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GASIFICATION IN PULVERIZED COAL FLAMES

Semi-Annual Progress Report, September 1977—March 1978

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MASTER

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Semi-Annual Progress Report
Department of Energy

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ABSTRACT

This project concerns the production of power and synthesis gases from pulverized coal via suspension gasification. Cyclone and confined jet gasifier configurations with swirling flow are being investigated. Emphasis in this report is on the final design and construction of the test facility and the two experimental reactors. Calibration procedures are presented, as are data reduction techniques and preliminary experimental results for methane and coal combustion tests.

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 cyclone 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 a combination of construction, experimentation, and analytical work. The pressure vessel and the movable block swirl generator for the jet reactor have been completed. The stand for the jet reactor and molds for its internal ceramic components are now being designed and built.

The coal feeder was moved into the test cell and extensive electrical and mechanical hookups were completed. The entrainment vessel, a device used to mix the pulverized coal with primary air, was also installed. Feeder calibration under both entrained and non-entrained

conditions is now complete. Initial experience with the system has been very favorable.

Work continues on an electronic flow metering system that will eventually replace the manometers and pressure gages currently in use. All the necessary components have been purchased and assembly is nearly complete. The system will be ready for use as soon as shakedown and calibration trials are carried out.

Considerable experimental work with the cyclone reactor has been accomplished during the last six months. A new series of methane combustion tests was carried out to confirm that the product gas sampling system could provide reliable data under clean combustion conditions. Three coal combustion tests were also carried out. The final test resulted in a stable, self-sustained coal flame with a maximum feed rate of 15 lb/hr. Results of the methane and coal combustion tests are summarized in Section III.

Analytical work has centered around the development of a model for coal combustion in the cyclone reactor. The model is in an early stage of development and no definitive results are available to date. An extensive computer program is now being written to reduce raw data from the combustion and gasification experiments. Finally, a paper was presented at the Spring, 1978 meeting of the Western States Section of the Combustion Institute describing the experimental facility and the results achieved thus far.

III. TECHNICAL PROGRESS

Test Cell

1. Air, Nitrogen, Steam and Methane Systems

Figure 1 is a schematic diagram of the test cell flow system. The system was designed to accommodate the flow and temperature ranges listed in Table 1 at reactor pressures of 1-20 atm. The nitrogen system provides reactor purging while the methane system allows coal ignition. Solenoid valves provide on/off capability; pneumatic controllers vary primary and secondary air and steam flow rates. Ignition air and methane are controlled with metering valves. A separate control room

Figure 1. Flow System Schematic

allows remote operation of the entire flow system. Only the steam system is not presently in operation.

TABLE 1.
Design Flow Rates and Temperatures for Test Cell

	Maximum Design Flow (lb/hr)	Expected Range (lb/hr)	Maximum Design Temperature (°R)	Expected Range (°R)
Coal	40	7-28		
Primary Air	60	10-45	960	560-760
Secondary Air	350	20-350	1460	960-1260
Steam	60	2-20	1460	1060-1460

2. Flow Metering and Temperature Measurement

Methane and ignition air flow rates are monitored with rotameters. Primary and secondary air and steam flow rates are monitored with orifice meters. Interchangeable low and high range secondary air orifices are available to provide good readability at low flow rates. A single orifice covers the entire range for primary air. Absolute and differential pressure measurements are made via a transducer/manometer network. Details of the flow meter design and calibration are covered elsewhere (George et al., 1977).

Important temperatures are indicated by thermocouples connected to a 40 position thermocouple switch. Temperature readout is provided by a digital readout device (Omega Engineering Model No. 175KC1). Thermocouples also provide temperature feedback to heater controllers.

3. Safety Interlock System

A large number of interlocks have been built into the control system to help insure safe operation. Interlocks protect against operating sequence errors, e.g., turning on a heater or the coal feeder without air flow. A system trip and nitrogen purge are initiated whenever an unsafe operating condition is detected. The following events

cause a system trip:

- a) loss of 120 VAC power
- b) loss of 240 VAC feeder power
- c) loss of 24 VDC power
- d) flame failure
- e) air flow loss
- f) reactor overpressure
- g) coal flow loss.

4. Reactor and Fluid Heaters

The cyclone reactor is heated externally to offset heat losses from the reaction zone and to prevent thermal shock of the refractory. Process air and steam are heated substantially before reaching the reactor by GTE Sylvania immersion type heaters. Temperature ranges for the air and steam flows are summarized in Table 1.

5. Coal Feeder

A Vibra Screw coal feeder has been calibrated and fitted with remote monitoring and control devices. Details of the feeder operation and calibration appear later in this section. The feeder is installed and fully operational. A coal entrainment and distribution system is also operational and has been found to have a negligible effect upon the coal feed rate. Current problems with coal dumping into the entrainment vessel after a trip due to pressure differences between the feed bin and entrainment vessel will be alleviated by installing a shut-off valve on the feeder exit. This valve has been designed and is now under construction.

6. Exhaust System

The exhaust system is cooled by a water jacket to maintain temperatures at the particle separator at less than 250⁰F due to material limitations. An ASME standard orifice is located downstream of the particle separator to provide an indication of the make gas flow rate. A backpressure valve will be installed in the line prior to high pressure gasification tests.

7. Sampling System

Make gas composition is monitored with a UTI Q-30C quadrupole mass spectrometer and a water-cooled stainless steel exhaust probe. Future plans call for internal probing of both gas composition and temperature. Details of the mass spectrometer calibration procedures appear elsewhere in this report.

A schematic diagram of the sampling system is shown in Fig. 2. Sample gases enter the water-cooled stainless steel probe where the chemical reactions are quenched. Heated, teflon lined tubing (Technical Heaters, Inc.) is used to minimize water adsorption and condensation, catalytic reactions and adherence of tars and solids between the probe and the mass spectrometer. A 1/2 inch cyclone and filter are used to remove particulates from the sample gas, as particles may damage the mass spectrometer. The vacuum pump pulls the sample to the mass spectrometer and regulates the sample gas flow rate and pressure at the mass spectrometer inlet. The N_2 back flow system will allow high pressure flow through the probe to remove any blockages which may occur.

Cyclone Gasifier

1. Background

The cyclone gasifier possesses several advantages compared to the concentric jet system (Syred and Beer, 1974): (1) greater turbulent mixing levels, (2) ease of operation at high pressures and (3) larger particle residence times. These three factors promote high temperatures and slagging conditions, and hence good carbon and gasification efficiencies. There are disadvantages, however: (1) chamber wall temperatures are much higher, causing material and heat transfer problems; (2) slagging operation presents difficulties due to heat losses and residue disposal; (3) injection of coal/air vs. coal/steam mixtures increases the opportunity for spontaneous combustion at high pressures.

Turbulent mixing and particle residence times in vortex systems are primarily determined by the tangential swirl velocity (Strickland, 1973). This dominant velocity profile is satisfactorily described by the Rankine model, i.e., potential or free vortex flow ($W \propto r^{-1}$) near the wall, and rotational or forced vortex flow ($W \propto r$)

Figure 2. Sampling System Schematic

at the chamber core. In idealized rotary motion (Schmidt, 1970), the free vortex zone is characterized by downward axial flow, while the rotational zone is characterized by upward flow. Thus coal particles move downward via a helical path, followed by upward movement along a helical path of smaller radius. Lighter particles will of course undergo more rapid migration to the center of the chamber.

To our knowledge, the only extensive investigation of pulverized coal gasification in a small-scale cyclone system was conducted by Yagi and Kunii (1957). Production of both power gas and synthesis gas was correlated with carbon efficiency and reduction zone temperature (1300-1650°K). By externally heating the 20 cm diameter chamber, 70-80% of the ash appeared as slag. Their preliminary results are quite encouraging, thus providing impetus for our cyclone gasifier work.

2. Design Considerations

Reactor size is influenced by cyclone geometric parameters and coal throughput ($\text{lbm coal/hr} \cdot \text{ft}^3$). Table 2 lists the design parameters for our cyclone reactor (Lenzer, 1977); these can be modified later to improve high pressure operation. Coal throughput is the most influential consideration in the sizing process. A significant design objective is the ability to operate at throughputs similar to those achieved in both industrial and pilot plant gasifiers without exceeding coal feed rates of 40 lbm/hr .

Due to a reduction in throughput at increased reactor volume, cyclones with diameters larger than 6 inches were eliminated from consideration. The increased flow disturbance due to sampling probe insertion in a smaller diameter cyclone precluded further increases in throughput capability. Consequently, a 6 inch diameter, 10 inch long cyclone was selected. At high pressures, however, a smaller chamber (or higher coal feed rate) may become desirable.

TABLE 2
Geometric Design Parameters
for the Cyclone Reactor

Swirl number, s	17.5
Length/diameter ratio, L/D	1.67
Throat/cyclone diameter ratio, D_t/D	0.417
Number of tangential nozzles, N	4
Total nozzle/throat area ratio, A_n/A_t	0.137

Heat transfer calculations were performed to determine thermal losses and to aid the materials selection process. Heat loss estimates are imperative due to the high surface to volume ratio of laboratory cyclones. Temperature profiles of the reactor assembly under various operating conditions were used to determine the type and amount of refractory and insulation. These calculations also formed the basis for heating element selection and pressure design (Lenzer, 1977).

3. Reactor Construction

The reactor assembly is shown in Figure 3. Major aspects of this design are high pressure gasification (20 atm), a symmetric reactant inlet arrangement, separate combustion and gasification zones promoted by independent steam injection, slagging operation and the use of air with no oxygen enrichment. While various combinations of these features have been previously employed by others, the incorporation of all of them is apparently unique.

The wall and ends of the cyclone are formed from four molded cylinders of A. P. Green Jade-Pak-88-P rammable plastic refractory. This material resists attack by slag and can withstand temperatures as high as 3400°F (2140°K). Satanite slag resistant mortar is used to cement the cylinders together. The cyclone wall is 3 inches thick; the roof and floor are approximately 4.5 inches deep. A 1 inch diameter hole in the refractory floor permits slag removal. The floor of the cyclone is supported and insulated by two layers of G-23 Insulating Firebrick. The side and top of the reactor are insulated with Kaowool bulk fiber. The reactor pressure vessel is 24 inches in diameter.

Figure 3. Cyclone Reactor Assembly

A stainless steel torch ignitor is used for coal ignition and final refractory preheating. Upstream of the reactor, primary air/coal and secondary air flows are each split into four reactant streams. Air and pulverized coal then enter the reactor through four coplanar tangential nozzles near the cyclone roof. Each nozzle has a concentric tubing arrangement; primary air and coal are injected through the inner tube, secondary air through the outer tube. Entrance velocities range from 100 to 300 ft/sec for primary air/coal and from 30 to 500 ft/sec for secondary air.

The slag quench bath is made from a capped seamless 4 inch vertical steel pipe. A 3 inch diameter stainless steel tube welded to the pipe extends upward to the exit of the slag tap. Currently, water replenishment is a batch operation; a more sophisticated system is being considered. Product gas leaving the reaction zone is immediately cooled by a 10 inch long, 4 inch diameter stainless steel cooling coil.

From the pressure vessel, reaction products flow through a 4 inch stainless steel pipe to a reducing tee where they enter the water jacketed make gas cooling system. A 4 inch forged steel pipe cap threads onto the tee and supports a sampling probe and observation window. The water cooled sampling probe consists of a triple walled stainless steel tubing arrangement which extends downward to a point slightly above the cooling coil. The window is a 1 inch diameter, 1/2 inch thick quartz disk. A small mirror positioned above the observation window permits monitoring of combustion activity from the control room.

Four quarter-cylindrical electric heating elements (Electro-Applications, Inc., Canonsburg, Pa.) provide preheat capability and minimize wall heat losses. These elements extend beyond the chamber end walls to promote a flat temperature profile in the reaction zone. An extensive thermocouple system provides reactant and product temperatures, critical material temperatures, and feedback for temperature controllers.

Jet Gasifier

1. Background

The jet gasifier is based on a swirling, confined, coaxial two phase jet. The performance of the system depends heavily on the mixing

which occurs among reactants. Heat transfer, particularly radiation, will also play a large part in the success of the gasifier. Jet theory cannot as yet provide an analytical prediction of gasifier performance. However, studies of swirled jets and jet burners have shown that the development of the jet is strongly related to the swirl numbers, the momentum of the primary jet, and geometric factors such as confining walls or a divergent quarl (Beer and Chigier, 1972; Syred and Beer, 1974; Heap et al., 1973; Field et al., 1967). The most important factor is swirl, which controls the shape and mass recirculation ratio (recirculating/initial mass flow) of a central recirculation zone, which forms on the axis of the jet at $S > 0.6$.

The momentum of the primary jet distorts the recirculation zone, but does not destroy it (Heap et al., 1973). For low momentum, entrainment of the primary jet is so rapid that no coal is injected into the recirculation zone and the flame forms an axially centered conical annulus. At the other extreme, the primary momentum is sufficient to carry a significant portion of the coal through the recirculation zone. The intermediate case is expected to be the most useful for gasification as the central recirculation zone will have the strongest concentrations of steam and coal from the primary jet.

The central recirculation zone is not available for flame stabilization due to the endothermicity of the gasification reactions. Radiation can be used to preheat and ignite the incoming coal particles since gasifiers will probably operate in refractory lined tubes. "Lazy" flame tangentially fired power boilers depend almost exclusively on radiation for flame propagation. In the swirled jet gasifier, this will be augmented by hot gas recirculation outside the jet which develops as the result of confinement.

2. Design Considerations

The reactor is designed to allow independent control of the major reactor variables (inlet velocities, confinement ratio, etc.) to assist in characterizing their effects. This procedure will elucidate those areas of existing burner technology which can be directly applied to gasification, and indicate new directions for areas in which simple

extrapolations are not possible. The reactor is designed to combust coal initially; after combustion has been stabilized and investigated, the reactor will be shifted to gasification.

The initial objective was to design a reactor which would allow free jet development of the coal flame. However, the large rates of spread characteristic of swirled jets (Kerr and Fraser, 1965; Beer and Chigier, 1972) would require a prohibitively large chamber. Further, most industrial flames experience some degree of confinement either by walls, tube banks or surrounding burners. Pershing and Wendt (1975) operate their coal burner at an apparent confinement ratio (diameter of chamber/diameter of the secondary air throat) of 4.4:1. Beer (1976) suggests that a 6:1 ratio is probably a reasonable approximation to industrial practice.

Since the confinement ratio has a strong effect on the external recirculation zone (which may be very important in stabilizing gasification reactions), flexibility of confinement ratio was included as a design criterion. An initial confinement ratio of 7.5:1 was chosen. However, the reactor is designed with interchangeable refractory sections of smaller I. D. to reduce the confinement ratio. By maintaining the original chamber diameter, confinement ratios up to 30:1 are possible at 20 atm.

A modified Thring/Newby analysis using the Kerr and Fraser (1965) jet spread and entrainment data (George et al., 1977) shows that the recirculated mass flow outside the jet decreases with swirl. For the gasifier then, the effectiveness of the outer recirculation zone as a flame stabilizer will also decrease with swirl. A recirculation ratio greater than one can be maintained up to a swirl number of 2.5. Unlike industrial units with cooled walls, the recirculated gases will retain most of their temperature and a recirculation ratio of unity may be sufficient for stability. The chamber length has been chosen to allow even an unswirled jet to contact the wall before the chamber end.

3. Reactor Construction

Figure 4 shows the general layout and dimensions of the reactor. Reactor sizing was based on an upper limit of 28 lbm coal/hr and

Figure 4. General Layout of the Jet Reactor

combustion at 20% excess air. A four to one turn-down ratio should be possible without reactor modification. High feed rates will be possible under pressure operation, and for gasification at atmospheric pressure.

The refractory lined reaction chamber is housed in a 24 inch pressure vessel designed for 20 atm operation. Access to the chamber is provided for an ignitor, two probes and two observation windows. The reactor can be tilted or lowered for assembly or probe exchange.

The refractory walls will be cast of Harbison Walker Lightweight Castable No. 30. This is an insulating castable with an upper recommended use temperature of 3460°R . Since it has very poor resistance to slagging and abrasion, a coat of A. P. Green Satanite approximately 1/8" thick will be applied to all inner surfaces. A 1/32 inch stainless steel sheet surrounds the refractory; it serves as an alignment tube for the refractory sections. Two inches of Kaowool bulk insulation surrounds the refractory alignment tube.

The secondary air throat and the divergent quarl are cast into a removable section of refractory in the upper chamber end wall. Changing the secondary velocity can be accomplished by changing throat blocks, secondary air temperature, or primary to secondary air ratio. Changing the divergent angle will require changing blocks.

For combustion, the secondary air throat will be 2 inches in diameter. Velocities will be less than 125 ft/sec, as recommended by Babcock and Wilcox (1963). Divergents with an included angle of 90° or less and a length/throat diameter ratio of unity can be incorporated into the block. Initially an included angle of 70° will be used as recommended by Beer and Chigier (1972).

The primary injector consists of a 3/4" O. D. tube with a 1/2" O. D. tube inserted at the exit. A slight flare on the 1/2" tube is used to improve radial mixing with the secondary air. Different primary injectors will be used to obtain the desired primary momentum. A spark initiated methane/air ignitor is positioned to fire across the coal jet. The ignitor will be used to preheat the chamber and to stabilize the coal flame until the walls are hot enough to insure a self-sustaining reaction.

The key to performance of the gasifier is swirl. The swirl number should, therefore, be both easily variable and precisely determined. The moving block swirl generator developed at IJmuiden can provide continuously variable swirl and the position of the blocks correlates well with swirl number (Beer and Chigier, 1972; Grant et al., 1977). Figure 5 shows the movable block swirl generator for the gasifier.

As noted by Grant et al. (1977), primary velocity has a significant effect on the swirl number for some conditions. In gasification, primary flow may be as high as 30% of the total mass flow. Hence, total swirl number must include both primary and secondary flows; the secondary swirl number (commonly used for characterizing industrial units) is not adequate. The necessary correlations, i.e., the total and secondary swirl number vs. swirl generator block position, are given by George et al. (1977).

The swirl blocks were designed with a larger block angle than the original IJmuiden generator to insure that recirculating flows will be available under gasification conditions. The swirl generator is capable of total swirl numbers in excess of 1.0 for all combustion and gasification conditions expected. Much higher swirl numbers will be possible under combustion conditions where the primary momentum is small with respect to the secondary momentum (George et al., 1977).

A stationary probe will be inserted through the exhaust gas cleanout cap. This probe will be used to obtain initial reactor performance data; it will also serve as a safety check for ignition and confirm gross reactor behavior after internal probing is initiated. A traversing offset probe will be inserted through the lower vessel head and used to map concentration and temperature profiles inside the chamber.

Mass Spectrometer and Coal Feeder Calibration

1. Mass Spectrometer Calibration

Calibration and testing of the UTI Q-30C mass spectrometer system is complete. Calibration tests were performed with sub-atmospheric gas mixtures containing H_2 , CH_4 , H_2O , N_2 , CO , O_2 and CO_2 .

SECTION BB

Figure 5. Moving Block Swirl Generator

The known gas mixtures were made via a simple calibration system based on the method of partial pressures. Water was handled by heating the calibration system such that the lowest system temperature was at the liquid-vapor interface within a water reservoir. The interface temperature determines the equilibrium water vapor pressure within the system. Water vapor can then be allowed to enter an evacuated mixing flask. After equilibrium is attained, subsequent gases can be introduced to form a water-containing mixture of known composition.

The gases considered in calibration have interfering fragmentation patterns (more than one gas producing a signal at a given mass/charge ratio). To resolve the complex gas mixtures, 10 separate peaks were monitored for the 7 gases considered. A system of 10 equations and 7 unknowns must therefore be solved. The computer program of McLean and Sawyer (1967), which utilizes a least squares technique to solve an overspecified system of equations, is used to resolve the gas mixture data. The program calculates the mole fraction of each gas, the standard error of calculation and the residuals left for each peak height. The known mixture composition can then be compared to the computer program results, as calculated from the mass spectra.

In all calibration tests, efforts were made to keep sampling conditions close to those expected in combustion and gasification experiments. The sample pressure, temperature and composition may all cause variations in the calibration data. Test gas mixtures of progressively increasing complexity were prepared to check the relative sensitivity and fragmentation pattern data. Further adjustments in the calibration data were made from these tests. A final set of mixtures, similar to those expected in experimental sampling, were used to test the ability of the mass spectrometer system to determine the mole fraction of each gas. Results from these tests appear to be within five percent of the actual mole fraction for each species.

2. Coal Feeder Calibration

The coal feeder is a Vibra Screw Live Bin Feeder; it employs a rotating, vibrating auger fed from a vibrating bin. To allow remote

operation, a non-contact magnetic sensor (Electro Products Corporation model 3030AN) was installed to provide a signal proportional to the rotational speed of the auger. An iron gear with 120 teeth was attached to a shaft geared directly to the auger shaft; the magnetic sensor produces a voltage spike each time a gear tooth passes it. A Heathkit model SM4100 frequency counter counts the spikes and provides a display proportional to the auger rotational speed. The overall sensitivity of the system is 2 Hz per rpm auger speed. In order to provide remote rotational speed control, a servo motor (Bodine Electric Company model 415) was installed to drive the feeder speed adjusting crank. Figure 6 is a schematic of the feeder control/monitoring system.

The feeder was calibrated with Southern Indiana bituminous coal, which is to be used for the initial gasification experiments. Using sixty second samples, the maximum experimental error under non-entrained conditions was found to be less than one percent. However, percent error increased significantly with reduced sampling time, indicating cyclic coal flows due to auger rotation. In order to alleviate the variations in feed rate, a vibrating wooden cone has been installed between the feeder discharge and a coal entrainment vessel (Fig. 7). The coal leaves the auger and falls onto the center of the cone and gradually slides off the smooth, sloping surface, falling into the entrainment vessel. Initial experience with this system has been quite favorable, as shown in Fig. 8. Note that the calibration is linear over the desired flow range and that good agreement was achieved between the entrained and non-entrained tests.

Preliminary Experimental Results

1. Data Analysis Techniques

Data accumulated during test runs are analyzed in terms of common performance parameters associated with combustion and gasification processes (Lenzer et al., 1976; George et al., 1977). Reduction of raw data for combustion tests is particularly straightforward. Parameters of interest include carbon efficiency and product gas composition. Predicted concentrations based on equilibrium models serve as a useful starting point in analyzing experimental results.

Figure 6. Feeder Control/Monitoring Schematic

Figure 7. Coal Entrainment Vessel

Figure 8. Coal Feeder Calibration

Process variables for gasification reactions are somewhat more complex but may still be conveniently categorized as independent and dependent variables. Dependent variables are divided into two categories: those which can be measured directly, and those which must be calculated through knowledge of measured quantities. Table 3 classifies the important variables for coal gasification as independent, dependent and measured, or dependent and calculated. Techniques for calculating performance indicators for gasification reactions are discussed by George et al. (1977).

2. Methane and Coal Combustion Tests

Methane tests provided an opportunity to observe the facility under clean combustion conditions. For these experiments, methane was introduced via the torch ignitor to the cyclone reactor. Results were generally favorable; in particular, the control and data acquisition system performed well. The ignitor was stable and easy to light off; however long-term stability was a problem, apparently due to dielectric breakdown. This problem was solved by increasing the electrical insulation surrounding the tungsten spark rod.

Early methane tests were also hampered by an inability to obtain reliable steam data, a problem which has been largely but not completely resolved. During sub-stoichiometric runs, when the make gas steam concentration is particularly high, water can condense inside the water cooled probe and collect in the sampling lines and filter. For coal combustion and gasification runs, however, steam levels will be in a much lower range and thus measurements can be made with confidence.

The results of our first series of methane combustion tests are shown in Fig. 9. Reliable data were obtained using the ignitor for 16 methane combustion runs at various stoichiometries. At each run condition, two sets of flow and temperature data and a minimum of three mass spectra were recorded. The flows and compositions determined from these data were then averaged. In Fig. 9, product gas compositions of N_2 , O_2 , and CO_2 for the sixteen combustion runs are compared on a dry basis to N_2 , O_2 , and CO_2 equilibrium compositions at 1000°K for a carbon-air-steam system.

Table 3
Gasification Variable Classification

<u>Variable Name and Units</u>	<u>Classification</u>
coal throughput, kg/m ³ hr	independent
coal feed rate ($\dot{m}_c$), kg/hr	independent
air/coal input ratio, kg air/kg coal	independent
steam/coal input ratio, kg steam/kg coal	independent
reactor pressure, atm	independent
reactant inlet temperatures, °C	independent
gas exit temperature, °C	dep.-measured
make gas composition, percent by volume	dep.-measured
make gas flow rate ($\dot{m}_g$), kg/hr	dep.-measured
make gas yield (Y), kg make gas/kg coal fed	dep.-calculated
combustible make gas yield (Y_p), kg comb. gas/kg coal fed	dep.-calculated
combustible mass fraction (ω_p)	dep.-calculated
chemical yield (ϵ_y), kg gas produced/kg coal reacted	dep.-calculated
make gas heating value (Q), kcal/kg gas produced	dep.-calculated
H ₂ /CO ratio	dep.-calculated
steam decomposition, percent	dep.-calculated
heat loss, percent	dep.-calculated
carbon efficiency (η_c), percent	dep.-calculated
cold gas efficiency (η_{cg}), percent	dep.-calculated
hot gas efficiency (η_{hg}), percent	dep.-calculated

Figure 9. Dry Product Gas Composition of Methane Combustion Runs

Figure 10 shows the results of our second and most recent series of methane combustion tests. For fuel lean conditions, the data are in good agreement with the equilibrium compositions at 1000°K as expected. These results, plus those of Figure 9, show that the mass spectrometer sampling system can resolve concentrations of N_2 , O_2 , H_2O and CO_2 typical of the anticipated gasification tests.

The carbon monoxide measurements shown in Figure 10 were made with an infrared CO analyzer while the mass spectrometer provided the balance of the product gas spectrum. Carbon monoxide, methane, and hydrogen were all detected by the mass spectrometer under fuel rich conditions but their concentrations were so low that they could not be resolved with an appreciable degree of confidence. Methane is not expected to be an important make gas constituent, and the concentrations of H_2 and CO will be much higher under gasification conditions; thus the mass spectrometer should be able to resolve all the significant components of the product gas with an acceptable level of precision during gasification experiments.

Preliminary coal combustion tests have also been performed in the cyclone reactor. Results at this time are mostly qualitative in nature. A stable, self-sustained coal flame has been achieved. Coal feed rates varied from 5 to 15 lb/hr, and $(\text{A/F})/(\text{A/F}_{\text{stoich}})$ ranged from 3 to 1. The measured exit gas temperature was about 1100°C with unheated primary and secondary air. Subsequent internal inspection of the reactor revealed that a small amount of slag had formed during the run, which lasted about 20 minutes.

On the basis of our experiences during preliminary methane and coal combustion tests the following conclusions can be drawn:

(1) The mass spectrometer sampling system can be used to accurately determine product gas composition, especially under fuel lean conditions.

(2) At low CO concentrations, CO and N_2 will continue to be difficult to distinguish via the mass spectrometer. However, the CO concentrations typical for gasification tests should present no problem.

(3) Satisfactory combustion can be achieved with the ignitor. Stable methane combustion runs were of sufficient duration to ignite incoming coal/air streams.

Figure 10. Product Gas Composition of Methane Combustion Runs

(4) The mass spectrometer sampling system and the product gas thermocouple provide fast and reliable response to ignition.

(5) A self-sustained coal flame and slagging conditions can be achieved in the cyclone reactor.

IV. WORK FORECAST

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

- (1) Complete construction of the jet reactor
- (2) Integrate the electronic flow metering system into the test facility
- (3) Complete cyclone coal combustion tests at atmospheric pressure.
- (4) Shake down the jet reactor and begin coal combustion tests.
- (5) Continue development of analytical models for coal combustion and gasification.

If time permits, we hope to also

- (6) Construct steam piping network and shake down the steam supply system
- (7) Begin coal gasification tests in both reactors at atmospheric pressure.

V. RESULTS AND CONCLUSIONS

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

- (1) Jet reactor pressure vessel fabrication
- (2) Coal feeder installation and calibration
- (3) Completion of methane combustion testing in cyclone reactor
- (4) Achievement of stable, self-sustained coal combustion in the cyclone reactor.

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