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PRESSURIZED DOWNDRAFT COMBUSTION OF WOODCHIPS

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ABSTRACT

A novel pressurized combustor Tor a gas turbine has been built and tested using woodchips. Air flows downward through a 23 cm diam. fuel bed which is supported by alumina gravel. The combustor is operated with high excess air and the reaction zone in the chips is a few cm thick. Test results are presented for continuous feed of 2 cm yellow poplar chips at pressures of 1 to 5 atm and inlet air temperatures of 20 to 200 C. For example the burning rate is 48 kg/hr at 4 atm, 200 C inlet air. 200% excess air and 15% moisture. Sensitivity of the burning rate to pressure, inlet air temperature, excess air and fuel moisture is presented. Caseous and particulate emissions data are presented. The physical and chemical processes within the combustor are discussed. Currently we are proceeding to connect the combustor to an Allison model 250 gas turbine.

INTRODRUCTION

Advanced industrial and utility power systems often use gas or liquid fueled gas turbine engines. Using coal or wood to directly power a gas turbine has yet to be accomplished commercially, primarily because the ash can cause erosion, deposition and corrosion of the turbine blades. If the combustion products contain a significant fraction of molten ash particles. deposition on the turbine blades occurs which blocks the flow path and degrades performance. If the ash particles are solid, erosion of the blades occurs which also degrades performance. In addition, mineral matter can cause corrosion of the blades. The size distribution. concentration and composition of the ash, as well as the turbine design, determine the lifetime of the turbine blades (1,2).

Current methods of powering a gas turbine with solid fuels include pressurized fluidized bed combustion (PFBC), coal water slurries (CWS), and pressurized gasipiers. PFBC requires hot gas cleanup due to ash emissions and carryover of bed material, and this has yet to be commercially demonstrated. CWS uses pulverized, beneficiated coal which is burned in suspension. The high temperatures required for complete burnout in a short residence time may tend to agglomerate ash particles to unacceptable sizes. Pressurized gasifiers tend to have much lower output per unit size because the velocities are lower than for combustors. It is too soon to say if these difficulties will be overcome. Early work starting in the 1940's emphasized dry pulverized coal in more or less typical gas turbine combustors (3.4). These efforts experienced excessive deposition and erosion of the turbine blades.

Our work reported here uses downdraft combustion of a bed of wood chips supported by a bed of refractory gravel. Before describing our setup, let us briefly review previous efforts using downdraft combustion. In the late 1940's Bituminous Coal Research Inc. and a group of stove manufacturers in the U.S. initiated a project to develop stoves that would burn bituminous coal without emission of smoke (5). The BCR smokeless heater had a box–shaped combustion chamber filled with coal. Primary air entered a slot near the bottom of one side and crossed through the burning coal to the outlet on the opposite side. Secondary air was added near the outlet, through a slot in an arch which separated the coal bed from the outlet chamber. Smoke emissions were low. These units were commercially available but were replaced by gas and oil. Similarly, the Rayburn smoke–eater. developed by the National Coal Board of Scotland, had low smoke emissions. Primary air passed downward and across a coal bed which rested on a grate. Volatiles were carried through a layer of char to a combustion chamber at the back of the heater where they mixed with secondary air (6). Both of these units operated at low flow rates and the ash subsided through grates. This work indicated that downdraft combustion is promising. In 1983 we started our initial work with a downdraft Combustor using wood chips (7,8). An alternative approach for gas turbines using suspension burning of pulverized biomass is being pursued by the Aerospace Research Corp. (9).

A gas turbine combustor operates at 5–15 atm pressure with high excess air. Turbine inlet temperatures are controlled by using excess air. Near-stoichimetric flame temperatures with preheated air can reach 2500 K for liquid fuels, whereas turbine blade metal temperatures are typically limited to 1400 K for industrial gas turbines. With liquid fuels excess air is mixed downstream or the primary combustion zone to reduce the temperature. For ash bearing fuels it is desirable to keep the flame temperature below the ash fusion temperature to minimize agglomeration of the ash. This means bringing excess air directly through the combustor. Our approach is to use a packed bed of fuel operating in a downdraft mode with high excess air. The fuel is supported by a bed of refractory gravel. High excess air intensifies the Combustion and reduces the peak temperatures. Mineral matter in the fuel should be finely divided, so that it can pass through the Combustor and turbine without significant damage to the turbine blades.

TEST SETUP

The combustor, fuel feed system and air supply are shown schematically in Figure 1. Wood chips are fed from a bin, through a 15 cm diam conveyor driven by a 1 hp motor, to a lockhopper which is operated with two 25 cm diam horizontal slide gate valves spaced 35 cm apart. Upon demand the conveyor and lock hopper cycle and deliver fuel to a 25 cm diam horizontal screw feeder, which feeds the combustor. The horizontal feeder is powered by a 1/2 hp motor with variable speed control which provides a continuous supply of fuel, and also protects the slide gate valves from over heating. Fuel level control is provided by an ultrasonic detector located above the horizontal feeder and by two light beams located above the gravel. The fuel feed system can provide from 50 - 100 kg/hr of wood chips (at 15% moisture) continuously and lesser amounts on an intermittent basis. Higher feed rates could be achieved by lengthening the lock hopper. The fuel feed rate is determined by calibration of the rpm of the horizontal auger. Small jets of air are directed onto the stops of the horizontal slide gate valves to clear any wood chips and prevent jamming of the gate.

Compressed air flows through a control valve to a regenerative heat exchanger consisting of 1.2 cm diam stainless steel tubes located in the exhaust duct. Air pressures to 5 atm, preheat temperatures to 250 C and flow rates of 28 std m^3/min are provided. Bypass air is blended to provide the desired inlet temperature to simulate the compressor temperatures. The air flows downward across the fuel feed inlet to the fuel bed. The fuel is deposited uniformly across the bed. A small quartz window viewport is located at the top of the combustor for viewing the fuel bed.

The combustor consists of 40 cm diam by 1.2 cm thick steel pipe coated internally with 76 mm thick castible refractory. The burning section has a cross sectional area of 0.041 m^2. The tee section is filled with 16 mm alumina balls. Near the top of the gravel a 1 cm layer of 4 mm alumina chips is interspersed with the larger balls. A bed of 2 cm wood chips lies on top of the gravel. The purpose of the gravel is to hold up the fuel and to act as a flame holder for the volatiles. The blind flange on the tee can be removed to dump the gravel. At the downstream end of the tee the gravel is held in place with ceramic rods. A straight exhaust section insulated with 76 mm thick vacuum formed kaowool is provided for measurements.

The combustion chamber pressure is maintained by a downstream control valve. A water spray is used ahead of the valve for cooling. The exhaust valve is used instead of a turbine at this stage of the testing. Air flow rate is controlled by the inlet air flow control valve which receives a setpoint from the carbon dioxide concentration in the exhaust. The exhaust valve opening is set to maintain a certain chamber pressure. Other exhaust measurements include pressure, temperature. O_2, CO, NO, and particulate concentration. Particulates are measured with a six stage cascade impactor run isokinetically for a 20 min sampling period.

COMBUSTION TESTS

Combustor tests were run with 2 cm, air dried (15% moisture by weight). yellow popular wood chips. Initially combustion tests were run at near atmospheric pressure and with 20 C inlet air. During later tests the pressure was gradually increased to 5 atm pressure and the air preheat was increased up to 250 C. Startup is done by removing a cap from the top of the combustor and dropping a piece of burning paper on top of a thin layer of wood chips. Ignition is rapid due to the downward flow of air. Then more wood chips are added. Approximately 60 min is required to fully heat up the combustor and preheater. The viewport showed that the combustion zone stabilized at the gravel interface and extended only a few mm into the fuel bed. Combustion does not propagate upward into the fuel bed, as in a gasifier, due to the high downward flow of air.

The burning rate was sensitive to the inlet air flow rate, inlet air temperature and the combustor pressure. The test procedure was to try to maintain a certain pressure and to run the highest air flow rate possible while maintaining the bed temperature at 900 to 1100 C. Typically the excess oxygen was about 15% and the carbon dioxide was 5%. Achieving this relatively low temperature, which is desirable to prevent ash fusion and agglomeration, required running the combustor near the blowout point. When blowout occurred. restart was accomplished by backing off the air and allowing heat conduction from the gravel to reignite the fuel. The combustor operated more steadily when the fuel feed was steady than when it was intermittent, because feeding tended to disrupt the bed.

Figure 2 shows a plot of fuel burning rate versus combustion chamber pressure. Two curves are shown - one with no preheat and one with air preheated to 141 to 243 C. At 2 atm pressure and no preheat the burning rate was 16 kg/hr. while with preheated air at 2 atm the burning rate was 26 kg/hr. At 4 atm chamber pressure with preheated air the burning rate was 52 kg/hr. Higher preheat gave higher burning rate at the same pressure, although there is scatter in the data due to differences in the air flow rate or because of unsteadiness. A linear fit of the data seems reasonable at this point.

Air flow rate versus combustor pressure is shown in Figure 3. The air flow rate is adjusted so that the bed temperature does not exceed 900–1100 C. For example, an air flow rate of 770 kg/hr at 4 atm pressure is 10.7 std m^3/min - 380 std ft^3/min. Using Fig. 2 the air/fuel ratio by weight is 14.8 whereas the stoichiometric air/fuel ratio for Yellow popular with 15% moisture is 5.0, so that the excess air is 200%. This corresponds to a calculated adiabatic flame temperature of about 1100 C for 15% moisture and 200 C preheat, The calculated CO_2 concentration is 7.9% (dry basis) which is representative of our measurements. A platinum thermocouple in a ceramic sheath was located 5 cm below the gravel fuel interface, and temperature measurements here typically varied from 800-1200 C, but more generally were near 1000 C. Temperature measured just downstream of the gravel bed were typically 150 C lower due to heat losses through the walls of the combustor.

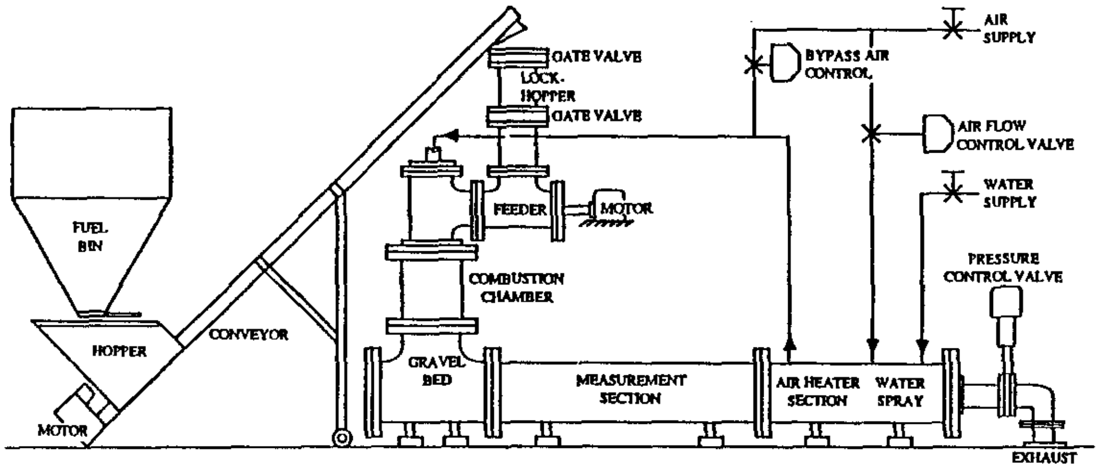

Figure 1. Test setup for pressurized downdraft combustor using wood chips.

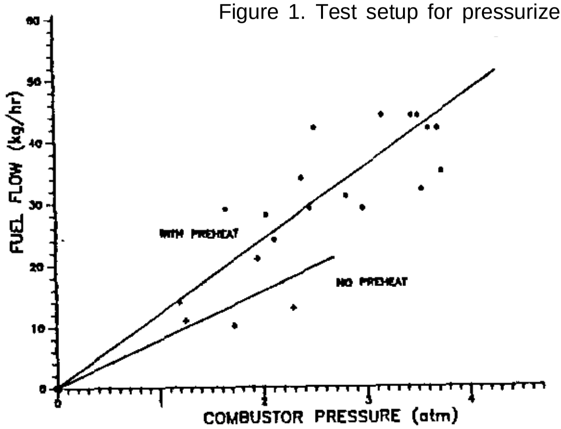

Figure 2. Burning rate of 2 cm yellow poplar chips (15% moisture) versus combustor pressure with and without preheated air.

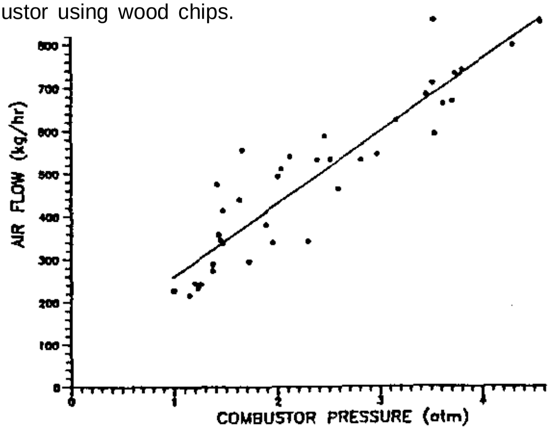

Figure 3. Inlet air flow rate versus combustor pressure.

Representative time traces of combustor pressure, inlet air temperature and flow rate, and bed and outlet temperatures are shown in Figure 4. The pressure trace exhibits fluctuations which are due to the operation of the lock hopper. the use of purge air to clear the fuel level viewport and to combustion itself. The gradual rise in pressure during this time interval is due to gradual rise in inlet air temperature which increases the burning rate. The inlet air flow rate (Fig. 4b) remained constant during this period, however small fluctuations in the air flow are observed. Combustion pressure fluctuations are fed back through the air heater to the orifice meter. However. fluctuations exist even during cold flow tests. The combustion rate is very sensitive to pressure and air temperature as indicated by the bed temperature trace in Figure 4c. The temperature fluctuations are slower than the pressure fluctuations. The carbon dioxide fluctuations, shown in Figure 4d are also amplified. Clearly, the challenge is to obtain a more steady Operation, and this seems to require a steady fuel feed and minimal disturbances from the lock hopper operation.

Gas sampling indicates that once the Combustor is fully warmed up the carbon monoxide concentration is about 250 ppm and the nitrogen oxide concentration is about 75 ppm on a dry basis. The CO concentrations are over 2000 ppm during startup, and these levels do not decrease until the gravel temperature is above 700 C. If the gravel temperature should drop below 700 C, during the run due to too much air, the CO increases rapidly. This indicates that burnout of the volatiles occurs in the gravel, and due to the high velocity through the gravel. the reaction zone is extended.

The size distribution of particulate matter for two tests runs at about 4 atm pressure with preheated air are shown in Fig. 5. Approximately 88% by weight of the particles were less than 10 microns in size and 83% less than 5 microns. About 60% of the particulate mass was collected on the backup filter The total particulate concentration was averaged 0.015 g/dry std m^3. These particulate levels are very encouraging for turbine operation.

Sparks are observed downstream of the gravel bed when the 16 mm alumina balls are used without the layer of 4 mm chips. With the layer of chips the pressure drop was 10–15% depending on the operating conditions. During a 3 hr run there is no apparent build up of pressure drop. The extent of long term deposition of ash and the alumina bed is not clear at this time. There is evidence that the potassium reacts with the alumina and this needs further investigation.

DISCUSSION

Our aim is to power a small gas turbine operating with a pressure ratio of 5/1 and combustor inlet air temperature of 200 C. Based on Figure 2 and our combustor cross–sectional area of 0.041 m^2, the burning rate is 1830 kg/hr m^2. Assuming a higher heating value of dry wood of 20,200 kJ/kg and using 15% moisture, the heat rate of our test rig is 8.7 MW/m^2. For an industrial turbine with a pressure ratio of 12/1 the

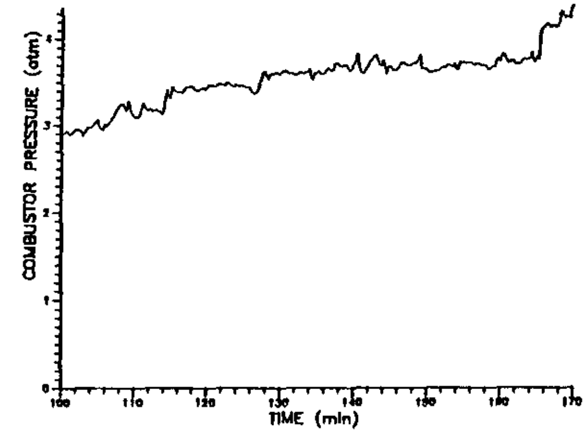

Figure 4a. Test data from run 37: combustor pressure.

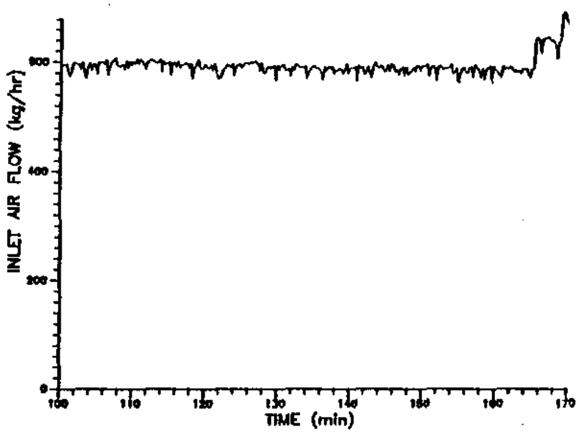

Figure 4b. Inlet air flow rate.

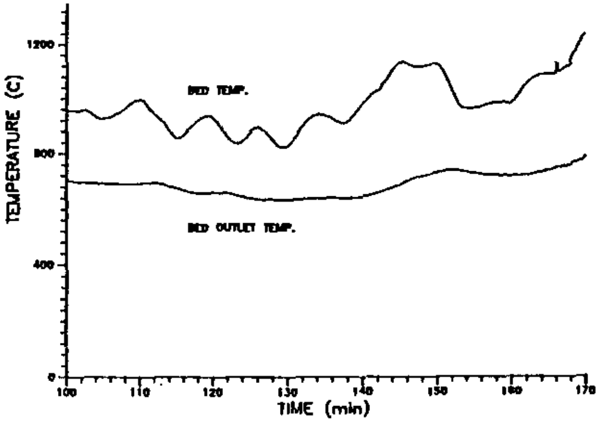

Figure 4c. Bed and outlet temperature.

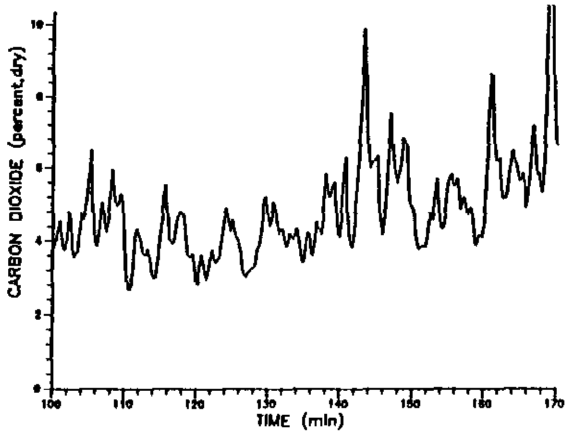

Figure 4d. Carbon dioxide.

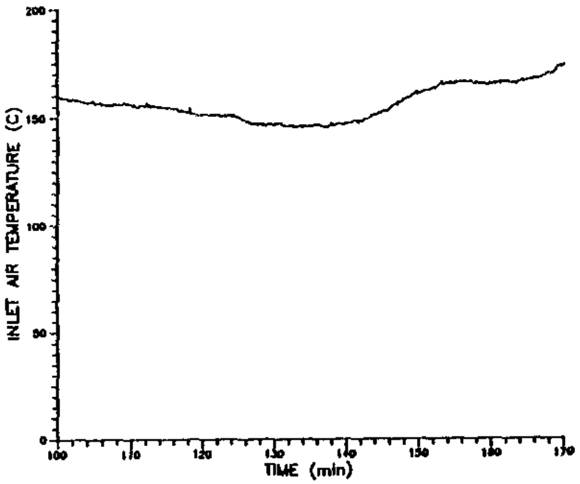

Figure 4e. Inlet air temperature.

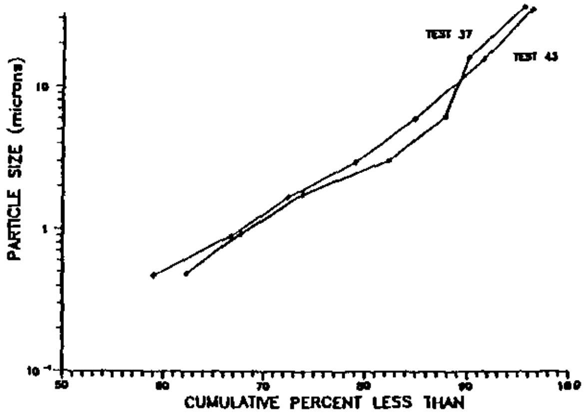

Figure 5. Size distribution of particulate emissions for runs 37 and 43.

combustor inlet air would be preheated to 325 C, and the heat rate is estimated to be 20 to 30 MW/m^2 for hardwood wood chips with 15% moisture.

The burning rate increases with pressure because the rate is limited by char burnout, which is limited primarily by the diffusion of oxygen to the surface of the char. At the same air velocity, the diffusive flux of oxygen increases linearly with pressure. The burning rate increases with inlet air preheat for two reasons. First, preheated air promotes drying of the fuel bed. Secondly, the temperature gradient in the fuel bed is increased and this allows for higher air flow rates without blow out occuring. The reaction zone is basically set by a balance between heat transfer by conduction and radiation upstream versus convective heat transfer downstream. Increasing the air preheat from 295 K to 475 K (on the average), increased the burning rate from 16 kg/hr to 26 kg/hr at 2 atm. Thus an increase in the air preheat by a factor of 1.6 increased the burning rate by a factor of 1.6. However, there is no apparent reason to expect that the relationship should be linear. The burning rate relationships are needed to match the combustor with the compressor.

In a liquid fueled gas turbine the output of the turbine is controlled by the fuel feed rate. For a gas turbine fired with Wood chips it may also be possible to control the output with the fuel feed rate if the fuel bed remains thin. This requires precise control of the feed rate because the combustion zone in the fuel bed is thin. In our tests a fuel bed of 15 cm or deeper was maintained to minimize the chances of blowout. Since the burning zone remains thin, there is always sufficient fuel to burn at the maximum rate.

The effect of moisture in the wood, chip particle size and wood type was investigated. At 1 atm pressure and without preheated air greenwood (100% moisture, dry basis) does not sustain combustion in the downdraft mode (8). However, greenwood does burn, but at a slower rate, at higher pressure with preheated air. The trade off between pressure drop across the gravel bed and the Size of the refractory needs to be examined further. Improvements in the control system are needed to insure Steady combustion without overheating the bed. Ash deposition processes in the refractory bed need further investigation.

CONCLUSIONS

A novel pressurized combustor operating on wood chips has been built and tested. The combustor operates in a downdraft mode with a bed of wood chips supported by a bed of refractory gravel. The 23 cm internal diameter combustor had a wood burning rate of 52 kg/hr at 4 atm pressure and 200 C air preheat. The carbon monoxide emissions were about 250 ppm and the nitrogen oxide emissions were about 75 ppm on a dry basis. The particulate emissions were 88% (wt) less than 10 µm and 83% less than 5 µm. The pressure drop through the combustor was 10 to 15% of the inlet pressure. Application as a combustor for a gas turbine looks promising. because combustion is very intense, but further understanding of control of the combustion is needed.

ACKNOWLEDGEMENTS

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