characteristics of ash present in the feed material. The higher oxygen content of the gas stream in the ash discharge/classifier helps to maintain a higher temperature zone within the fluidized bed to promote agglomeration of ash, which is removed by gravity through the classifier conduit and discharged from the bed. This type of ash-agglomerating fluidized-bed combustor achieves a low level of carbon loss in the non-leachable discharged ash and provides high overall combustion efficiency.

The fines produced in the fluidized bed along with the reducing gases generated in the first-stage combustor enter the second-stage cyclonic combustor for combustion at about 1800° to 2200°F. The solid residue is separated from the gaseous products of combustion and returned to the first stage, where it is assimilated into the ash agglomerates for ultimate disposal.

Limestone or dolomite is introduced into the fluidized bed along with the carbonaceous feed materials to provide removal of sulfur compounds formed during combustion and fixation of sulfur in a solid state that is environmentally acceptable and which may be safely disposed. The quantity of the sorbent added is such that the molar ratio of calcium in the sorbent to the amount of sulfur present in the carbonaceous feed material is in the range of 1.5 to 2.0. The particle size of the sorbent is chosen such that its fluidization properties are compatible with those of ash particles in the fluidized bed.

The calcium-based sorbent decomposes to solid calcium oxide and gaseous carbon dioxide upon entering the fluidized bed due to high temperatures in the bed. The solid calcium oxide then reacts with hydrogen sulfide and carbonyl sulfide, according to the following reactions:

$$CaO(s) + H_2S(g) \longrightarrow CaS(s) + H_2O(g)$$

$$CaO(s) + COS(g) \longrightarrow CaS(s) + CO_2(g)$$

Almost complete thermodynamic conversion of H_2S and COS is achieved, and it is strictly dependent upon the partial pressure of water present within the combustor.

As calcium sulfide moves downward through the ash discharge conduit, it encounters an oxidizing atmosphere containing a relatively high concentration of oxygen. In this zone, the calcium sulfide is fixed by the reaction with oxygen to produce calcium sulfate according to the reaction

$$CaS(s) + 2O_2(g) \longrightarrow CaSO_4(s)$$

The temperature, retention time, and oxidizing atmosphere in the discharge conduit is maintained such that substantially all calcium sulfide is converted to calcium sulfate, which then can be discarded along with agglomerated ash and unreacted sorbent in an environmentally accepted manner.

The sorbent fines that are elutriated from the fluidized bed enter the oxygen-rich second-stage cyclonic combustor and react with SO_x under oxidizing conditions to produce calcium sulfate. Likewise, elutriated calcium sulfide fines are converted to calcium sulfate. Thus, the sulfur is converted to an environmentally accepted form in both stages of the two-stage combustion process. Almost 90% of the feed sulfur is removed in this manner. The air in the second stage is introduced tangentially. The excess oxygen in this stage is approximately 5% to 10%. The flue gases leaving the cyclonic combustor contain extremely low quantities of SO_x, NO_x, CO, THC, and particulates. It is suitable to be discharged to the atmosphere only after additional particulate removal.

Thermal energy to be withdrawn from the combustor to maintain proper temperatures in the various combustion stages can be achieved either by providing water walls around the combustor or by providing water tubes in the fluidized bed. Additional heat may be removed by providing a heat exchanger in the passage of fines returned from the second stage to the first stage.

Advantages

The major advantages of IGT's two-stage combustor are:

- High-efficiency, high-intensity combustion with reduced CO and THC emissions
- Simultaneous reduction in both SO_x and/or HCl and NO_x emissions
- Removal of ash and spent sorbent in the form of easy-to-handle, environmentally benign granulated solids
- High turndown ratio
- Smaller and more economical boiler design because of low excess air operation and relatively high combustion temperatures
- Flexible two-stage combustor design to minimize NO_x production and to maximize SO_x and/or HCl removal with different types of coals, biomass, and waste fuels
- Extended boiler tube life and smaller baghouse due to minimal carryover of particulates from the combustor.

The combustor characteristics are given in Table 1. Additional benefits are given in detail.[5]

Table 1. Projected combustor characteristics.

• Total Excess Air	<10%
• Carbon Burnout	>99.9%
• Bottom Ash Removal as Agglomerates (Slag)	<98%
• NO_x Emissions	<150 vppm*
• CO Emissions	<100 vppm*
• THC Emissions	<50 vppm*
• Sulfur Emission Reduction	>90%**
• Chlorine Emission Reduction	>99%**
• Turndown Ratio	>3 to 1
• Fuel	Different Coal Types, Peat, Coal Wastes, Refuse Derived Fuels (RDF), Hospital Wastes, etc.

* Corrected to 0% O_2.

** With limestone at Ca/S and/or Ca/Cl ratio ≤ 2.

FLUIDIZED-BED DESULFURIZATION DATA

IGT has recently conducted a series of in-situ desulfurization tests with coal and limestone cofeeding to a high-pressure coal gasifier.[3] The purpose of these tests was to determine the effects of pressure and temperature on the extent of in-bed sulfur removal within the first stage of combustion.

The test work was conducted in a high-pressure Process Development Unit (PDU) based on IGT's U-GAS fluidized-bed coal gasification technology. The work was sponsored by the Office of Fossil Energy of the U.S. Department of Energy. A series of five tests was conducted, at gasifier pressures ranging from 150 to 400 psig and temperatures ranging from 1760° to 1870°F. All of the tests were conducted using steam and air gasification. Steam was fed to the gasifier to maintain sufficient fluidization within the bed as well as to avoid installing heat transfer surfaces inside the reactor. The molar ratio of calcium to sulfur in the feed mixture was varied from 1.7 to 4.2. Pittsburgh No. 8 bituminous coal (Table 2) was the feedstock and New Enterprise limestone (Table 2) was the sorbent for all the tests.

Table 2. PDU feedstock characteristics.

Feedstock	Pittsburgh No. 8 Bitumin.	Limestone
Mine	Ireland	New Enterprise Ashcom Plant
Proximate Analysis, wt % (as fed)		
Moisture	1.1	--
Ash	10.2	--
Volatile Matter	41.7	--
Fixed Carbon	47.0	
	100.0	
Ultimate Analysis, wt % dry		
Carbon	71.8	--
Hydrogen	5.2	--
Oxygen	7.1	--
Nitrogen	1.1	--
Sulfur	4.5	--
Ash	10.3	--
	100.0	
Bulk Density, lb/ft^3	55.1	106
HHV, Btu/lb (dry)	13,177	--
Free Swelling Index (FSI)	6.5	--
Chemical Analysis, wt %		
$CaCO_3$	--	71.21
$MgCO_3$	--	25.76
SiO_2	--	2.36
Sulfur	--	0.20
Inert	--	0.47
		100.00

The operating conditions were intended to exhibit a range of sulfur capture efficiencies while maintaining a coal conversion efficiency of at least 90%. Consistent with the criteria for the selection of operating conditions, analysis of the resulting data indicated that the sulfur capture varied from 58% to 86%, while coal conversion during all the tests exceeded 90%. The average moisture- and ash-free coal conversion for the test series was 95%. A calcium-to-sulfur ratio of 2.0 appeared to be sufficient for a good approach to equilibrium sulfur capture. A summary of the results is presented in Table 3.

Table 3. Summary of PDU data for coal/limestone test program.

FEED MATERIAL: PITTSBURGH SEAM BITUMINOUS COAL -- IRELAND MINE
SORBENT: NEW ENTERPRISE LIMESTONE

Set Point	1	2	3	4	5
Bed Temperature, °F	1845	1870	1860	1767	1762
Reactor Pressure, psig	150	303	303	406	290
Inlet Superficial Velocity, ft/s	4.3	4.3	4.3	4.1	4.2
Fluidized-Bed Density, lb/cu ft	37.4	36.7	37.6	39.5	37.6
Fluidized-Bed Height, ft	5.0	6.6	6.9	7.6	6.1
Process Gas Input, mol/h	36.8	68.6	68.8	89.7	68.8
Steam, mol %	36.6	47.3	47.3	49.5	48.7
Oxygen, mol %	14.6	10.6	11.9	9.7	10.8
Nitrogen, mol %	48.8	42.1	40.9	40.8	40.6
Solids Feed Rate, lb/h	326.3	314.5	446.4	442.8	442.6
Coal, lb/h	214.0	232.5	306.3	236.8	214.8
Limestone, lb/h	109.0	78.3	135.5	202.5	224.6
Venturi Discharge Rate, lb/h	92.9	77.5	131.8	119.0	171.0
Carbon, %	2.8	1.0	1.30	2.70	3.10
Mineral, %	82.5	91.3	91.7	87.6	84.1
Fines Discharge Rate, lb/h	33.1	29.4	28.0	36.8	40.7
Carbon, %	49.1	35.3	34.5	6.5	8.1
Mineral, %	47.8	59.7	60.1	86.2	84.8
Reactor Gas, mol/h	46.89	79.39	83.29	98.49	76.97
Reactor Gas Composition, mol %					
CO	10.54	4.31	6.62	1.90	3.53
CO_2	13.05	12.53	13.42	11.35	11.95
H_2	12.13	8.34	10.78	4.92	7.35
H_2O	23.27	36.64	32.90	43.08	38.71
CH_4	2.47	1.55	2.19	1.33	1.99
N_2	38.43	36.45	33.87	37.26	36.39
H_2S	0.11	0.18	0.22	0.16	0.08
MAF Coal Conversion Attained, %	90.2	94.7	95.9	97.1	95.0
Ca/S Feed Molar Ratio	2.60	1.72	2.25	4.21	3.80
Sulfur Capture, %	85.5	60.2	58.5	57.5	81.4
Approach to Equilibrium Sulfur Removal, %	95.9	84.9	74.4	93.4	103.7

The fuel-bound nitrogen conversion to molecular nitrogen was about 80%.

CYCLONIC INCINERATOR DATA WITH LOW-Btu GAS

The horizontal cyclonic combustor was tested using simulated low-Btu gases.[1]

Table 4 shows the composition of the low-Btu off-gases tested. The 54 Btu/SCF gas composition represents the minimum heating value and the 67 Btu/SCF represents the average of the minimum and maximum heating value. The gas also contained up to 0.56% NH_3 and 0.15% H_2S.

Table 4. COMPOSITIONS OF LOW-BTU GASES TESTED

	H_2	N_2	CO	CH_4	CO_2	H_2O,	HHV,
			% Dry			% Wet	Btu/SCF
Average	9.2	61.3	1.7	3.7	24.1	7.3	67
Minimum	7.0	59.8	0.5	3.4	29.3	8.7	54

At the design firing rate of 3 X 10^6 Btu/h, the flame with the average heating value gas was unstable until the gas and combustion air were preheated to 335° and 750°F, respectively. At these conditions, the combustor wall temperatures stabilized; therefore, a gas temperature of 350°F, an air temperature of 750°F, and a firing rate of 3 X 10^6 Btu/h were selected as the nominal firing conditions for the combustor performance tests.

Figure 2 shows the effect of excess air on CO and NO_x emissions in the flue corrected to 0% oxygen. The CO concentration decreased rapidly with an increase of excess air (up to 15% excess air) and then slowly leveled off, while the NO_x concentration increased with excess air throughout the range tested. These results are similar to those generally observed with conventional burners.

Figure 3 shows the effect of fuel ammonia concentration on CO and NO_x emissions. The loss in the heating value of the gas at reduced NH_3 concentrations was made up by adding an equal amount (heating value) of natural gas through a calibrated rotameter.

The results show that NO_x decreased slowly with a decreasing NH_3 concentration at high NH_3 levels and rapidly at low NH_3 levels. For instance, an 80% reduction in the fuel NH_3 concentration (from 0.5% to 0.1%) reduced NO_x by 40%.

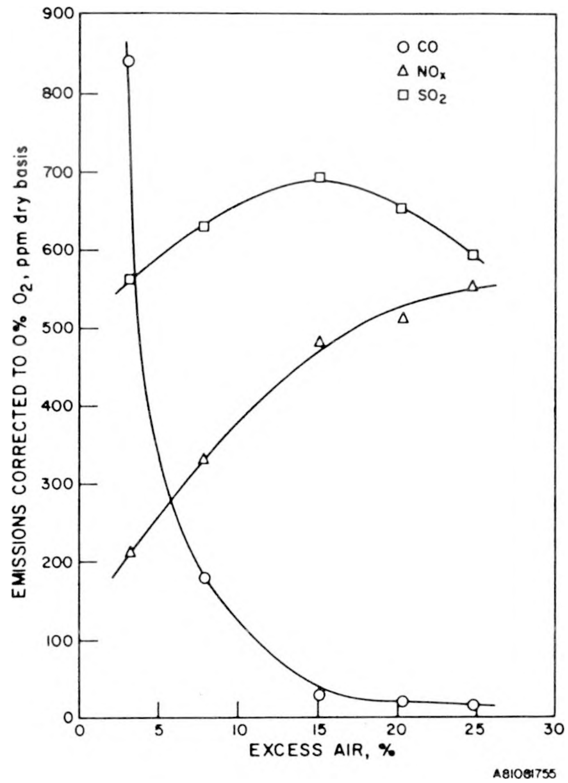

Figure 2. Effect of excess air on gaseous emissions for average gas.

Following the combustor performance tests, stability tests were conducted to determine if the cyclonic combustor was capable of burning the minimum heating value gas.

The gas temperature was increased to 490°F and the firing rate was reduced to 1.9 X 10^6 Btu/h. The flame was stable up to 11.3% moisture in the gas, which represents a heating value of 50 Btu/SCF. The gas temperature

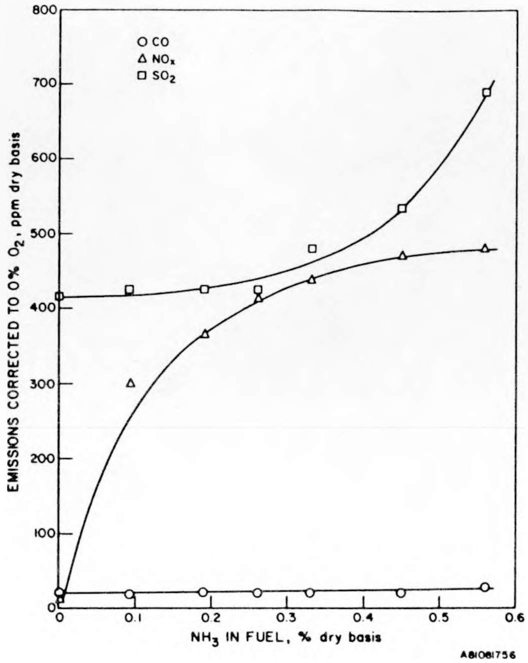

Figure 3. Effect of fuel NH_2 concentration on emissions for average gas with 15% excess air.

was then slowly reduced. The flame lifted off at a gas temperature of 350°F.

CONCLUSIONS

The development of SGFB and the cyclonic incinerator has provided a considerable data base to illustrate the viability of the two-stage combustor. IGT is currently seeking cooperation from various industrial partners and governmental agencies to provide needed funding for building the test facility to gather design data for this advanced concept. Two-stage combustion holds a great promise toward improving the nation's environmental quality.

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6 refs. 3 Figs. 4 tabs.

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Combustion of a low-BTU gas in the cyclone combustor is described.

emission