ADVANCED TWO-STAGE FLUIDIZED-BED/ CYCLONIC COMBUSTOR

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ADVANCED TWO-STAGE FLUIDIZED-BED/CYCLONIC COMBUSTOR

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ABSTRACT

The Institute of Gas Technology's (IGT) two-stage fluidized-bed/cyclonic 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, HCl, 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). The limitation of operating temperatures of lower than 870°C (1600°F) also results in relatively large equipment sizes.

IGT's two-stage fluidized-bed/cyclonic combustion system is based on the sloped-grid fluidized-bed (SGFB) concept and the cyclonic incineration concept. The development of the fluidized-bed process began in the late 70's(1) whereas the development of the cyclonic combustor was initiated in the middle 80's(2). The primary objective of this development is to combine these two technologies 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 been tested for applications such as gasification of coal and other carbonaceous fuels, reclamation of foundry sands, and destruction of organic contaminants present in spent blast grits(3,4). So far such testing has been limited to the pilot scale only. 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(2,5).

Process Description

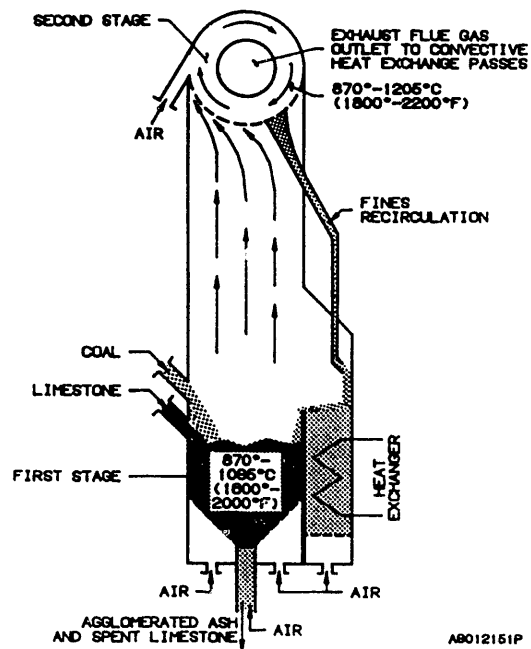The two-stage fluidized-bed/ cyclonic combustion process is shown in Figure 1.

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Figure 1. Advanced two-stage fluidized-bed/cyclonic
combustor

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 such as lockhopper, slurry pump and so on. 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 ash in the bulk of the bed and provide conversion of fuel-bound nitrogen to molecular nitrogen, generally about 870° to 1095°C (1600° to 2000°F). The combustor may be operated from atmospheric pressure to 69 Bars (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. During the tests with several coals, it was shown that the coal ash would agglomerate with 5% to 21% oxygen at the grid and 21% to 70% oxygen in the discharge conduit. The superficial velocity at the grid was maintained at 0.61 to 0.91 m/s (2 to 3 ft/s) whereas 30.5 to 91.5 m/s (100 to 300 ft/s) was maintained for the gas entering the discharge conduit. Rate of agglomeration also depended significantly upon the temperature of the bed surrounding the agglomeration

zone. An extensive fundamental study was undertaken to understand the phenomenon of the agglomeration in the fluidized bed; the results of which are reported by Rehmat et al.(6,7). 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 870° to 1205°C (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 for sulfur removal approaching equilibrium in the gas. 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 favorable temperatures in the bed. The solid calcium oxide then reacts with hydrogen sulfide and carbonyl sulfide, according to the following reactions:

$$CaO(s) + H_2S(g) \longrightarrow CaS(s) + H_2O(g) \qquad (1)$$

$$CaO(s) + COS(g) \longrightarrow CaS(s) + CO_2(g) \qquad (2)$$

The removal of H_2S is dictated by the thermodynamic considerations and hence it is dependent upon the partial pressure of water present within the combustor.

As calcium sulfide moves downward through the bed and into the ash discharge conduit, it encounters an oxidizing atmosphere near the grid and in the discharge conduit. In these zones, the calcium sulfide is fixed by the reaction with oxygen to produce calcium sulfate according to the reaction

$$CaS(s) + 2O_2(g) \longrightarrow CaSO_4(s) \qquad (3)$$
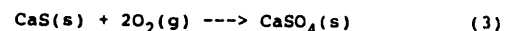
The discharge conduit is designed to provide suitable temperature, retention time, and oxidizing atmosphere to obtain optimum conversion of calcium sulfide to calcium sulfate, which then can be discarded along with agglomerated ash and unreacted sorbent in an environmentally accepted manner. It is shown that the conversion of calcium sulfide to calcium sulfate depends heavily on the type of sorbent utilized. If the starting sorbent was pure limestone, only 30% of the sulfide was converted to calcium sulfate whereas with dolomite containing 50% $MgCO_3$, up to 98% of sulfide was converted to calcium sulfate(8). The

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conversion was dependent upon the pore structure of
the calcined sorbent. Similarly, the leachability of
sulfated sorbent will also depend upon its pore
structure. Such a study is now underway.

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. The air in the second
stage is introduced tangentially. The excess air 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 combus-
tion 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.
These requirements are generally dictated by the end
use and the state-of-the-art development in materials
of construction.

Advantages

The major advantages of IGT's two-stage
fluidized-bed/cyclonic 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

- Adequate turndown capability

- 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 if used in place of
  pulverized coal burners due to reduced amounts of
  particulates in the flue gas.

The combustor characteristics are given in
Table 1. Additional benefits are given in detail(9).

FLUIDIZED-BED DESULFURIZATION DATA

IGT has recently conducted a series of in-situ
desulfurization tests with coal and limestone co-
feeding to the first stage fluidized-bed coal
combustor(10). 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

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.

stage of combustion; as well as to determine the
quality of gas produced in the first stage.

The test work was conducted in a high-pressure
Process Development Unit (PDU), Figure 2, based on
IGT's U-GAS fluidized-bed coal gasification technol-
ogy. The work was sponsored by the Office of Fossil
Energy of the U.S. Department of Energy. The process
flow schematic is shown in Figure 3. A series of five
tests was conducted, at gasifier pressures ranging
from 11.4 to 28.6 Bars (165 to 415 psia) and tempera-
tures ranging from 960° to 1021°C (1760° to 1870°F).
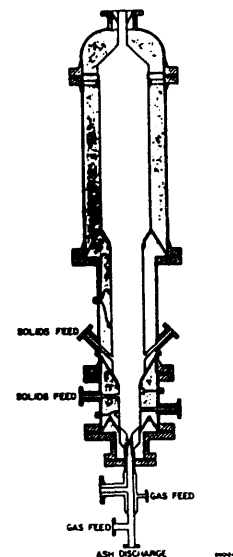All of the tests were conducted using steam and air
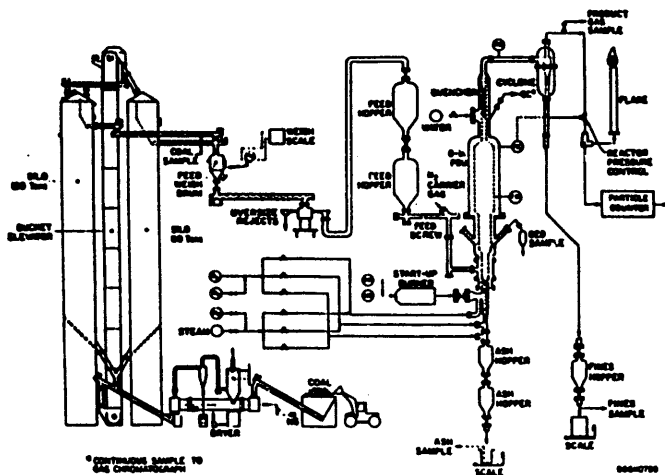

Figure 2. High-pressure PDU reactor

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Figure 3. Flow schematic of high-pressure ash-agglomerating fluidized-bed PDU

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, kg/m^3 (lb/ft^3)	882.7 (55.1)	1698 (106)
HHV, Joule/kg (Btu/lb) (dry)	31.14 X 10^6 (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

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.

The operating conditions were intended to exhibit a range of sulfur capture efficiencies while maintaining a coal utilization 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.

As indicated in this table, a very low heating value gas, ranging from 1.3 X 10^6 to 3.6 X 10^6 J/m^3 (35.2 to 97.6 Btu/SCF) was produced in the partial combustor. The main reason for such low value of heating value is the addition of steam to maintain the temperature in the reactor. No external heat removal was provided. The objective of ash discharge containing mainly ash was attained; however, the level of ash agglomeration in the discharged ash was rather low. The agglomerated particles were composed of ash and sulfided sorbent; sorbent in some instances being inside the agglomerates and in other cases melted ash actually penetrated the pores of the sorbent. The contact time between the discharged ash and

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, °C (°F)	1008 (1845)	1021 (1870)	1016 (1860)	964 (1767)	961 (1762)
Reactor Pressure, Bar (psia)	11.4 (165)	21.9 (318)	21.9 (318)	29.0 (421)	21.0 (305)
Inlet Superficial Velocity, m/s (ft/s)	1.31 (4.3)	1.31 (4.3)	1.31 (4.3)	1.25 (4.1)	1.28 (4.2)
Fluidized-Bed Density, kg/m^3 (lb/cu ft)	599 (37.4)	588 (36.7)	602 (37.6)	633 (39.5)	602 (37.6)
Fluidized-Bed Height, m (ft)	1.5 (5.0)	2.0 (6.6)	2.1 (6.9)	2.3 (7.6)	1.9 (6.1)
Process Gas Input, g-mol/s (lb mol/h)	4.64 (36.8)	8.65 (68.6)	8.68 (68.8)	11.31 (89.7)	8.68 (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, kg/h (lb/h)	148.0 (326.3)	142.7 (314.5)	202.5 (446.4)	200.9 (442.8)	200.8 (442.6)
Coal, kg/h (lb/h)	97.1 (214.0)	105.5 (232.5)	138.9 (306.3)	107.4 (236.8)	97.4 (214.8)
Limestone, kg/h (lb/h)	49.4 (109.0)	35.5 (78.3)	61.5 (135.5)	91.9 (202.5)	101.9 (224.6)
Ash Discharge Rate, kg/h (lb/h)	42.1 (92.9)	35.2 (77.5)	59.8 (131.8)	54.0 (119.0)	77.6 (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, kg/h (lb/h)	15.0 (33.1)	13.3 (29.4)	12.7 (28.0)	16.7 (36.8)	18.5 (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, g-mol/s (lb-mol/h)	5.91 (46.89)	10.01 (79.39)	10.50 (83.29)	12.42 (98.49)	9.71 (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$_2$O	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$_2$S	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
Gas Heating Value, J/m^3 (Btu/SCF)	3.64 X 10^6 (97.6)	2.09 X 10^6 (56.1)	2.90 X 10^6 (77.9)	1.31 X 10^6 (35.2)	2.42 X 10^6 (64.9)

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incoming air through the ash discharge port was not
sufficient to effect the sulfation of the sulfided
sorbent and therefore these levels of conversion were
not measured in these tests. Further testing is
required to modify gas flow distribution at the bottom
of the fluidized bed to improve ash agglomeration as
well as to test the concept of sulfation in the exit
pipe to produce the stable ash discharge.

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). The cyclonic
incineration unit is shown in Figure 4 and the test
arrangement is given in Figure 5.

Table 4 shows the composition of the low-Btu off-
gases tested. The 2.01 X 10^6 J/m^3 (54 Btu/SCF) gas
composition represents the minimum heating value and
the 2.50 X 10^6 J/m^3 (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. The
gas compositions compared closely to those produced in
the fluidized-bed partial combustor except H_2O was
replaced by N_2. The primary objective of these
combustion tests were to obtain the combustion
characteristics of low Btu gas produced in the
fluidized-bed partial combustor.

Table 4. COMPOSITIONS OF LOW-BTU GASES TESTED

	H_2	N_2	CO	CH_4	CO_2	H_2O,	HHV, J/m^3
			% Dry			% Wet	(Btu/SCF)
Average	9.2	61.3	1.7	3.7	24.1	7.3	2.50 X 10^6 (67)
Minimum	7.0	59.8	0.5	3.4	29.3	8.7	2.01 X 10^6 (54)

At the design firing rate of 879 kW (3 X 10^6 Btu/
h), the flame with the average heating value gas was
unstable until the gas and combustion air were pre-
heated to 169° and 400°C (335° and 750°F), respective-
ly. At these conditions, the combustor wall tempera-
tures stabilized; therefore, a gas temperature of
177°C (350°F), an air temperature of 400°C (750°F),
and a firing rate of 879 kW (3 X 10^6 Btu/h) were
selected as the nominal firing conditions for the
combustor performance tests.

Figure 6 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 7 shows the effect of fuel ammonia concen-
tration on CO, SO_2, and NO_x emissions. The loss in
the heating value of the gas at reduced NH_3 concentra-
tions 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%.

Following the combustor performance tests,
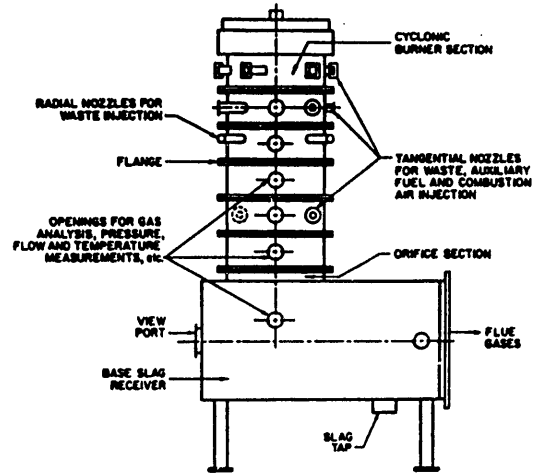stability tests were conducted to determine if the
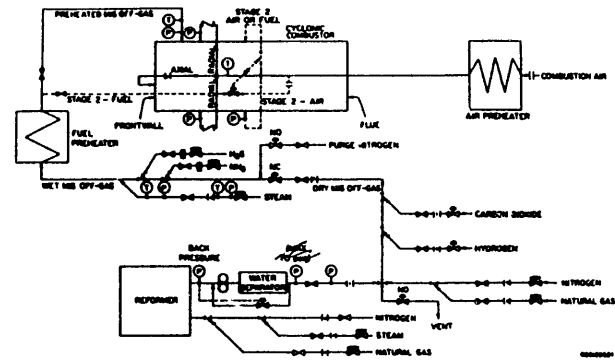

Figure 4. Cyclonic incinerator unit
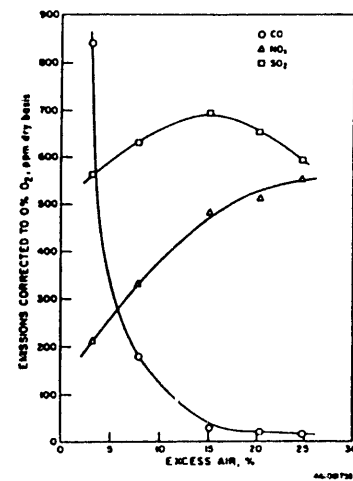

Figure 5. Flow diagram for low-Btu gas tests

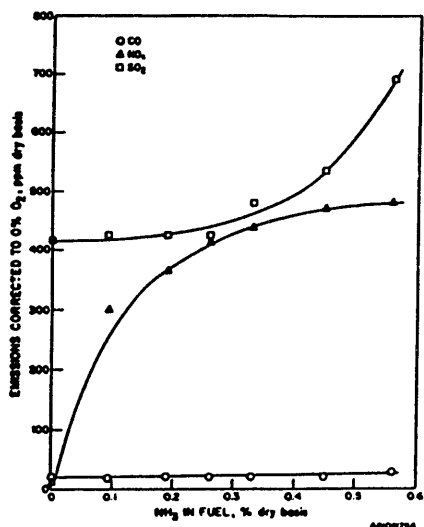Figure 6. Effect of excess air on gaseous
emissions for average gas

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Figure 7. Effect of fuel NH_2 concentration on emissions for average gas with 15% excess air

cyclonic combustor was capable of burning the minimum heating value gas.

The gas temperature was increased to 255°C (490°F) and the firing rate was reduced to 557 kW (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 1.87 X 10^6 J/m^3 (50 Btu/SCF). The gas temperature was then slowly reduced. The flame lifted off at a gas temperature of 177°C (350°F).

The results of the cyclonic combustor indicated that the emissions expected from it would depend upon the quality of gas produced in the fluidized bed combustor viz., NO_x could be significantly reduced if NH_3 formation in the first stage is suppressed; and also if excess air is reduced. Combustion of low-Btu gas could be easily achieved in the cyclonic combustor for extremely low clorific value gases. The testing in the integrated system is necessary for optimizing the system.

CONCLUSIONS

The development of SGFB and the cyclonic incinerator has provided a considerable data base to illustrate the viability of the two-stage fluidized-bed/cyclonic 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. This two-stage combustion system holds a great promise towards improving the nation's environmental quality.

REFERENCES

1. Rehmat, A., Vora, M. K. and Sandstrom, W. A., "Low-Btu Gas From the IGT Ash-Agglomeration Gasification Process," paper presented at the 13th Intersociety Energy Conversion Engineering Conference, San Diego, Calif., Aug. 20-25, 1978.

2. Abbasi, H. A. et al., "Cyclonic Combustor for Low-Heating Value Off-Gas Incineration," paper presented at the Engineering Foundation Conference on Combustion of Tomorrow's Fuel-I, Davos, Switzerland, Oct. 21-26, 1984.

3. Institute of Gas Technology, "High-Pressure Fluidized-Bed Coal Reaction Studies," topical report, prepared for the United States Department of Energy, Office of Fossil Energy, DOE/MC/22061-10, June 1987.

4. Sandstrom, W. A. and Patel, J. G., "Thermal Reclamation of Used Blast Grit," paper presented at the 1988 Ship Production Symposium, Seattle, Wash., Aug. 24, 1988.

5. Khinkis, M. J., Kunc, V. and Romanovich, P. J., "Development and Operation of an Efficient Cyclonic Incineration Demonstration System for Industrial Wastewater," paper presented at American Flame Research Committee Fall International Symposium on Incineration of Hazardous, Municipal and Other Wastes, Palm Springs, Calif., Nov. 2-4, 1987.

6. Rehmat, A. and Saxena, S. C., "Agglomeration of Ash in Fluidized-Bed Gasification of Coal by Steam-Oxygen (or Air) Mixture," Industrial and Engineering Chemistry Process Design Division, Vol. 19, 1980, pp. 223-230.

7. Rehmat, A. et al., "Modeling of Agglomeration in a Fluidized Bed," paper presented at the Third Chemical Congress of North America, American Chemical Society, Fuel Division, Toronto, Canada, June 5-11, 1988.

8. Rehmat, A. et al., "Reactions of Calcium-Based Sorbents With Sulfur in Coal During Gasification," paper presented at 1987 International Conference on Coal Science, Maastricht, The Netherlands, Oct. 26-30, 1987.

9. Khinkis, M. J., Patel, J. G. and Sandstrom, W. A., "Two Stage Combustion," U.S. Patent No. 4854249, Aug. 8, 1989.

10. Goyal, A. and Rehmat, A., "The U-GAS Process --From Research to Commercialization," paper presented at the A.I.Ch.E. Annual Meeting, San Francisco, Calif., Nov. 25-30, 1984.

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