EVALUATION OF AN INTEGRATED BIOMASS GASIFICATION/FUEL CELL POWER PLANT

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ABSTRACT

The Chariton Valley Biomass Power Project, sponsored by the U. S. Department of Energy Biomass Power Program, has the goal of converting switchgrass grown on marginal farmland in southern Iowa into electric power. Two energy conversion options are under evaluation: co-firing switchgrass with coal in an existing utility boiler and gasification of switchgrass for use in a carbonate fuel cell. This paper describes the second option under investigation. The gasification study includes both experimental testing in a pilot-scale gasifier and computer simulation of carbonate fuel cell performance when operated on gas derived from switchgrass. Options for a comprehensive system integration between a carbonate fuel cell and the gasification system are being evaluated. Use of waste heat from the carbonate fuel cell to maximize overall integrated plant efficiency is being examined. Existing fuel cell power plant design elements will be used, as appropriate, in the integration of the gasifier and fuel cell power plant to minimize cost complexity and risk. The gasification experiments are being performed by Iowa State University and the fuel cell evaluations are being performed by Energy Research Corporation.

KEYWORDS

Biomass Energy; Switchgrass; Gasification; Carbonate Fuel Cell; Electrical Power.

INTRODUCTION

Utilization of renewable energy sources such as biomass offers environmental benefits while providing sustainable power generation for utilities and industry. It offers markets for dedicated energy crops such as switchgrass, while providing needed energy for power generation, thereby offsetting or reducing the need for fossil fuels. In areas where fossil fuels are scarce and biomass fuels are available, biomass

utilization offers alternative low cost methods for power generation. The Chariton Valley Biomass Power Project investigates the potential of growing dedicated feedstocks as a renewable energy source.

Gasification of biomass, rather than combustion, offers efficiency, environmental, and operational advantages including the ability to use the producer gas in fuel cells. A fluidized bed gasifier, shown in Fig. 1, will be used to test the gasification of switchgrass. The producer gas composition from this gasifier will be used in a fuel cell power plant simulation study. Fuel cells convert hydrocarbon fuels to electricity at efficiencies exceeding conventional heat engine technologies while generating extremely low emissions. A proof-of-concept carbonate fuel cell power plant in Santa Clara, California, has achieved 5700 hours of operation in a grid-connected setting. The 2 MW plant, shown in Fig. 2, consists of 16 125-kW fuel cell stacks.

GASIFICATION

The fluidized bed gasifier used in this study is located at Iowa State University (ISU). A schematic of the gasifier rig is shown in Fig. 3. The air-blown gasifier operates at atmospheric pressure and is nominally rated at 2.8 MMBtu/hr thermal input. This capacity corresponds to an average feed rate of 400 lb/hr for a fuel with a higher heating value (HHV) of 7000 Btu/lb, roughly that of switchgrass. A proximate and ultimate analysis of switchgrass is found in Table 1. At the time of this writing, modifications to the material handling system were underway to enable the feeding of switchgrass. This new switchgrass feed system will consist of a bale shredder, preparation equipment, and a delivery system.

The gasifier has been instrumented to provide information concerning producer gas composition and temperature. Current gas analysis equipment consist of gas chromatographs. The gasifier is currently being equipped with a gas sampling and analysis system to quantify moisture, tars, particulates, chlorine, and alkali content in the producer gas. Additional gas analysis equipment to be added to the sampling system include a Fourier-Transform Infrared Spectrometer and the Ames Laboratory On-Line Alkali Monitor developed for the U. S. Department of Energy (DOE).

Table 1. Proximate and Ultimate Analyses of Switchgrass.

Proximate	Moisture	Volatile Matter	Ash	Fixed Carbon
As received	8.4	73.0	4.9	13.7
Dry	0.0	79.7	5.3	15.0

Ultimate	Carbon	Hydrogen	Nitrogen	Oxygen	Sulfur	Ash
As received	42.9	5.6	0.5	46.0	0.1	4.9
Dry	46.8	5.1	0.6	42.1	0.1	5.3

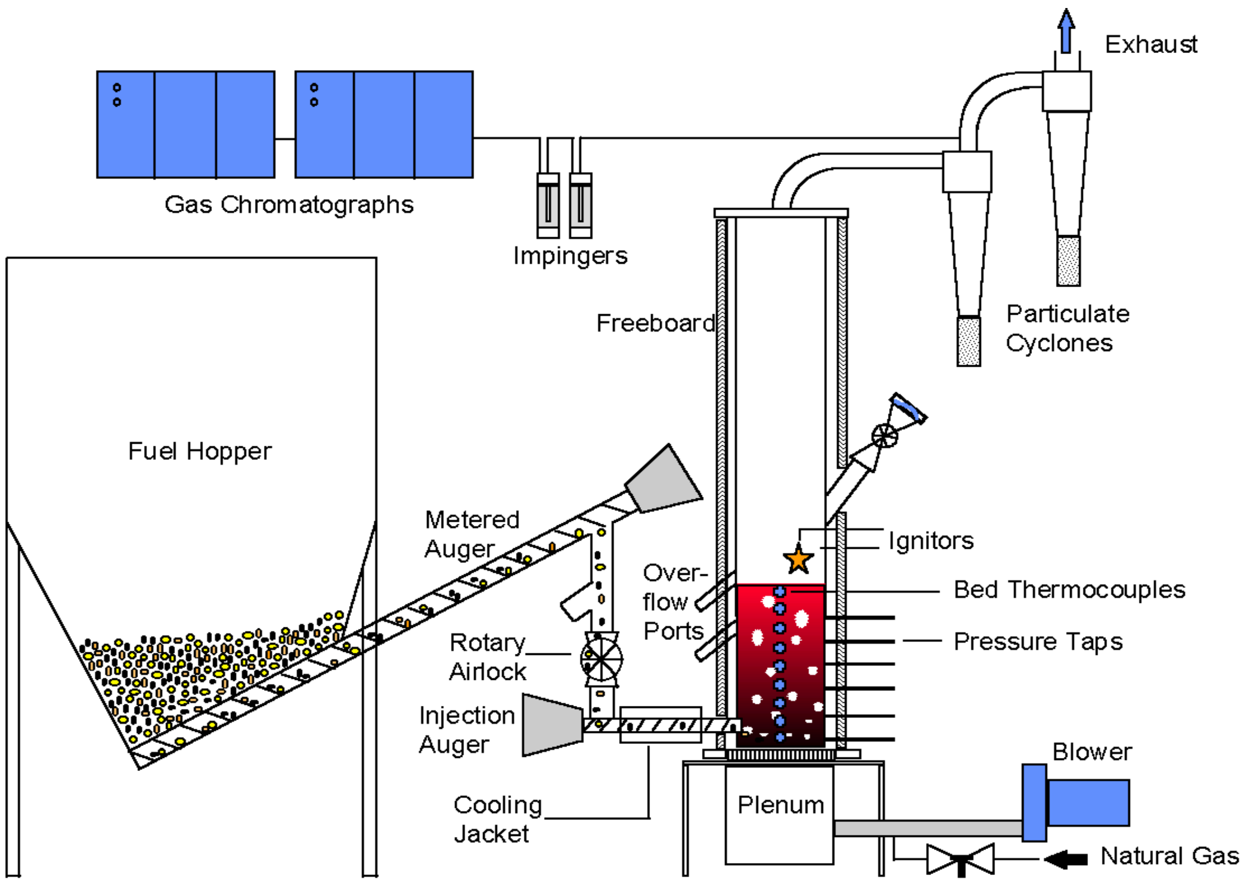


Fig. 3. Schematic of fluidized bed biomass gasification rig.

Preliminary testing of the gasifier took place with shelled corn as the feedstock. This feedstock was chosen because of its ready availability and ease of handling. Agglomeration was a significant problem in early testing. Analyses of the agglomerates revealed a sticky, viscous material high in potassium and phosphorous coated the sand particles, cementing them together in large chunks. This problem was resolved by the addition of a small fraction of limestone to the bed material.

Thermochemical conversion of biomass produces carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), hydrogen (H_2), nitrogen (N_2), tar, fly ash, and carbon as the major constituents in the producer gas. In recent experiments the higher heating value (HHV) of the producer gas was 115 Btu/scf (standard cubic foot). Carbon conversion efficiency was determined to be 85% although tar production has not been quantified. Application of an energy balance to the fluidized bed reactor determined the cold-gas conversion efficiency to be approximately 52%.

Table 2. Compositional Analysis of Producer Gas (volumetric percent).

Carbon Monoxide 21.7%

Carbon Dioxide 12.5%

Hydrogen 4.1%

Methane 3.3%

Nitrogen 48.4%

Oxygen 0.0%

Moisture 10.0%

Total 100.0%

When the sensible heat of the exhaust gas is included, a thermal efficiency approaching 75% is achieved. Table 2 contains the composition of typical producer gas from this gasifier operating on shelled corn.

Future modifications to the gasifier rig include installation of a switchgrass handling system, a steam superheater, and additional gas analysis equipment. The steam superheater will be used to supply steam for fluidization. This steam, delivered at 1200 ° F, will offset the fluidization air requirements and increase the heating value of the producer gas. Another benefit of steam addition will be increased carbon conversion. A matrix of experiments will be performed that tests the following independent variables: size of feedstock, air/fuel ratio, feedstock moisture, limestone content of gasifier bed material, fuel feed rate, and steam injection.

CARBONATE FUEL CELL

The carbonate fuel cell is an electrochemical device that converts biomass derived producer gas to electricity by electrochemical oxidation to produce water vapor and carbon dioxide as shown in Fig. 4. Biomass derived producer gas enters the anode side and air plus carbon dioxide enters the cathode side. The carbon dioxide is obtained from the anode exhaust. Due to its high operating temperature of 1200 ° F, hydrocarbons in the fuel gas can be internally reformed, as illustrated in Fig. 5, utilizing waste heat, thereby improving the efficiency of the fuel cell. Fuel cell system efficiencies in the mid forties (LHV) can be achieved in this way operating on low Btu gas from switchgrass or shelled corn. Addition of a bottoming cycle to recover energy from the high temperature exhaust gases can improve efficiency further.

Development of Process Flow Diagram

The performance of a carbonate fuel cell operating on low Btu gas from an ISU air blown gasifier operating on shelled corn was estimated. Other conditions pertinent to fuel cell operation include the lower heating value, temperature, and pressure of the producer gas, determined to be 108.3 Btu/scf, 1000 ° F, and atmospheric pressure, respectively.

Fig. 4. Carbonate Fuel Cell System

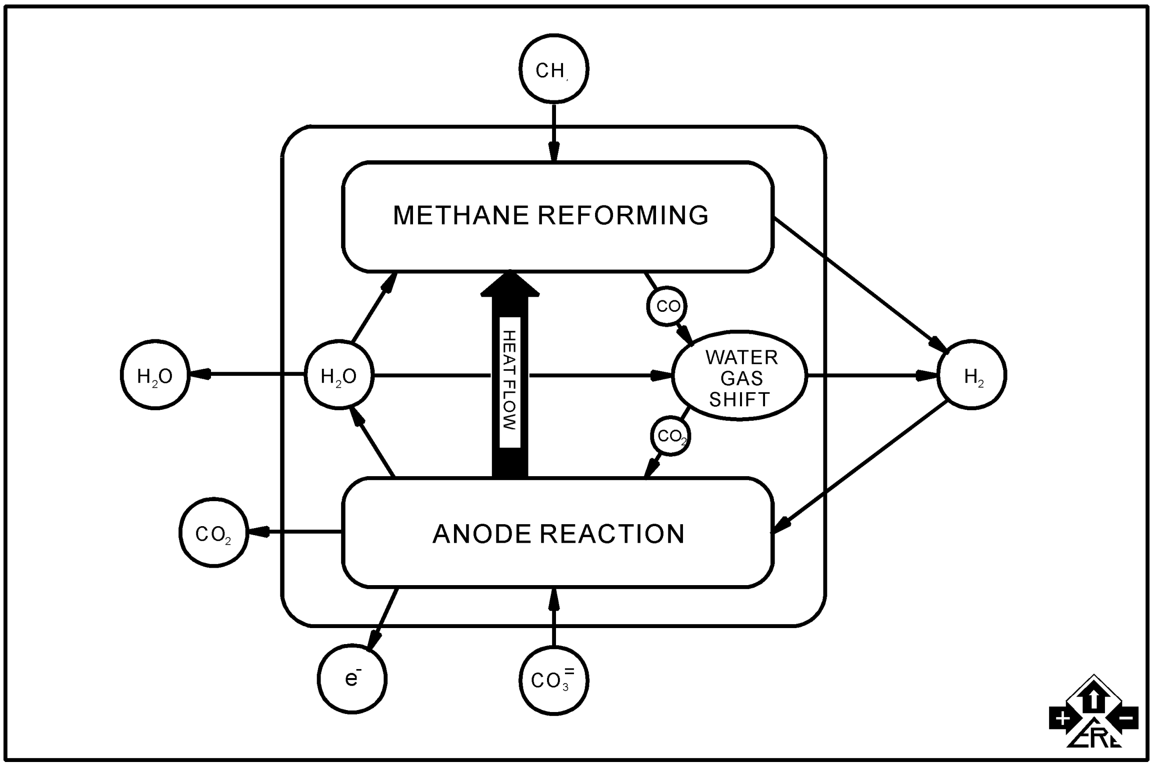
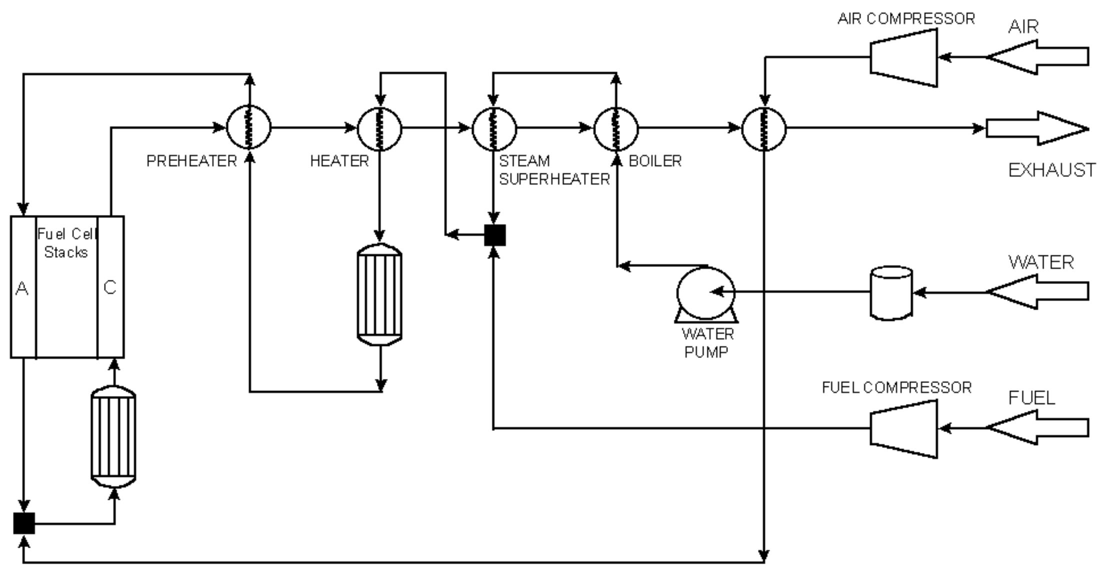


Fig. 5. Carbonate Fuel Cell Internal Reforming



Name	FUEL	WATER	AIR	EXHAUST
- - Overall - -				
Molar flow (lbmol/hr)	315.8228	15.5981	918.5172	1209.1980
Mass flow (lb/hr_	8872.0010	281.0000	26500.0000	35653.0508
Temperature (□F)	90.0000	60.0000	70.0000	806.7401
Pressure (psia)	15.0600	60.0000	14.5000	14.7550
Vapor mole fraction	1.0000	0.0000	1.0000	1.0000
Component mole fractions				
Hydrogen	0.041000	0.000000	0.000000	0.000000
Methane	0.033000	0.000000	0.000000	0.000000
Carbon Monoxide	0.217000	0.000000	0.000000	0.000000
Carbon Dioxide	0.125000	0.000000	0.000000	0.097944
Water	0.046000	1.000000	0.000000	0.052861
Nitrogen	0.538000	0.000000	0.790000	0.740608
Oxygen	0.000000	0.000000	0.210000	0.108587

1753 kW NET AC POWER
46% SYSTEM EFFICIENCY (LHV)
108.3 Btu/scf (LHV) FUEL HEATING VALUE

Fig. 6. Process flow diagram for fuel cell plant operating on switchgrass producer gas.

The system and performance of the 2.85 MW direct carbonate commercial design, operating on a recent shelled corn gasification composition, is presented in Fig. 6. The 2.85 MW commercial power plant is derated to deliver approximately 1.75 MW at an efficiency of 46%. Heat recovery from the 806 ° F exhaust can further improve the fuel use efficiency to 60% in large installations by including a steam bottoming cycle assuming a conservative 32% bottoming cycle efficiency and an exhaust temperature of 180 ° F. In small installations the exhaust can be used to generate steam for cogeneration. Overall fuel to electricity conversion will depend on waste heat recovery and has not yet been evaluated.

Derating is necessary primarily for thermal management of the fuel cell stacks. When the plant is operated on natural gas, which is typically about 91% methane, reforming of the fuel, within the cell stack uses a large portion of the waste heat generated by the fuel cells. Fuel from the air blown gasifier has a very low (3.3%) methane content. The prereformer in the system provides both reforming and shifting but the methane content entering the reformer units within the cell stack is still only 3.7%. The result is insufficient cooling capability from the fuel stream to the cell stack. Additional cooling is provided by increasing the process air flow and limiting the temperature gradient of the air through the cells by adding an air preheater.

In this evaluation it has been assumed that there are no changes to the cell stack and burner configuration but the heat exchangers and prereformer would be redesigned to limit pressure losses at the higher mass flows.

Selection of power plant size

The power plant size depends on the logistics and economics of the gasification process and the feedstock utilized. A commercial fuel cell power plant is currently planned in the 2-3 MW range. This plant can be utilized for a biomass application in this size range. Due to the modular nature of fuel cell technology, larger plants can be configured by multiples of the 2-3 MW plant. However, for plants larger than this size, a bottoming cycle of the full capacity of the plant may be desirable.

SUMMARY

The use of switchgrass as a dedicated energy crop is being investigated. Simulation of an integrated gasification carbonate fuel cell system results in a 1.75 MW power plant (derated from 2.85 MW) operating at 46% efficiency. Power plant output would be increased by improving the heating value of the producer gas, preferably by increasing the methane content. The effects of tars and other trace contaminants on fuel cell performance have not yet been investigated, but will be a product of this investigation.

Future work includes the installation of a switchgrass handling system, additional gas sampling and analysis equipment to identify potential trace contaminants, and a steam superheater to supply steam for fluidization to the gasifier rig. A matrix of experiments will be performed that tests the following independent variables: size of feedstock, air/fuel ratio, feedstock moisture, limestone content of gasifier bed material, fuel feed rate, and steam injection.

ACKNOWLEDGEMENTS

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