Fuel-Flexible Gasification-Combustion Technology for Production of Hydrogen and Sequestration-Ready Carbon Dioxide

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Abstract

Electricity produced from hydrogen in fuel cells can be highly efficient relative to competing technologies and has the potential to be virtually pollution free. Thus, fuel cells may become an ideal solution to this nation's energy needs if one has a satisfactory process for producing hydrogen from available energy resources such as coal, and low-cost alternative feedstocks such as biomass.

GE EER is developing an innovative fuel-flexible advanced gasification-combustion (AGC) technology for production of hydrogen for fuel cells or combustion turbines, and a separate stream of sequestration-ready CO_2. The AGC module can be integrated into a number of Vision-21 power systems. It offers increased energy efficiency relative to conventional gasification and combustion systems and near-zero pollution. The R&D on the AGC technology is being conducted under a Vision-21 award from the U.S. DOE NETL with co-funding from GE EER, Southern Illinois University at Carbondale (SIU-C), and the California Energy Commission (CEC). The AGC technology converts coal and air into three separate streams of pure hydrogen, sequestration-ready CO_2, and high temperature/pressure oxygen-depleted air to produce electricity in a gas turbine.

The three-year program integrates lab-, bench- and pilot-scale studies to demonstrate the AGC concept. Process and kinetic modeling studies as well as an economic assessment will also be performed. This paper provides an overview of the program and its objectives, and discusses first-year R&D activities, including design of experimental facilities and results from initial tests and modeling studies. In particular, the paper describes the design of the bench-scale facility and initial process modeling data. In addition, a process flow diagram is shown for a complete plant incorporating the AGC module with other Vision-21 plant components to maximize hydrogen production and process efficiency.

Introduction

Projections of increased demands for energy worldwide, coupled with increasing environmental concerns have given rise to the need for new and innovative technologies for energy plants. Incremental improvements in existing plants will likely fall short of meeting future capacity and environmental needs economically. Thus, the implementation of new technologies at large scale is vital. In order to prepare for this inevitable paradigm shift, it is necessary to have viable alternatives that have been proven both theoretically and experimentally at significant scales. The DOE's Vision 21 program aims to support these development needs through funding the development of enabling technologies such as GE EER's advanced gasification-combustion (AGC) process.

GE EER's AGC process features a technology that provides an innovative approach to the use of fossil fuels for energy production. It is expected to meet or exceed environmental goals economically. In addition, it is fuel-flexible, allowing the use of low-cost alternative feedstocks, such as biomass, in addition to coal. The process is also product-flexible, and its operation can be adjusted based on power plant demand to produce various ratios of high-purity hydrogen for a fuel cells and high-temperature/pressure O_2-depleted air for a gas turbine. Inherent to the process is a step that increases H_2 purity by separating CO_2 from the gasification step and releasing it in a sequestration-ready mode.

Objective

The overall objective of this program is to design and use computational models and experimental systems to establish and demonstrate the technical and economic viability of the AGC process. Specific objectives include:

- Demonstrate and establish the chemistry of the AGC concept, measure kinetic parameters of individual process steps, and identify fundamental processes affecting process economics.
- Design and develop bench- and pilot-scale systems to test the AGC concept under dynamic conditions and estimate the overall system efficiency for the design.
- Develop kinetic and dynamic computational models of the individual process steps.
- Determine operating conditions that maximize the separation of CO_2 and pollutants from vent gas, while simultaneously maximizing coal/opportunity fuels conversion and H_2 production.
- Integrate the AGC module into a Vision-21 plant design and optimize its work cycle efficiency.
- Determine the extent of technical/economical viability & the commercial potential of AGC module.

Approach

Experimental testing at three different scales is used to establish kinetics, identify operating conditions, and optimize system operation. Lab-scale testing focuses on the kinetics of the reactions, identifying kinetic parameters to aid in computational modeling efforts, and interactions between bed materials and the fuel during fluidization. Testing conducted on the bench-scale system aids in identification of optimal operating conditions and validates computational models. These testing and modeling efforts will facilitate the design of a pilot-scale system that demonstrates the viability of the AGC technology. Work conducted to date has focused on the design and construction of the lab-scale and bench-scale systems and development of engineering and modeling tools. Design of the pilot-scale system has been initiated, and results from modeling and experimental testing will further guide this effort.

Technology

The AGC technology makes use of three circulating fluidized bed reactors containing CO_2 sorbent and oxygen transfer material, as shown in Figure 1. Coal and opportunity fuels are partly gasified with steam in the first reactor, producing H_2, CO and CO_2. As CO_2 is absorbed by the CO_2 sorbent, CO is also depleted from the gas phase via the water-gas shift reaction. Thus, reactor 1 produces a H_2-rich product stream suitable for use in liquefaction, fuel cells, or turbines.

Gasification is completed in reactor 2, where the oxygen transfer material undergoes a reduction reaction as it provides the oxygen needed to oxidize the remaining carbon. The CO_2 sorbent is regenerated as this increase in temperature forces the release of CO_2 from the sorbent, generating a CO_2-rich product stream suitable for sequestration. Air fed to the third reactor re-oxidizes the oxygen transfer material via a highly exothermic reaction that produces oxygen-depleted air for a gas turbine.

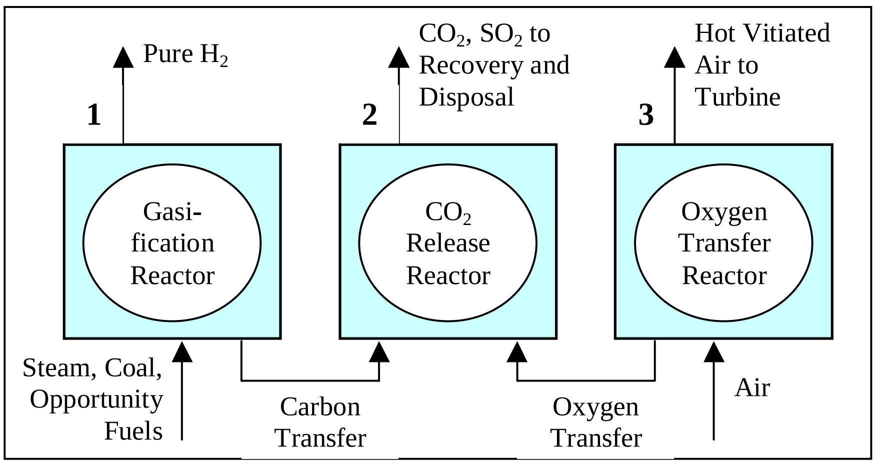

Figure 1. Conceptual design of the AGC technology.

Solids transfer occurs between all three reactors, allowing for the regeneration and recirculation of both the CO_2 sorbent and the oxygen transfer material. Periodically, ash and bed materials will be removed from the system and replaced with fresh bed materials to reduce the amount of ash in the reactor and increase the effectiveness of the bed materials.

Accomplishments

In the first year of this Vision 21 program, progress has been made in the design and construction of the bench-scale and lab-scale facilities. Process models were developed and will be validated with experimental data. Additionally, analyses were conducted of the availability and cost of opportunity fuels and the economic forces affecting the market viability of the entire system. The design of the pilot-scale system has been initiated with the identification of the critical design parameters. Below is a narrative of first year progress.

Bench-Scale Facility

The design and assembly of the bench-scale facility have been completed. The reactor, coal injection system, and steam generation system were identified as critical components, and subjected to more rigorous design and verification. The process and instrumentation diagram for the bench-scale system is provided in Figure 2. This diagram shows the reactor at the center, with the separate branches for coal, air, and steam feed lines. The product line is also shown, with its condenser for water removal and flowmeters for quantification of the gas produced.

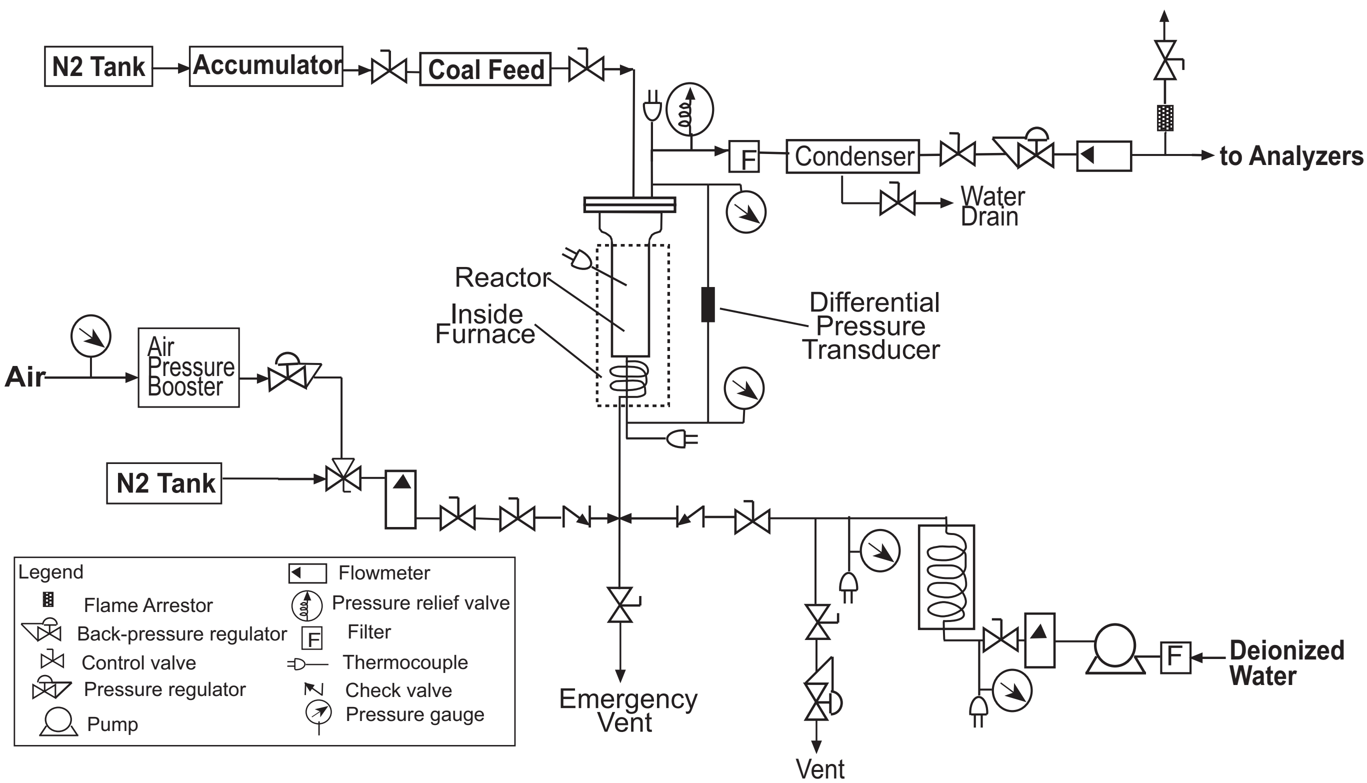

Figure 2. Bench-scale system process and instrumentation diagram.

<u>Reactor Design</u>

The reactor is the heart of the system, and was designed to withstand an environment of 1000°C and 300psi. The reactor is heated by a Lindberg Model 54579-V-s 16kW furnace with a maximum temperature of 1500°C and a 4” inside diameter. Due to the external heating of the reactor, the reactor materials were selected to withstand the full operating temperatures of the process. However, because of gasket temperature limitations, the flanges used to seal the reactor were located outside the hot zone of the furnace.

The reactor consists of a 4” OD outer shell, and a 2”ID inner shell with an expansion zone. The outer shell is welded to a flange, while the inner shell has a lip that allows it to rest between the outer shell’s bottom flange and the flange lid, with two gaskets used to maintain high-pressure seals. A diagram of the reactor is shown in Figure 3, alongside a photo of the completed reactor.

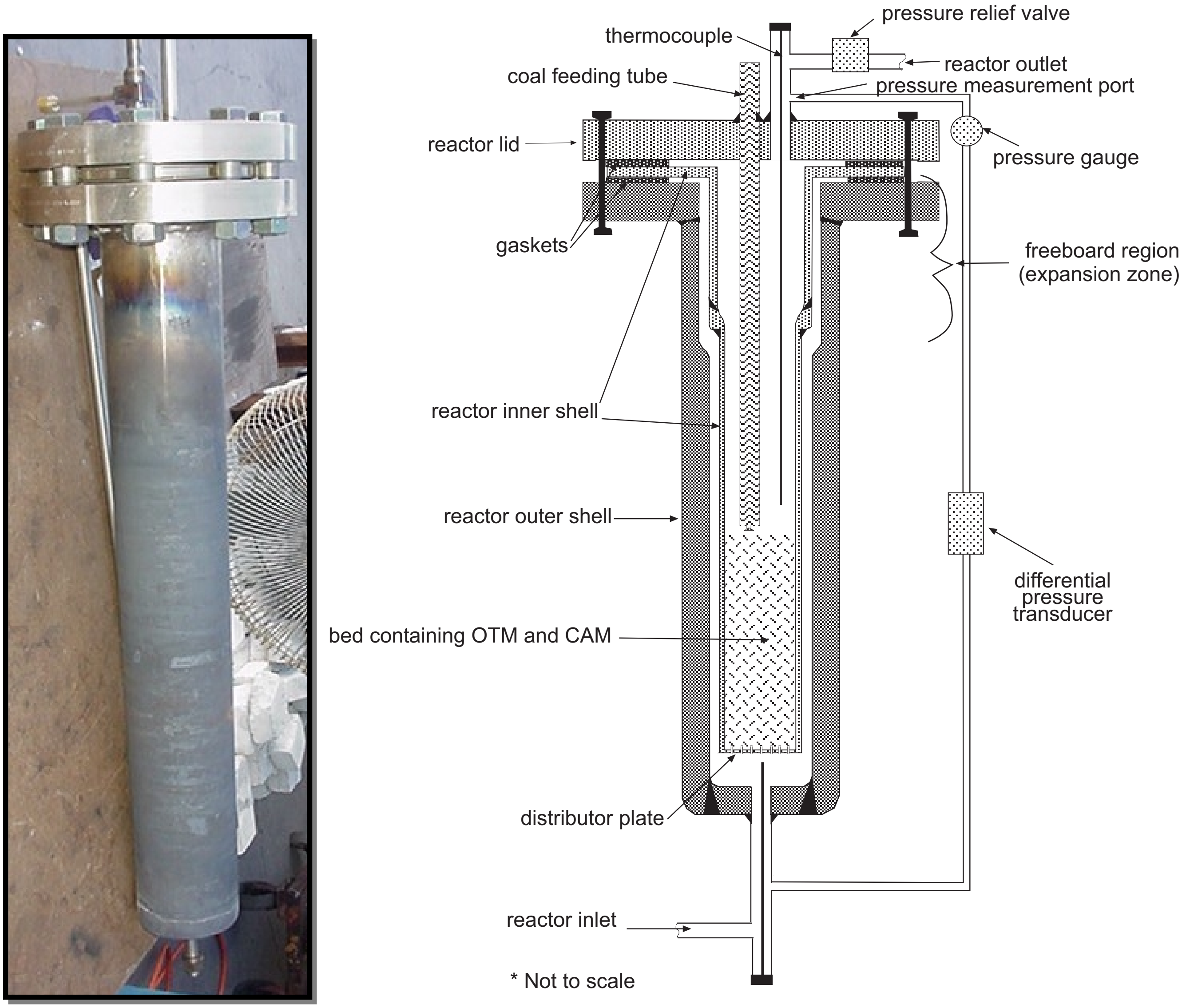

Figure 3. Bench-scale reactor photo and diagram.

An Incoloy 800HT alloy was used for the outer shell, selected on the basis of its strength at high temperatures and its ability to withstand the severely oxidizing and severely reducing environments of the process. A detailed stress analysis was conducted to specify the reactor wall thickness. The heat loss through the outer shell walls was estimated in order to specify the reactor length so that the flange at the top of the reactor will not exceed 400°C during operation.

The completed reactor was sent to an independent testing laboratory for certification. The reactor was subjected to conditions of 1000°C and 325psi for over 24 hours with no signs of leakage or permanent deformation. Figure 4 shows the temperature profile across the reactor, with an inset photo of the red-hot reactor taken during the certification test. As shown in the figure, the temperature at the top flange of the reactor did not exceed 400°C.

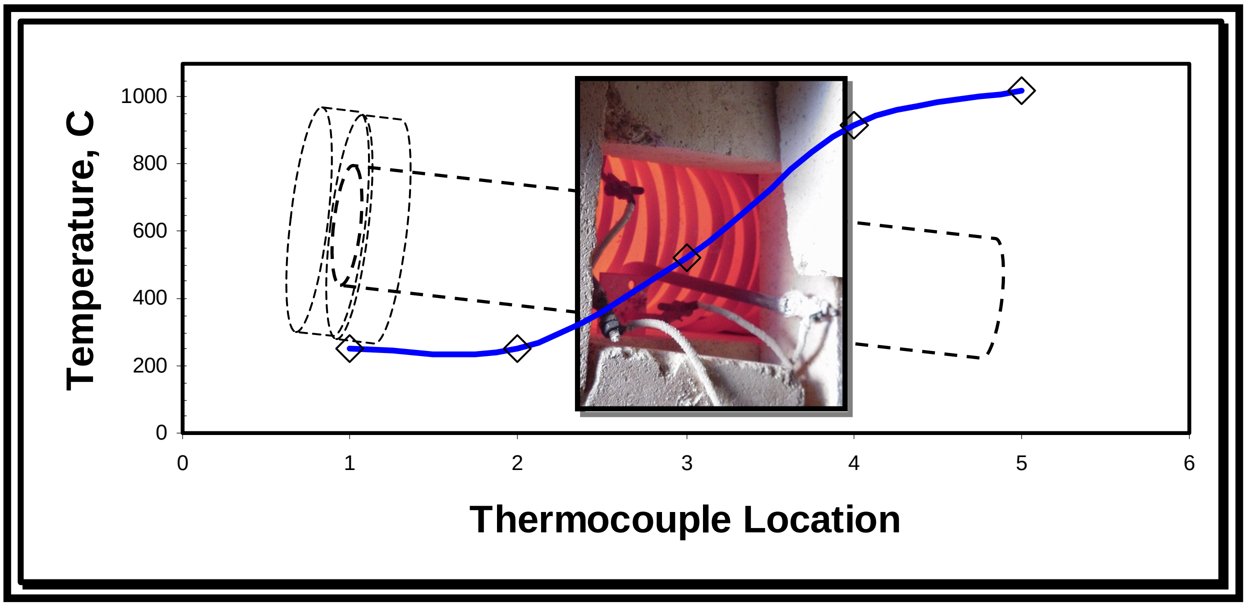

Figure 4. Temperature profile in reactor during certification testing.

Coal Injection

The coal feeding system was designed to inject measured amounts of coal into the high-pressure, high-temperature reactor with minimal plugging, deposits, and coal devolatilization in the feed tube. The coal feeding tube enters the reactor through the flange lid, and extends down into the reactor bed (as shown in the reactor diagram, Figure 3) for enhanced coal mixing with the bed and to prevent coal entrainment. The coal is loaded into a coal reservoir and then an accumulator tank is filled with high-pressure N_2. Once the accumulator is pressurized to a predetermined pressure, the coal reservoir is slowly pressurized. Then the valve between the coal reservoir and the reactor is opened, sending the slug of coal rapidly through the coal delivery tube and into the reactor bed. Shakedown testing of this system was first conducted at ambient temperature and pressure, with differential pressures on the order of 100psi, then testing continued at operating pressures, and finally at high temperature and pressure. The system was modified and optimized as needed to prevent trapping of coal in the upstream portion of the system. This involved streamlining the coal delivery line, eliminating components that led to necking in the flow path. Utilizing heat tape, shakedown testing demonstrated the successful delivery of coal at 550°C. Coal recovery increased with increasing differential pressure, reaching 90% recovery at 100psid.

Steam Generation

The steam feed system consists primarily of a water pump and a coil located inside an electric steam furnace, as depicted in Figure 5. Instrumentation is provided to measure temperature, pressure, and flow rates at intermediate points of the system in order to evaluate performance. As steam will not be fed to the reactor during start-up, ramping of furnace temperature, etc., a bypass line is used to allow for continuous steam generation while maintaining system pressure. Instrumentation is in place to monitor the temperature and pressure of the steam both before and after the steam preheater coil. Shakedown testing demonstrated the successful generation of steam for water flow rates from 5 – 40 g/min and a furnace temperature of 600 °C. During shakedown testing, an average of one hour was required to reach a steady state of steam production.

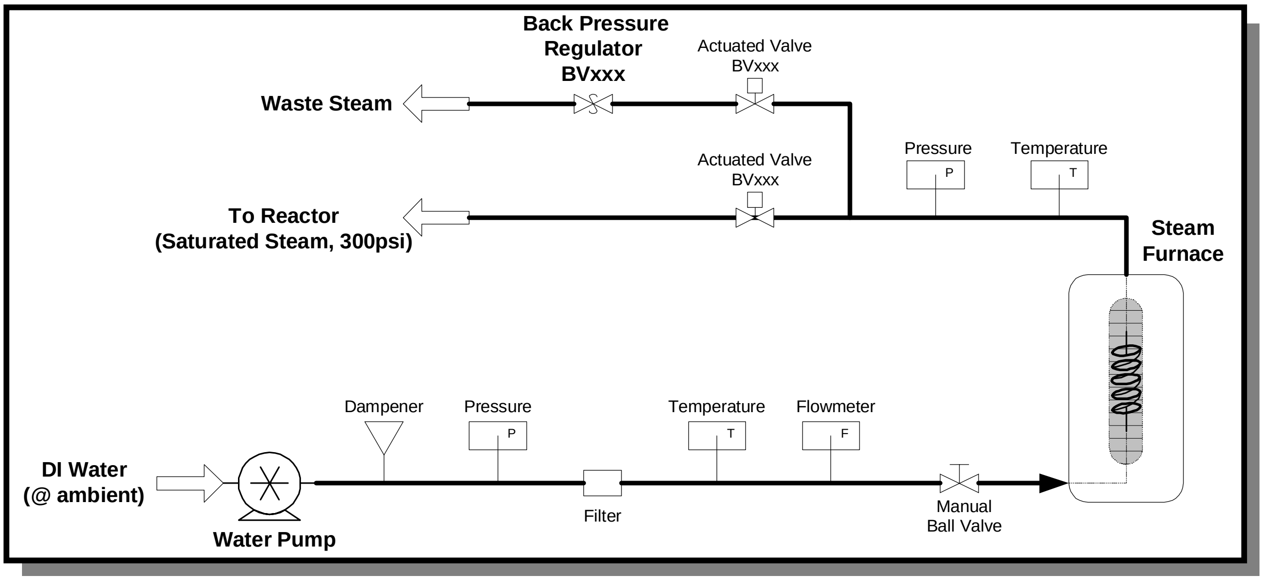

Figure 5. Schematic diagram of steam generator system.

Lab-Scale Testing

The lab-scale fluidized bed reactor and furnace have been designed and constructed and are undergoing shakedown testing. A ceramic furnace was custom-built with Ni-Cr 80 coiled heating elements encased in thermal ceramic refractory and mounted on a support. The furnace is three feet long and completely surrounds the reactor. Figure 6 illustrates the lab-scale reactor design. The reactor consists of a four-inch heavy-gauge pipe that encloses a smaller one-inch suspended pipe. The distributor plate is a sintered metal frit welded between two plates near the center of the reactor. Three sets of flanges are used to seal the reactor while providing flexibility and ease in bed recovery.

During shakedown testing, the maximum furnace temperature achieved was 866°C. The temperature at the flanges has been monitored to ensure that the graphite flange gaskets do not exceed 400°C during system operation.

In addition to the reactor, auxiliary systems have been designed and constructed for the lab-scale testing effort. These include solids handling, steam generation, and product gas conditioning. The solids input system involves the use of an inert gas as a pneumatic transport medium. The outlet solids collector makes use of solids filters and changing the direction of gas flow. The steam generation system is composed of a metering pump and a length of pipe filled with alumina boiling chips that is heated with high-temperature heat tape. A product gas conditioning system has also been designed and assembled to allow continuous measurements of dry product gas concentrations. Experimental testing on this system will focus on evaluation of key kinetic and thermodynamic limitations of the AGC process.

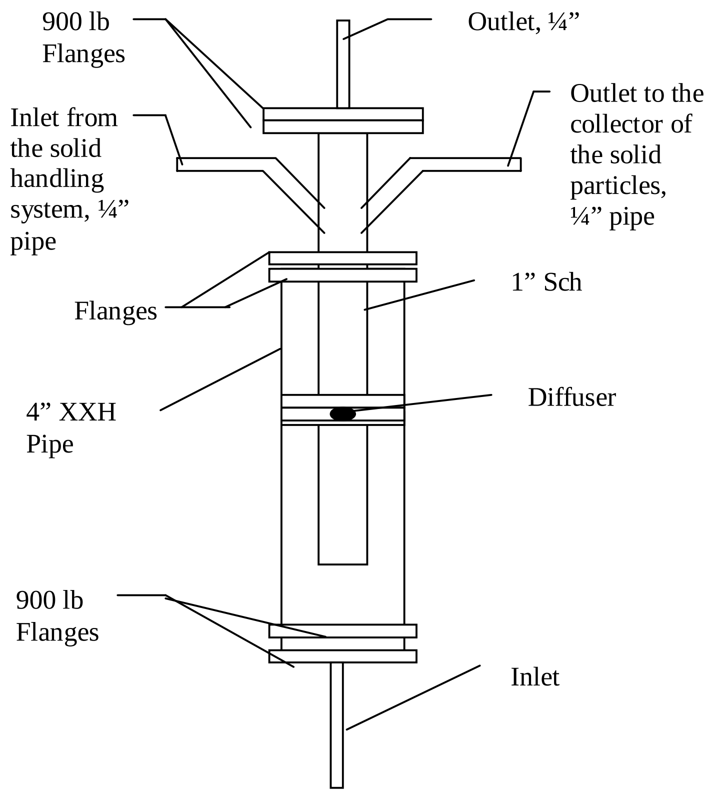

Figure 6. Lab-scale reactor design.

Pilot Plant Preliminary Design

The initial consideration in the design of the pilot plant is the specification of system scale. It is necessary to identify a moderately sized plant that effectively demonstrates the technology. The scale-up of fluidized beds is not a straightforward process, and the added complication of solids handling and transfer makes selection of system size a significant concern.

It is generally acknowledged that a commercial-scale plant should not be designed using a purely theoretical approach. A variety of methods can be utilized in the scale-up of chemical technologies, such as application of dimensionless groups, process modeling, practical methods, and combinations thereof. The approach selected for the pilot-scale design is process modeling coupled with consultation with experts and lab and bench-scale operational experience. Shakedown testing of the bench-scale apparatus has already revealed critical aspects to be addressed in the pilot plant, particularly with the coal feeding mechanism and the optimum fluidization mode. A thorough review of relevant literature is in progress to provide technical background, with a focus on existing commercial fluidized coal gasifiers, mechanisms for re-circulating solids, and high-pressure/temperature solid feeders, as well as critical components such as distributors for commercial fluidized beds, valves for handling solids in motion, steam generation units, etc.

Process Modeling

A computer model was developed to perform analytical calculations for all the unit operations in the multi-bed reactor system. The model is interfaced with the NASA thermodynamic code (McBride, B. and Gordon, S. Chemical Equilibrium with Thermal Transport Properties, Lewis Research Center, Cleveland, Ohio, 1993) for calculation of reaction equilibrium and constituent compositions. The model can be used to determine the process efficiency as a function of different parameters, such as feed flow rates, system pressure, and solids recirculation rate. The model can also be used for optimizing process design. The model performs mass and energy balances for each component of a process flow diagram (PFD) and for the whole system.

Using the process model, an overall process efficiency was estimated for the PFD illustrated in Figure 7 to be approximately 67%. The overall process efficiency is defined as the ratio between the energy recovered to the higher heating value (HHV) of the coal fed. The energy recovered is the sum of the HHV of H_2 and total electricity generated by the process.

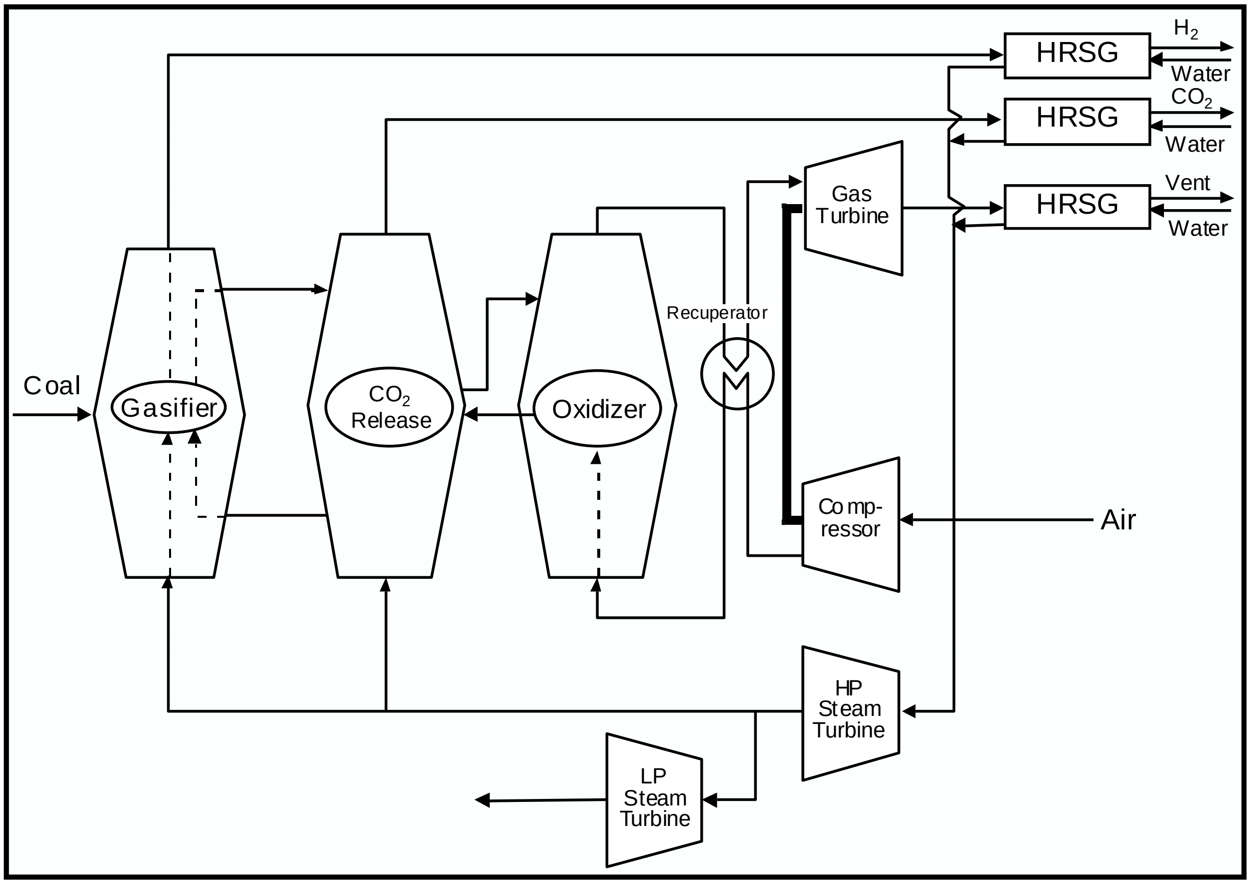

Figure 7. Process flow diagram incorporating the AGC module with other unit operations.

Opportunity Fuel Resource Assessment

An opportunity fuels resource assessment was conducted to identify and select alternative "opportunity" fuels to be tested in conjunction with coal in experimental evaluations of the AGC process. This effort included development of an extensive bibliography as well as a compilation of information based on literature searches, previous opportunity fuel assessments and discussions with experts in the opportunity fuel industry such as fuel producers, fuel handlers, fuel users, and fuel recyclers.

The study estimated:

- Total opportunity fuel production rates;
- Fuel availability, considering current handling practices, uses and fate of fuels, seasonality of generation, sustainability of production, etc.;

- Fuel costs, including purchasing / tipping and transportation; and
- Location of fuels by state.

This assessment will be used as a guide for identifying suitable opportunity fuels for use with coal in the AGC process. Current information with regard to the availability of opportunity fuels will aid in leveraging the fuel-flexibility of the AGC process to enhance its economic viability. Key results from this assessment are summarized in Table 1.

Table 1. Results of opportunity fuel resource assessment.

Opportunity Fuel Category	Availability MM BDT/yr	Availability Ranking	Cost $/BDT	Cost Ranking	Overall Ranking
Wood Construction / Demo	9	7	0 - 20	5	1
Wood Municipal Solid Waste	6	11	0 - > 30	7	1
Urban Tree / Yard	12	6	0 - > 30	7	1
Forest Slash / Thinings	45	3	> 20	8	1
Woody Orchard	3	13	0 - 10	3	1
Waste Paper	16	5	-30 - > 20	2	2
Waste Plastic	8	8	-30 - > 20	2	2
Livestock Manure	80	2	0 - > 10	4	3
Biosolids Sewage Sludge	6	12	- 30 - 0	1	4
Corn Stover	118	1	20 - 50	9	5
Ag Processing Residue	3	14	0 - > 20	6	6
Cotton Stalks	7	10	20 - 50	9	7
Rice Straw	7	9	20 - 50	9	7
Wheat Stalks	35	4	20 - 50	9	7
Lumber Mill Residues	1	15	> 20	8	8

Preliminary Economic Assessment

A preliminary economic assessment was initiated to establish target investment values that provide competitive costs of electricity (COE) and other co-products for coal/biomass power generation in order to compare the AGC system with other coal/biomass to electricity technologies. Initial work on the preliminary assessment concluded that target system costs for the AGC should be comparable to IGCC and hydrogen production facilities. Co-products of hydrogen, electricity and steam must also be competitive. The sensitivity of capital costs will be evaluated for various product mixes that will be determined by pilot testing. Small-scale systems based on gasification and IC engines up to one MW should be evaluated. Environmental allowances for NO_x, SO_x, and CO_2 will be incorporated in detailed analyses.

Coal/biomass IGCC studies indicate target capital costs of $1,200/kWe in order to produce power for $0.06/kWh with feedstock costs in the range of $1.80/GJ. Projected capital costs for a plant should be \$34/GJ. As additional process information is gathered, the economic assessment will be updated to provide more specific comparisons of costs.

Benefits

The innovative approach of the AGC technology results in a process with substantial benefits. These benefits include:

- Production of high-purity H_2 requiring minimal back-end purification
- Isolation of CO_2 from products
- Use of well-known unit operations
- Use of a previously-demonstrated gasification/CO_2 absorption process
- Use of a well-known steam-char gasification process
- System-level efficiencies in excess of 60% for electricity production from coal
- Flexibility in fuel utilization including low-cost alternative feedstocks in addition to coal
- Flexibility in product generation
- Meets or exceeds environmental goals

The development of the AGC process is being coupled with ongoing economic analyses to ensure that the process is economically, as well as technically viable.

Future Activities

Work conducted in the immediate future will focus on testing and analysis of results from both the lab-scale apparatus and the completed bench-scale system (Figure 8). This information will be used in ongoing pilot-scale design efforts. In addition, continuing modeling efforts will provide a more clear understanding of the kinetics and fluidization processes. Other engineering studies will aid in ensuring that the technology is developed in such a way that it meets market needs, both through its economic viability, as well as through its use of opportunity fuels.

In the next two years of this program, the design, construction and testing of the pilot-scale system is planned. The demonstration of the AGC technology at the pilot scale is a critical step in the eventual commercialization of the technology, and all lab-scale, bench-scale and modeling efforts conducted to date are aimed at ensuring the success of the pilot-scale demonstration.

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Figure 8. Bench-scale system.