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GASIFICATION IN PULVERIZED COAL FLAMES

Semiannual Progress Report, July—December 1976

January 1977

Work Performed Under Contract No. E(49-18)-2029

**Combustion Laboratory
Purdue University
Lafayette, Indiana**

MASTER

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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GASIFICATION IN PULVERIZED COAL FLAMES

Semi-Annual Progress Report
Energy Research and Development Administration
ERDA-FE-2029-5

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ABSTRACT

This project concerns the production of power and synthesis gases from pulverized coal via suspension gasification. Control, flow and monitoring systems are nearing completion. The coal feeder has been tested and a coal suitable for cyclone firing is available. Construction of the cyclone reactor and exhaust line are underway. The mass spectrometer calibration system is complete.

I. OBJECTIVE AND SCOPE OF WORK

The objective of this program is to investigate the feasibility of using currently available pulverized coal burners to produce power or synthesis gas from coal. Two configurations are considered:

(1) the annular confined jet with secondary swirl, and (2) the vortex tube with tangential entry. The first burner is characterized by a single axial injector of high primary velocity; secondary swirl is used to control mixing and residence times. The second burner is modeled after the cyclone combustor; large residence times and slagging operation should lead to high carbon efficiencies.

In both burners, coal combustion with air and/or air-oxygen mixtures supports the endothermic gasification reactions. The burners are designed such that axially injected, preheated steam is surrounded by swirling air, thus promoting efficient gasification. Pulverized coal is carried by primary steam in the confined jet system, and by primary air in the vortex gasifier.

Species concentrations and temperature are measured both within and downstream of the gasifier chambers. These profiles are used to assess the influence of process variables such as pressure, solid/gas feed rates, swirl intensity, inlet temperature and geometrical injection pattern on both the rate and extent of coal conversion. Simple models governing entrained flow systems will be developed to further interpret the experimental data.

II. SUMMARY OF PROGRESS

The efforts over the past six months have been directed toward development of the experimental apparatus. The reactor supply, control and monitoring systems in the test cell and control room have reached advanced stages of construction. Feeder tests are in progress. The cyclone pressure vessel is complete and installation of internal components is underway. A southern Indiana coal is available for initial tests; its suitability for cyclone firing has been confirmed.

All material for the exhaust sampling system including the mass spectrometer is on hand and ready for assembly. A simple calibration system using a test gas mixing technique has been completed. Operating

and data reduction procedures for the mass spectrometer are being reviewed and refined. An analysis relating major dependent variables to measurable reactor parameters is presented.

III. TECHNICAL PROGRESS

Test Cell

The primary effort over the past six months has been directed toward construction of the test cell flow and control systems. Three undergraduates and the technicians assigned to the lab provided assistance. The air and nitrogen systems are now 90% complete and awaiting hydrostatic testing. The mass flow meters supplied by Thermal Instrument Company (Trevos, Pa.) were not acceptable as delivered. We are attempting to have this problem corrected. The interlock system has been wired, but has not been tested. All power wiring is installed except for the boiler, steam heater, and reactor heaters which are pending additional equipment installation. The upper air/steam control panel is complete, and the central control panel is complete except for two switches.

The Vibra Screw feeder has been checked out and initial calibration runs performed. In addition, remote monitoring and positioning systems for the feeder are nearing completion. Work is proceeding on the exhaust system.

1. Air and Nitrogen Systems

Figure 1 is a schematic showing the air, nitrogen, steam and methane systems. Air at 2000 psig is filtered, reduced to 350 psig and supplied to a distribution manifold. The manifold supplies the secondary air, primary air, ignition air, and control air. A safety valve (set pressure: 400 psig) and burst disk (450 psig rated) provide protection against system overpressure. A 125 psig safety valve protects the low pressure control air system. All flow lines are complete to the point where they will be tied into the separate reactor systems. Final connection of the signal and pressure lines will be made after hydrostatically testing the flow systems.

We have experienced some difficulty with the flow meter manufacturer. Although the meters are installed, we are not yet fully satisfied that they will meet our specifications. They will be tested as

Figure 1. Flow system schematic

soon as the system has been hydrostatically tested. Thermal Instrument Company supplied different electronic monitoring instrumentation than specified in their brochures and failed to supply accurate instruction manuals. Complete calibration data were not provided, the steam meter was calibrated incorrectly, and delivery was 19 weeks behind schedule. The poor response and workmanship on the part of Thermal Instrument Company indicates that a thorough field test and calibration check of these meters will be necessary. This will inevitably cause some delay.

The nitrogen system will use standard industrial quality nitrogen bottles to supply a distribution manifold operating at 250 psig for initial runs. During high pressure runs, the manifold will operate at 350 psig. The manifold is protected by a safety valve (set at 300 psig for initial runs) and a burst disk (450 psig rated). Nitrogen will be used for purging, pressurizing feedwater and cooling water supplies, and capping the boiler and water systems during shut-down periods. The nitrogen system is complete except for the bottle manifold and rack.

2. Interlock System

The interlock system has been wired according to diagrams which reflect the logic shown on Figure 2. It will provide signals for opening valves, turning on heaters, and other on/off control functions. When required, interlocks prevent opening valves or turning on equipment out of sequence. The system utilizes 24 VDC and 120 VAC "cube" relays for most functions and is fused to prevent overcurrent. Relays for the steam system have not been installed. The air flow and flame failure trips have not been installed pending selection of primary equipment. Space has been allowed for 16 additional relays.

The interlock system is housed under the central control panel (Figure 3) which incorporates all the switches and light indications for the system. The panel is complete except for the trip and reset switches which are expected shortly. A complete system resistance check will be performed before powering the system. Power will be required before the hydrostatic test on the flow systems in order to operate the solenoid valves.

Figure 2. Interlock logic diagram

Figure 3. Central control panel

3. Power Wiring

All wire for the secondary and primary air heaters has been pulled except for the high temperature wire at the heater proper. Wiring for the steam heaters, reactor heaters and feeder is complete as far as installed equipment allows. Controllers for all heaters are installed. All wiring and conduit is installed per the National Electrical Code and Combustion Laboratory safety requirements. A schematic of the power wiring is presented in Figure 4.

4. Upper Air/Steam Control Panel

Regulation of the steam and air flows to the reactors will be from a panel directly over the test cell window. This panel also incorporates the pressure monitoring gages for the flow system, but not those directly related to the reactors. Figure 5 shows the panel layout. This panel is complete except for the final tubing connections to the signal and supply lines in the test cell. These connections must be made after hydrostatic testing of the main systems to protect gages and regulators.

5. Coal Feeder

The Vibra Screw feeder to be used for atmospheric tests has been checked and operated. Initial calibration data (Appendix A) indicate that the long period stability of the feeder is very good after an initial settling period. Short term stability may be a problem as fluctuations on the same time scale as the rotation of the feed screw are inherent in this type of feeder. We expect to build a stirred reactor type flow stabilizer to reduce the feed fluctuations. Initial design work based on the flow loop system of How, Kear and Whittingham (1954) will begin shortly.

To allow remote positioning and monitoring of the feeder, we have devised a servo-motor drive positioner for speed control. This will be pulsed to the correct feeder speed setting from a control room location. The feeder shaft speed will be monitored using a gear tooth pulsed magnetic sensor connected to a frequency counter. The coal mass flow will be calibrated to frequency values for each type of coal used. We hope to find a common calibration curve, but variations in moisture may cause

Figure 4. Three Phase Power Distribution System

Figure 5. Upper control panel

some deviation. Figure 6 shows schematically the speed control and monitoring devices.

6. Exhaust System

The exhaust system will provide the common exit for gases produced in the reactors. Particles will be removed by a cyclone separator prior to a backpressure valve and flow metering device. In addition, the exhaust line will be wrapped with cooling coils to insure exhaust temperatures less than 250°F at the cyclone. This temperature limitation is based on cyclone materials, and a higher temperature cyclone may be constructed if this proves infeasible. The exhaust system schematic is included in Figure 1.

The cyclone separator has been constructed, and the pipe ordered. We are planning to use an ASME standard orifice meter for flow measurement, although it will be affected by gas composition. Based on an equilibrium gasification model, we expect gas composition to introduce a 10% maximum error in the indicated flow. This will be corrected after the mass spectrometer data is analyzed.

7. Steam System

Work on the steam system will not begin until the boiler has been received and installed. The boiler was scheduled to ship from Kent, Washington on December 30, 1976, so we expect it will arrive before the end of January. Plans for the building to house the boiler have been completed and approved, but construction will not be complete until late April, unless favorable weather conditions develop. We do not expect steam availability until late May or June.

Cyclone Reactor System

1. Cyclone Reactor

The reactor assembly is shown in Figure 7. The reaction zone is 6 inches in diameter and 10 inches long. Pulverized coal and air enter through four equally spaced tangential nozzles in the upper portion of the chamber. Each nozzle has a concentric tubing arrangement; primary air and coal are injected through the inner tube, secondary air through

Figure 6. Feeder control/monitoring schematic

Figure 7. Cyclone Reactor Assembly

the outer tube. Primary air entrance velocities range from approximately 100 to 300 ft/sec. A torch ignitor for chamber preheating and coal ignition fires downward from the annulus at the chamber roof.

Steam for gasification will be injected to the core of the chamber from the bottom. This separate injection of fuel/air and steam, coupled with cyclone flow characteristics, should establish two zones of reaction within a single reactor stage: exothermic combustion reactions in the annular zone and endothermic gasification reactions in the core.

Reaction products leave via the throat in the chamber roof and are cooled before leaving the pressure vessel by a stainless steel heat exchanger which employs water. Beyond the pressure vessel, coiled copper tubing conducts cooling water around the exhaust line. A sampling probe and observation window are located at an elbow in the exhaust line just downstream of the pressure vessel. Before being vented, reaction products flow through a cyclone separator for the removal of particulate matter. When pressure operation is desired, a backpressure valve will be installed in the exhaust line.

The walls of the reaction zone are formed from a rammable plastic refractory (Jade Pak-88-P, manufactured by A. P. Green Refractories Co., Mexico, Mo.). This material resists attack by slag and can withstand temperatures as high as 3400⁰F (2140⁰K). The cylinder wall is 3 inches thick; the roof and floor are 4.5 inches thick. Two layers of insulating brick (A. P. Green Co.'s G-23) support and insulate the plastic refractory. A hole in the chamber floor allows slag to flow to a quench bath. Bulk insulation (Kaowool bulk fiber, manufactured by Babcock and Wilcox Co., Oak Brook, Ill.) fills the void between the reaction chamber and the pressure vessel wall.

Wall heat losses are minimized by four quarter-cylindrical electric heating elements (Electro-Applications, Inc., Canonsburg, Pa.) which enclose the refractory wall. These elements, 16 inches long, extend beyond the chamber endwalls to promote a flat temperature profile in the reaction zone. A slot in each element allows the four feed tubes to reach the chamber. Total heating capability is 8kW.

The pressure vessel has been designed in accordance with the ASME Boiler and Pressure Vessel Code to operate at 20 atm. It is fabricated from a 30 inch length of 24 inch seamless pipe (A-53 Grade B carbon

steel, schedule 20). A 3 inch circular steel plate forms a flat head at the bottom; a blind flange bolted to a slip-on flange seals the top. Two electrical conductor sealing glands (Conax Corp., Buffalo, N. Y.) provide power to the heating elements. A transducer gland (Conax Corp.) permits the placement of eight thermocouples within the pressure vessel.

Presently, all raw materials are either already on hand or are readily accessible. The pressure vessel has been fabricated; insulating bricks are being cut to size. Molds are being made for the rammable refractory which will ultimately be cured in available kilns. The torch ignitor will soon be ready for testing. Considerable work remains to be done on the exhaust cooling system, the observation window, and the sampling probe. The eight thermocouple locations within the pressure vessel have not been finalized.

2. Coal Suitability

Initial cyclone combustion runs will employ a southern Indiana coal. Analyses of this coal have been performed by Commercial Testing and Engineering Co. Results are shown in Table I.

The suitability of a coal for reaction in cyclone chambers can be determined from the criteria discussed in Babcock and Wilcox's Steam (1972). Moisture, volatile matter, and ash content and composition are all significant. To maintain an adequate slag layer, 6 to 25 percent ash content (dry basis) is acceptable, while volatile matter content should exceed 15 percent (dry basis) to reach the necessary high combustion rates. Coals ranging widely in moisture content can be successfully burned in cyclones, although pre-drying or elevated secondary air temperatures may be required for high moisture content coals. Table I illustrates that the ash and volatile matter contents of the coal in question are within acceptable limits. The moisture content of the coal will be reduced in a coal drying facility.

The two major criteria which govern the suitability of coal for cyclone use are the relation between sulfur content and the ratio of iron content to calcium plus magnesium content and the viscosity of the slag formed in the cyclone. The first criterion is a measure of the tendency of a coal to form iron and iron sulfide, both undesirable. Figure 8

TABLE I

Analyses of Coal Proposed for Use in the Cyclone Reactor
(all percents are on weight basis)

Proximate Analysis (as received)		Ultimate Analysis (dry basis)	
Moisture	15.33	Carbon	65.60
Ash	14.67	Hydrogen	4.73
Volatile matter	32.61	Nitrogen	1.26
Fixed carbon	37.39	Chlorine	0.02
	<u>100.00</u>	Sulfur	3.40
		Ash	17.33
		Oxygen (diff)	<u>7.66</u>
			<u>100.00</u>
Mineral Analysis (ignited basis)		Heating Value (Btu/lbm)	
Phos. pentoxide, P_2O_5	0.38	As received	10079
Silica, SiO_2	43.51	Dry basis	11904
Ferric oxide, Fe_2O_3	17.64		
Alumina, Al_2O_3	26.60	Ash Fusion Temperatures	
Titania, TiO_2	0.82		
Lime, CaO	3.31		
Magnesia, MgO	1.11		
Sulfur trioxide, SO_3	2.75		
Potassium oxide, K_2O	3.08		
Sodium oxide, Na_2O	0.60		
Undetermined	0.20		
	<u>100.00</u>		
		Reducing	Oxidizing
		Initial deformation	2070°F
		Fluid	2240°F
			2180°F
			2400°F

$$T_{250} = 2470^{\circ}F$$

Figure 8. Coal suitability for cyclone furnaces based on tendency to form iron and iron sulfide (Steam, 1972). The locus for the proposed coal is also shown.

illustrates the suitable and unsuitable ranges of this relation, along with the locus for the proposed coal. The second criterion is an indication of slag-tapping ability. Slag can be easily tapped when it has reached a viscosity of 250 poises. The temperature at which this viscosity is achieved, T_{250} , should not exceed 2600°F for a coal to be suitable for cyclone use. The T_{250} of the proposed coal is 2470°F (Table I), substantially within the upper limit.

3. Data Analysis

Review of the entrained flow coal gasification literature (Lenzer and Laurendeau, 1976) indicates that the major dependent variables determining gasifier performance are carbon efficiency (η_c), combustible gas yield (Y_p), make gas heating value (Q) and cold gas efficiency (η_{cg}). These four variables are defined as follows:

$$\begin{aligned}\eta_c &= \text{kg coal reacted/kg coal fed} \\ Y_p &= \text{kg combustible gas produced/kg coal fed} \\ Q &= \text{chemical heating value of gas produced (kcal/kg gas} \\ &\quad \text{produced)} \\ \eta_{cg} &= H_p/H_c\end{aligned}$$

where H_p is the enthalpy of combustion of the make gas (kcal/kg coal fed) and H_c the enthalpy of combustion of the input coal (kcal/kg coal fed). The hot gas efficiency (η_{hg}), a parameter relating the contributions of both the chemical and sensible enthalpy of the make gas to the input chemical enthalpy, is more useful than η_{cg} in evaluating the performance of gasifiers producing low BTU power gas (combined cycle systems). Definition and discussion of the hot gas efficiency is provided in Appendix B (Laurendeau and Waite, 1977).

To calculate and interpret η_c , Y_p , Q and η_{cg} , we must experimentally measure the following: (1) coal heating value (H_c), (2) reactant (coal, air, steam) feed rates, (3) percent carbon losses and (4) make gas mass flowrate and composition. To calculate η_{hg} , the make gas and reactant temperatures are also required. Coal heating value is determined by coal analysis; the reactant feed rates are independent operating variables.

Carbon losses and thus η_c can be estimated from the amount of char recovered by the cyclone separator in the exhaust line. Carbon embedded in the slag and separator inefficiency render precise measurements somewhat impractical. An exhaust line orifice allows measurement of the make gas flowrate; mole fractions are obtained via the mass spectrometer.

The most suitable parameter for evaluating gasifier performance is the cold (or hot) gas efficiency, since η_{cg} is a function of the directly measured dependent variables - η_c , Y_p and Q . We can show this by defining the following additional dependent variables:

- Y = make gas yield (kg gas produced/kg coal fed)
- ω_p = combustible mass fraction (kg combustible gas produced/kg gas produced)
- ϵ = chemical yield (kg gas produced/kg coal reacted)

The make gas yield (Y) is obtained from the coal feed rate and the make gas flowrate; ω_p and Q can be calculated from knowledge of the make gas composition. We then have:

$$Y_p = \omega_p Y$$

$$\therefore \eta_{cg} = H_p/H_c = Q \cdot Y/H_c = Q \cdot Y_p/(\omega_p \cdot H_c)$$

Now, if a precise value for η_c is known, the combustible gas yield Y_p is given by

$$Y_p = \omega_p \eta_c \epsilon$$

and thus

$$\eta_{cg} = Q \eta_c \epsilon / H_c$$

Note that $\epsilon = Y_p/\omega_p \eta_c$ and thus ϵ can be compared with the value of ϵ predicted from a kinetic or equilibrium reaction model plus knowledge of the reactant flowrates. As discussed in Appendix B, knowledge of η_{cg} plus the sensible enthalpy contributions (determined from make gas and reactant temperatures) allows calculation of the hot gas efficiency (η_{hg}).

Gas Sampling System

In our gasification program we will attempt to measure gas-phase composition and temperature, not only at the exhaust but also within each gasifier. The presence of water and particulates will present special problems; however, the measurements can be made by an appropriately designed mass spectrometer-probe system.

1. Mass Spectrometer

The UTI Q-30C precision quadrupole mass spectrometer system is in working order and is presently being calibrated. Experiments by Drs. Bruce Raby and Kuo-chin Lin of UTI confirm that the Q-30C is suitable to resolve a gas mixture similar to that expected during coal gasification. The heated inlet system gives the Q-30C the capability of directly measuring high water vapor concentrations. Small hydrogen concentrations (< 15%) which are commonly difficult to measure, present no problem for the Q-30C. CO and N₂, which have identical base (largest) peaks can be distinguished by analyzing their minor (smaller) peaks, which are at different mass numbers.

2. Calibration System

A simple calibration system has been designed and built (Figure 9). The system is capable of mixing calibration gases of known composition from pure gases by carefully monitoring the partial pressures. Pure bottled gas is introduced into the manifold and then into the glass mixing vessel. A manometer monitors the pressure each time more gas is introduced into the mixing vessel. System leaks can be detected by a McLeod gage.

3. Calibration and Data Reduction

The mass spectrometer will be initially calibrated for H₂, CH₄, H₂O, N₂, CO, C₂H₄, C₂H₆, O₂, and CO₂ gases. The fragmentation of each individual gas is obtained from the pure gas, and the relative sensitivity of each gas is obtained from a mixture with some standard (N₂ or Ar). Instrument adjustments will be made to optimize fragmentation patterns, sensitivity, and resolution for our specific needs. Final calibration

Figure 9. Mass spectrometer calibration system schematic

will be obtained by using gas mixtures which approximate the temperature, pressure, and concentrations found in actual sampling.

All significant peaks found in the gas fragmentation patterns will be measured. This enables gases of the same atomic mass such as N_2 , CO, and C_2H_4 to be distinguished. As there are more significant peak heights than species present, an overdetermined system of linear algebraic equations for the species mole fractions must be solved. The computer program of McLean and Sawyer (1967), which employs a method of least squares, will be used to solve the system of equations; both the species mole fractions and the standard errors of calculation will be determined.

4. Sample Inlet System

Materials for the sample inlet system have been purchased and are ready for assembly. Sample gases will be pulled through heated, teflon-lined tubing to reduce water adsorption and condensation and adherence of tars and solids. Particles will be removed by a small cyclone (inertial separator) and filters to protect the pumps and mass spectrometer.

IV. WORK FORECAST

During the next six months we expect to accomplish the following:

- (1) Complete test cell construction
- (2) Complete cyclone gasifier construction
- (3) Calibrate the mass spectrometer
- (4) Integrate the gasifier, sampling system and mass spectrometer
- (5) Shakedown test cell and gasifier
- (6) Run cyclone combustion experiments at 1 atm
- (7) Complete design and construction of the confined jet gasifier
- (8) Complete boiler installation.

V. RESULTS AND CONCLUSIONS

The major results achieved during the past six months are the following:

- (1) Near completion of test cell air and nitrogen system
- (2) Completion of control wiring
- (3) Initial feeder testing and design of remote feeder control
- (4) Design and initial construction of the exhaust system
- (5) Cyclone pressure vessel fabrication
- (6) Construction of calibration system for the mass spectrometer.

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VII. APPENDIX A: FEEDER TEST DATA

FEEDER SETTING: 9

TOTAL RUN TIME PRIOR TO TEST: 1/2 hr.

COAL TYPE: W. Virginia bituminous, unsized

DRY? yes

INITIAL HEAD IN HOPPER: 8 inches

MEASUREMENT INTERVAL: A: 15 sec B: 30 sec C:

TIME STARTED 2:00 pm

TIME ENDED 2:20 pm

DATE: 12/2/76

SAMPLE/INTERVAL	A	B	C
1	74.4	151.1	
2	76.0	152.0	
3	75.6	152.7	
4	74.6	153.1	
5	76.6	151.0	
6	74.4	152.7	
7	76.2	152.7	
8	76.3	150.8	
9	77.2	152.8	
10	76.6	153.9	
11	76.6	154.2	
12	76.2	154.5	
13	77.4	153.7	
14	76.8	153.8	
15	77.1	153.7	
16	76.0	154.3	
17	77.6	153.9	
18	77.3	155.6	
19	76.8	154.5	
20	77.4	155.2	

COMMENTS

Note steady rise in mass collected per interval

Hopper refilled to 8 in after run

PER INTERVAL, MEAN	STD. DEVIATION	PER SECOND, MEAN	STD. DEVIATION
A 76.355 gm	.975	A 5.090	0.065
B 153.31	1.344	B 5.110	0.045
C		C	

% ERROR A 1.277 B .877 C

HOURLY FLOW RATE A 40.4 B 40.6 C LBM/HR

FEEDER SETTING: 9

TOTAL RUN TIME PRIOR TO TEST: 1-1/2 hr

COAL TYPE: W. Virginia bituminous, unsized

DRY? yes

INITIAL HEAD IN HOPPER: 8 inches

MEASUREMENT INTERVAL: A: 15 sec B: 30 sec C:

TIME STARTED 2:00 pm

TIME ENDED 2:20 pm

DATE: 12/2/76

SAMPLE/INTERVAL A B C

1	77.5	156.0
2	78.3	155.2
3	78.5	156.4
4	78.8	158.7
5	76.6	156.7
6	77.9	156.5
7	78.8	155.1
8	77.3	158.2
9	79.1	156.1
10	79.3	152.3
11	76.8	155.3
12	77.9	156.7
13	78.1	155.7
14	78.0	154.7
15	78.9	156.0
16	78.8	156.9
17	76.9	157.2
18	77.8	157.7
19	78.5	155.8
20	78.2	155.0

COMMENTS

Note lack of increasing/decreasing trends due to increased run time prior to test (1-1/2 vs. 1/2 hr)

PER INTERVAL, MEAN STD. DEVIATION PER SECOND, MEAN STD. DEVIATION

A 76.355 gm .975 A 5.090 0.065

B 153.31 1.344 B 5.110 0.045

C C

% ERROR A 1.277 B .877 C

HOURLY FLOW RATE A 40.4 B 40.6 C LBM/HR

VIII. APPENDIX B: PERFORMANCE PARAMETER FOR COAL GASIFICATION TO POWER GAS

A suitable performance parameter for SNG production from coal is the so-called cold gas efficiency,

$$\eta_{cg} = H_p/H_c ,$$

where H_p is the enthalpy of combustion for the products (kcal/kg-coal) and H_c the enthalpy of combustion of the input coal (kcal/kg-coal). Note that both the make gas heating value (kcal/kg-gas) and yield (kg-gas/kg-coal) are incorporated into the definition of η_{cg} . Physically, η_{cg} represents the percent of coal chemical heat input recoverable as make gas chemical heating value.

Since the sensible energy of a low BTU power gas can be used in combined power cycles, a new parameter comparable to η_{cg} , but incorporating the sensible contribution, must be developed. We suggest the hot gas efficiency,

$$\eta_{hg} = \frac{H_p + \Delta H_{pr}}{H_c}$$

where ΔH_{pr} is the difference in sensible enthalpy between the products and reactants (kcal/kg-coal). This parameter describes more accurately the potential efficiency of processes converting coal to low BTU gas since η_{hg} reflects (1) the energy conversion efficiency appropriate to power gas use and (2) gasifier heat losses.

The differences between η_{cg} and η_{hg} are shown in Figure 10 for a gravimetric steam/coal ratio of 0.25 and various oxygen/coal ratios. These results were obtained using the NASA SP-273 equilibrium computer program (Gordon and McBride, 1971) for adiabatic and non-adiabatic atmospheric gasification of an Indiana bituminous coal with steam and air. Computations at elevated pressures (Lenzer et al., 1976) (5 and 20 atm) simply indicate a minor upward shift in η_{cg} and η_{hg} at lower OX/C ratios. The coal analysis is listed in Table II; input conditions are listed in Table III. The input enthalpies reflect both the chemical and sensible enthalpy for the given input temperatures. The input enthalpy for the coal was calculated via the stoichiometric combustion reaction and the

Figure 10. Cold and hot gas efficiencies for coal-air-steam gasification at 1 atm ($H_2O/C = 0.25$). Non-adiabatic curves are for gasifier temperatures $270^{\circ}K$ less than the corresponding adiabatic temperatures.

TABLE II
ASSUMED DRY COAL ANALYSIS

<u>Proximate:</u>		<u>Ultimate:</u>	
Volatile matter	41.4%	Carbon	72.3%
Fixed carbon	48.2%	Hydrogen	4.8%
Ash	10.4%	Oxygen	8.3%
		Nitrogen	1.4%
Caloric Value:	7180 kcal/kg	Sulfur	2.8%
		Ash	10.4%

TABLE III
EQUILIBRIUM GASIFICATION MODEL: INPUT CONDITIONS

<u>Reactants</u>	<u>Molecular Form</u>	<u>Input Enthalpy (kcal/mole)</u>	<u>Input Temp (°K)</u>
Coal	C _{6.718} H _{5.352} O _{.579} N _{.112} S _{.098} + SiO ₂ (Ash)	-36.10	298
Air	N _{1.562} O _{.420} Ar _{.0093} C _{.0003}	2.95	700
Steam	H ₂ O	-53.39	810

given heating value. The cold and hot gas efficiencies were calculated from the gas temperature and the predicted species concentrations. In general, the calculated results compare quite favorably with the trends found in the coal gasification literature (Lenzer et al., 1976; Lenzer and Laurendeau, 1976).

As expected, the cold gas efficiency maximizes as the OX/C ratio is varied. The exception occurs at higher H_2O/C ($H_2O/C > 0.75$) and low OX/C ratios (and consequently, low temperatures), where methane concentrations become important (greater than 2% of the make gas yield). Non-adiabatic conditions are more detrimental to η_{cg} at lower OX/C ratios due to a decrease in carbon monoxide yield; at higher temperatures, the CO + H_2 content remains relatively constant despite heat losses. Unless carbon efficiency drops below 100% (a distinct possibility at lower temperatures), the hot gas efficiency is clearly unity for the adiabatic case.

Comparison of the hot and cold gas efficiency for the non-adiabatic case reveals the importance of considering the sensible enthalpy of the products. Note the significant overall increase in efficiency; indeed, the hot gas efficiency is considerably greater than either the adiabatic or non-adiabatic cold gas efficiency at higher OX/C ratios. Moreover, the peak in η_{hg} shifts to higher OX/C ratios, as compared to η_{cg} . These results are of great importance in practical gasifiers since we can increase the OX/C ratio to preserve carbon efficiency and reaction temperature, thus efficiently producing low BTU gas at the high temperatures ideal for combined power cycles.

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16. Abstracts The objective of this program is to investigate the feasibility of using currently available pulverized coal burners to produce power or synthesis gas from coal. Two configurations are considered: (1) the annular confined jet with secondary swirl, and (2) the vortex tube with tangential entry. The first burner is characterized by a single axial injector of high primary velocity; secondary swirl is used to control mixing and residence times. The second burner is modeled after the cyclone combustor; large residence times and slagging operation should lead to high carbon efficiencies. Species concentrations and temperature are measured both within and downstream of the gasifier chambers. These profiles are used to assess the influence of process variables such as pressure, solid/gas feed rates, swirl intensity, inlet temperature and geometrical injection pattern on both the rate and extent of coal conversion. Simple models governing entrained flow systems will be developed to further interpret the experimental data.			
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