Fuel-Flexible Gasification-Combustion Technology for Production of H_2 and Sequestration-Ready CO_2

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DISCLAIMER

ABSTRACT

It is expected that in the 21st century the Nation will continue to rely on fossil fuels for electricity, transportation, and chemicals. It will be necessary to improve both the thermodynamic efficiency and environmental impact performance of fossil fuel utilization. General Electric Energy and Environmental Research Corporation (GE EER) has developed an innovative fuel-flexible Advanced Gasification-Combustion (AGC) concept to produce H_2 and sequestration-ready CO_2 from solid fuels. The AGC module offers potential for reduced cost and increased energy efficiency relative to conventional gasification and combustion systems. GE EER was awarded a Vision-21 program from U.S. DOE NETL to develop the AGC technology. Work on this three-year program started on October 1, 2000. The project team includes GE EER, California Energy Commission, Southern Illinois University at Carbondale, and T. R. Miles, Technical Consultants, Inc.

In the AGC technology, coal/opportunity fuels and air are simultaneously converted into separate streams of (1) pure hydrogen that can be utilized in fuel cells, (2) sequestration-ready CO_2, and (3) high temperature/pressure oxygen-depleted air to produce electricity in a gas turbine. The process produces near-zero emissions and, based on preliminary modeling work in the first quarter of this program, has an estimated process efficiency of approximately 67% based on electrical and H_2 energy outputs relative to the higher heating value of coal. The three-year R&D program will determine the operating conditions that maximize separation of CO_2 and pollutants from the vent gas, while simultaneously maximizing coal conversion efficiency and hydrogen production. The program integrates lab-, bench- and pilot-scale studies to demonstrate the AGC concept.

This is the fifth quarterly technical progress report for the Vision-21 AGC program supported by U.S. DOE NETL (Contract: DE-FC26-00FT40974). This report summarizes program accomplishments for the period starting October 1, 2001 and ending December 31, 2001. The report includes an introduction summarizing the AGC concept, main program tasks, and program objectives; it also provides a summary of program activities covering program management and progress in tasks including lab- and bench-scale experimental testing, pilot-scale design, and economic studies.

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LIST OF ACRONYMS

AGC	Advanced gasification-combustion
CAM	CO_2 absorber material
CEC	California Energy Commission
CEMS	Continuous emissions monitoring system
CTQ	Critical to quality
DFSS	Design for six sigma
FMEA	Failure mode and effects analysis
GE EER	General Electric Energy and Environmental Research Corporation
IGCC	Integrated gasification combined cycle
NETL	National Energy Technology Laboratory
NPI	New product introduction
OTM	Oxygen transfer material
P&ID	Process and instrumentation diagram
SIU-C	Southern Illinois University – Carbondale
U.S. DOE	United States Department of Energy

INTRODUCTION

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 many of 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 including biomass, municipal solid waste, sewage sludge, and others.

This Vision-21 program addresses a novel, energy-efficient, and near-zero pollution concept for converting a conventional fuel (coal) and opportunity fuels (e.g., biomass) into separate streams of hydrogen, oxygen-depleted air, and sequestration-ready CO_2. This concept is referred to throughout this report as *Advanced Gasification-Combustion (AGC)*. When commercialized, the AGC process may become one of the cornerstone technologies to fulfill Vision-21 energy plant objectives of efficiently and economically producing energy and hydrogen with utilization of opportunity feedstocks.

The AGC technology is energy efficient because a large portion of the energy in the input coal leaves the AGC module as hydrogen and the rest as high-pressure, high-temperature gas that can power a gas turbine. The combination of producing hydrogen and electrical power via a gas turbine is highly efficient, meets all objectives of Vision-21 energy plants, and makes the process flexible. That is, the AGC module will be able to adjust the ratio at which it produces hydrogen and electricity in order to match changing demand.

The three-year Vision-21 AGC program is being conducted primarily by General Electric Energy and Environmental Research Corporation (GE EER) under a Vision-21 contract from U.S. DOE NETL (Contact No. DE-FC26-00FT40974). Other project team members include Southern Illinois University at Carbondale (SIU-C), California Energy Commission (CEC), and T. R. Miles, Technical Consultants, Inc. The AGC project integrates lab-, bench- and pilot-scale studies to demonstrate the AGC concept. Engineering studies and analytical modeling will be performed in conjunction with the experimental program to develop the design tools necessary for scaling up the AGC technology to the demonstration phase. The remainder of this section presents objectives, concept, and main tasks of the AGC program.

Program Objectives

The primary objectives of the AGC program are to:

- 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 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 Vision-21 plant design and optimize work cycle efficiency.
- Determine extent of technical/economical viability & commercial potential of AGC module.

AGC Concept

Figure 1 shows the conceptual design of the AGC technology where three reactors are used. In Reactor 1, coal and opportunity fuels (5-10% by heat input) are gasified by steam in the presence of a CO_2-absorbing bed material. As CO_2 is scavenged, CO is also depleted from the gas phase due to the water shift reaction. Consequently, mainly H_2 is released from Reactor 1. Only part of the solid fuel fed to Reactor 1 is gasified to produce hydrogen. The remaining char and bed material are transferred to Reactor 2, where the carbon is oxidized to supply the thermal energy necessary to regenerate the CO_2-absorbing bed material and release CO_2, as shown in Figure 1. Oxygen-transfer bed material is moved from Reactor 3 to Reactor 2 to provide the oxygen necessary to oxidize the char in Reactor 2, in turn raising the bed temperature for decomposition and release of CO_2. Air is supplied to Reactor 3 to regenerate the oxygen-transfer bed material. Exiting Reactor 3, the hot oxygen-depleted air passes to a gas turbine to generate electricity and the hot bed materials return to Reactor 2. Ash and some bed material will be removed from the system periodically to reduce the amount of ash in the reactor and to replenish the bed materials with fresh compounds.

Project Plan

The tasks planned for the AGC project are summarized in Table 1. These tasks will be conducted over the three-year period that started October 1, 2000. Success of the AGC program depends on the efficient execution of the various research tasks outlined in Table 1 and on meeting the program objectives summarized above.

Table 1. Main tasks of the AGC program.

Task	Task Description
Lab-Scale Experiments – Fundamentals *Task 1*	Design & assembly Demonstration of chemical processes Sulfur chemistry
Bench-Scale Test Facility & Testing *Tasks 2 & 3*	Bench test facility design Subsystems procurement & assembly Bench test facility shakedown Reactor design testing Parametric evaluation Fuel-flexibility evaluation Pilot operation support
Engineering & Modeling Studies *Task 4*	Opportunity fuels resource assessment Preliminary economic assessment Kinetic & process modeling Integration into Vision-21 plant Pilot plant control development
Pilot Plant Design, Assembly, & Demonstration *Tasks 5, 6, & 7*	Process design Subsystems specification/procurement Reactor design & review Reactors manufacture Components testing Pilot plant assembly Operational shakedown modifications Operational evaluation Fuel-flexibility evaluation Performance testing
Vision 21 Plant Systems Analysis *Task 8*	Preliminary Vision-21 module design Vision-21 plant integration Economic & market assessment
Project Management *Task 9*	Management, reporting, & technology transfer

PROGRAM PLANNING AND MANAGEMENT

Program planning activities have focused on meeting the objectives of the program as stated previously. GE EER has made use of several GE methodologies to obtain desired results and systematically conduct program design, construction and testing activities. These methodologies include New Product Introduction (NPI) and Design For Six Sigma (DFSS). The NPI program is a detailed and systematic methodology used by GE to identify market drivers, and continually ensure that the program will meet both current and future market needs. The NPI program is also strongly coupled with the DFSS and other quality programs, providing structure to the design process and ensuring that the design meets program objectives. This is accomplished through regular program reviews, detailed design reviews, market assessments, planning and decision tools, and specific quality projects aimed at identifying system features and attributes that are critical to quality (CTQ) for customers.

The project team meets weekly to assess progress, distribute workload, and identify and remove potential roadblocks. An expanded NPI project team that includes upper management personnel also meets biweekly to gauge progress and ensure that company resources are allocated and technical issues resolved to allow steady progress toward program objectives. Another purpose of the biweekly NPI meeting is to ensure that the technology is developed in a manner that continues to allow it to meet emerging market needs by following the GE NPI methodology. This includes detailed design reviews as progress is made on system designs. Members of the project team are also involved in DFSS projects that aim to identify system CTQs and use a systematic methodology to ensure that they are met. DFSS projects completed to date include a management overview of the entire program and identification of the significant components, a design of the overall bench-scale system, a design of the bench-scale reactor, and an assessment of options for product gas analysis equipment. Projects currently in progress include the design and validation of the steam generator system, and the bench-scale safety system. The results of these DFSS projects include an identification of the CTQs, block diagrams, operating procedures, emergency procedures, and failure mode and effects analyses (FMEA). These projects aid in identification of possible problems in the subsystems, thus avoiding time lost to rework and extensive modifications.

Program management activities also involve continuous oversight of program expenditures. This includes monthly review of actual expenditures and monthly projections of labor, equipment, contractor costs, and materials costs.

EXPERIMENTAL ACTIVITIES AND RESULTS

During the fifth quarter, preliminary results from experimental facilities have been obtained, and many experimental difficulties have been resolved. The laboratory-scale activities are being conducted by SIU in Carbondale, IL, while the bench-scale system is located at GE EER's test facility in Irvine, CA.

Laboratory-Scale (Task 1) Activities

The primary objective of Task 1 is to perform a laboratory-scale demonstration of the individual chemical and physical processes involved in GE EER's fuel-flexible AGC technology. Specific objectives of Task 1 include:

- Support bench- and pilot-scale studies;
- Assist in process optimization and engineering analysis;
- Identify key kinetic and thermodynamic limitation of the process; and
- Verify the process parameters at laboratory scale.

Work conducted in the fifth quarter has focused on the testing and shakedown of the high temperature/high pressure reactor and its auxiliary systems. Thermal testing of the furnace/reactor is currently underway to identify relationships between performance and operating temperatures.

Preliminary testing was complicated by the plugging and eventual failure of the distributor plate, which necessitated the replacement of the distributor plate with one made from a more durable material. The procedures for purging the reactor have been modified and updated to minimize undesirable reactions that result in downtime for reactor cleaning. Several operational issues have since been resolved.

Gasification experiments were conducted in the lab-scale system using a bed composed of a mixture of CO_2-absorber material (CAM), oxygen transfer material (OTM) and coal: 5.2 g OTM, 45 g CAM, and 30 g coal. Testing was conducted at 450psi and 725°C with a 25 vol % steam feed. Figure 2 illustrates typical gasification concentration profiles as measured in the lab-scale system. Gasification performance with a CAM bed is characterized by low CO and CO_2 concentrations and high H_2 concentration, as expected with the AGC process. Continuing experiments are planned to quantify performance and identify process kinetics.

Bench-Scale Testing (Task 3)

The objectives of the bench-scale testing task are to collect data on process operation and kinetics under dynamic conditions and aid in developing the modeling tools and the pilot plant equipment design. The bench-scale system is also intended to provide data on individual AGC processes to aid in pilot plant design and testing.

Preliminary testing conducted in the fifth quarter has identified operational difficulties and appropriate modifications were made to the experimental setup. These included the addition of insulation and heating to prevent condensation in the lines, as well as the repair and replacement of defective instrumentation. The latest revision of the process and instrumentation diagram (P&ID) of the bench-scale system is provided in Figure 3, reflecting changes in the location of key thermocouples that are now used to monitor conditions that may lead to condensation in the feed and product lines.

During system design, the need for consistent flow to the analyzers was identified as a concern. Due to the cyclic nature of the bench-scale experiments, it is necessary to add a known flow rate of N_2 to the product gas to ensure consistent flow to the analyzers even when the only flow through the reactor is steam (which is condensed prior to the analyzers). The N_2 feed was added after the backpressure regulator, at a point where the pressure is low. An additional bleed stream of N_2 was later added with the steam at the reactor inlet to ensure the effective operation of the condensers when no product gases are being generated. The flow rate of product gas varies from zero (prior to steam injection) then up to a peak flow rate value (during gasification) and finally down to zero again (after gasification is complete). Although a constant flow rate of N_2 is fed to the system, this cyclic variation in product flow rate results in effective dilution ratios that vary during the course of an experiment. Thus, gas concentrations measured by the CEMS analyzers must be corrected with these varying dilution ratios. This has the potential for introducing error to the data, and is currently being evaluated. For this reason, experimental results are reported as component flow rates, which are independent of N_2 dilution rate, rather than as measured concentrations.

The capabilities of the bench-scale experimental system have been verified through preliminary testing, and detailed planning has been conducted to develop a comprehensive approach to testing. Selection of the type and sequence of tests to best provide information about the AGC process for modeling and pilot plant design has been a high priority. The type of information desired from bench-scale testing includes: characterization of coal conversion; quantification of CAM and OTM activity over time; development of global reaction rates for each reactor; characterization of the impact of bed and coal particle size on performance; and parametric testing to identify optimal operating conditions. In addition, data analysis templates have been developed and methodologies for calculation of performance parameters reviewed and validated.

Preliminary experimental testing has focused on fluidization experiments to verify the cold flow modeling results for fluidization flow rates and coal gasification experiments with either an inert bed or a CAM bed. Preliminary data from these tests are discussed below.

Fluidization experiments were performed using an inert bed composed of alumina oxide at 300 psi and 850°C. Experimental values of pressure drop were obtained for a range of fluidizing flow rates. Figure 4 illustrates the range of differential pressures measured, and their comparison to theoretical values. The experimental and theoretical values are in good agreement, and their scatter can be attributed to experimental variations.

Coal injection and gasification tests were conducted with an inert bed to provide a baseline for comparison of CO_2 absorption performance. The coal injection system is currently being scrutinized to identify potential improvements. Minimal fluctuations in reactor temperature and pressure have been observed due to the coal injection transport gas (N_2), with a recovery time of approximately one minute required to restore the initial conditions.

Gasification experiments were also conducted with a bed composed of CAM. Coal was injected into the CAM bed and significant CO_2 absorption was observed. Figure 5 shows the difference in CO_2 concentration for gasification experiments conducted in an inert bed and in a CAM bed. The CO_2 concentration increases more rapidly and with a higher peak concentration during gasification in an inert bed. The CO concentration behaves in a similar manner, with increased concentrations during gasification in an inert bed, as illustrated in Figure 6 for the same test. The reduced CO_2 concentrations are due to the absorption of CO_2 by the CAM bed. Meanwhile, the reduction in CO is caused by the participation of CO in the water-gas shift reaction ($CO + H_2O -» CO_2 + H_2$), driven by the low CO_2 and CO concentrations in the reactor. The product gas flow rates observed during these tests (Figure 7) are consistent with the explanations provided, as the decreased CO_2 concentrations also result in lower product gas flow rates. A unique feature of the AGC process is its inherent production of high-purity H_2 due to the absorption of CO_2 and related reduction in CO concentration. Testing conducted to date has focused on measurements of the CO_2 and CO, although direct measurements of H_2 concentration will be conducted with a GC analyzer in the next quarter.

The reproducibility of the tests is also continuously being evaluated. Figure 8 shows the CO_2 flow rates from three different gasification tests conducted with CAM beds. The general trends are similar, although Run B shows higher concentrations than Runs A and C. However, Runs A and C were each conducted with fresh CAM beds, and run B was conducted with a regenerated bed after Run A. Thus, differences in CO_2 concentrations may be due to incomplete regeneration of the CAM bed, which is currently being investigated experimentally.

These preliminary results are currently under review and detailed calculations are being conducted to verify the mass balance around the system and evaluate the reproducibility of the results, as well as the reliability of the system. Additional results and more detailed analysis will be available in the next quarter.

Engineering and Modeling Studies (Task 4): Preliminary Economic Assessment

The objective of the preliminary economic assessment is to establish target investment values that provide competitive costs of electricity (COE) and other co-products for coal/biomass power generation to compare the AGC system with other coal/biomass to electricity technologies. As part of this effort, a comparison is being developed to clearly identify key technical and other differences between AGC and IGCC systems. A summary of the preliminary assessment is provided in Table 2. Although both IGCC and AGC systems produce electricity in a gas turbine, the AGC system also produces high-purity H_2 and reduces the need for air pollution control devices such as those required in the IGCC syngas cleanup step. In addition, the AGC process does not require a costly oxygen plant. The IGCC technology has been demonstrated at large scales at different locations in the world and thus the economics of IGCC plants are well characterized and will be used as a target for AGC costs.

Work conducted in the fifth quarter has also focused on identifying the parameters of the envisioned AGC baseline case. This has included the development of a mass and energy balance (Figure 9) for an integrated AGC power plant. In addition a framework has been developed for the estimation of both operating and capital costs. Actual costs will be estimated or obtained by a variety of methods and input into the framework to arrive at values that can be compared to the costs associated with other technologies. Once the baseline case economics have been established, parametric studies will be conducted to assess the impact of different operating parameters and assumptions on the cost of electricity and hydrogen production. The objectives of these parametric evaluations include:

- Identification of limiting performance specifications for operating parameters
    - “Showstopper” operating requirements and the impact of critical assumptions such as coal price, unit efficiency, etc.
- Quantification of economic impact of design options
    - Plant size, operating pressure, bed configuration that differ significantly from the baseline case
- Assessment of the value of CO_2 sequestration
    - Equipment required for sequestration, alternate uses of CO_2 stream

The economics of the AGC process are critical to its eventual commercialization. Developing relationships between technical performance goals and economic targets will ensure that AGC development results in a viable commercial product.

Table 2. Comparison of features of AGC technology and IGCC (Integrated gasification combined cycle) technology.

Feature	AGC	IGCC
Major components	Steam gasification (Reactor 1)	Gasification (with air or O_2)
	CO_2, sulfur sequestration (Reactor 2)	Syngas cleanup
	Metal oxidation/heat generation (Reactor 3)	
	Gas turbine combined cycle	Gas turbine combined cycle
		Oxygen plant
Product streams	High-purity hydrogen stream (>90%)	
	Sequestration-ready CO_2 stream containing sulfur and other pollutants	Syngas cleanup products (potential for marketable products)
	Power from gas turbine	Power from gas turbine
Intermediate streams		Syngas (8.6-61% H_2),
	High-pressure air	High-pressure syngas
	High-pressure, high-temperature feed for gas turbine	High-pressure feed for gas turbine
Pollutants	Minimal cleanup of H_2-rich fuel required for fuel cell operation (majority of pollutants concentrated in CO_2 stream)	Syngas
	No NOx formation	Gas turbine optimized to minimize NOx formation
	Hg concentrated in Reactor 1 product stream	Hg concentrated in syngas stream
Gas turbine operation	N_2-rich stream expanded in gas turbine	Syngas combusted in gas turbine
Fuel flexibility	Coal, biomass planned	Demonstrated use of coal, coke, biomass, waste
Economics	TBD	Turnkey cost (coal fuel) $1,000-$1250/kW

Pilot Plant Design and Engineering (Task 5)

Specific objectives of the pilot plant design effort include:

- Creation of a conceptual design for an AGC pilot-scale plant;
- Documentation of the process and instrumentation diagram (P&ID);
- Development of reactor designs for 1) fluidized gasification of coal/CO_2 absorption (Reactor 1), 2) CAM decomposition (Reactor 2) and 3) OTM oxidation (Reactor 3); and
- Identification and specification of subsystems.

During the fifth quarter, work proceeded on the design of the pilot-scale unit. Relevant literature in the field of coal gasification, kinetics, circulating fluidized beds, CO_2 absorption was collected and reviewed. The information was summarized and stored on GE EER's server.

An approach to defining dimensions and process conditions for the pilot-scale AGC unit was developed, based on establishing specification limits for the critical parameters. Reactor 1 was used as the initial case. By setting boundaries on the design of Reactor 1, the other two reactors and sub-systems can also be defined because they are linked through process and energy requirements. The approach used to define critical parameters on Reactor 1 is detailed below.

Some reactor design parameters can be specified based on engineering judgment and the empirical experience of expert consultants to create the boundaries required for the design process. Hydrodynamics correlations reported by experts in the field of Fluidization[1,2,3,4,5] were utilized to develop a design tool with an Excel spreadsheet. The initial form of this spreadsheet is applicable to the design of Reactor 1 only. A similar approach will be used to extend its applicability to include Reactors 2 and 3 as well. An example of a condensed version of the template is provided in Appendix A.

To run design calculations, it was assumed that Reactor 1 would operate in the bubbling fluidized bed regime. Operation in the fast fluidization and entrained bed regimes was not considered for this reactor to minimize loss of solid material and to avoid elevated bed temperatures. Expert design partners on this program provided information on specification limits for key design parameters on pilot-scale units of similar nature. The input parameters, used in creating boundaries to define the scale of the pilot-plant effort, are summarized in Table 3 below.

Table 3. Specification limits on key design parameters.

		REQUIREMENTS	
Parameter	**Source**	**Lower Spec Limit**	**Upper Spec Limit**
Bed static depth	Fluidization literature	1 ft	3 ft
Bed particle size	T. Miles and literature	400 μm	750 μm
Steam sup. veloc.	Literature	u_{mf}	u_t
Bed capacity	Literature		2 MMBTU/h.ft^2
Coal feed input	T. Miles		1 MMBTU/h
Turn-down ratio	Literature	1	5

As an example of the application of this design tool, the above information was coupled with assumptions and/or input parameters to estimate dimensions plus other essential operating parameters of the fluidized-bed gasification reactor (Reactor 1). The assumptions and/or input parameters are described below:

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[1] Levenspiel, O., *The Chemical Reactor Omnibook*, Chapter 25, OSU Book Stores, Inc., 1989.

[2] Kunii, D. and Levenspiel, O., “Circulating Fluidized-bed Systems”, Chem.Eng.Sci., 52(15), pp.2471-2482, 1997.

[3] Grace, Can.J.Chem.Eng. 64, 353, 1986.

[4] Perry, R.H. and Chilton, C.H., *Chemical Engineers’ Handbook*, 5th ed., Mc-Graw-Hill, 5-54 and 20-64, 1974.

[5] Foust, A.S., Wenzel, L.A., Curtis, W.C., Maus, L. and Andersen, L.B., *Principles of Unit Operations*, Chapter 22, John Wiley & Sons, 1980.

a. Reactor 1 operated in the Bubbling Bed Regime, which means that the linear velocity of the fluidizing agent is maintained in the region between the minimum fluidization and the terminal velocities. This assumption sets limits for the bed particle size as well. Steam is used as fluidization agent and reactant. A bed particle size of 500 μm was selected, with particle sphericity of 0.6. The bulk density of the bed is known.
b. The turndown ratio, defined as the ratio of the maximum operating linear velocity and the minimum fluidization velocity, is assumed to be 4.
c. The internal diameter of the reactor is 25 cm.
d. The aspect ratio of the fluidized bed, L/D is 2, where L is the length of the fluidized-bed.
e. The expansion zone ratio is 1.4, which means the reactor diameter will expand by this ratio in the region above the fluidized bed.
f. The steam-to-carbon ratio for the reaction of gasification is fixed at 4 based on equilibrium calculations.
g. Operating pressure and temperature are fixed at 300 psi and 800^{o}C, respectively. That also defines properties of steam, such as density and dynamic viscosity.

For the above conditions, the main output parameters resulting from the use of the design tool are:

a. The total length of Reactor 1 is near 10 ft, which includes the fluidized bed length plus the length of the freeboard area (expansion zone).
b. The mass flow rate of coal to be fed is approximately 86 lb/h, which nearly corresponds to the 1 GJ/h of energy input suggested by pilot-scale design experts.
c. The mass of the bed is approx. 54 lb.

These preliminary results do not represent the final design parameters, but are provided to illustrate the capability of the design tool, and its flexibility in identifying complete sets of operating parameters. This design tool has been validated against another tool for calculation of fluidization parameters developed at GE EER.

Pilot scale design progress will continue with more detailed assessments of the availability and practicality of solid feeders and devices to transfer solids between reactors. The process flow diagrams and process and instrumentation diagrams for the pilot-scale system are currently under development, and future work will focus on their completion as well as the completion of a detailed mass and energy balance that takes into account physical and mechanical limitations of the subsystems. A clearer picture of the pilot-scale system is emerging and will be presented in the next quarterly report.

SUMMARY AND CONCLUSIONS

Work conducted this quarter has continued to develop the framework for demonstration of AGC process capabilities. The laboratory-scale efforts of this quarter have included high-temperature, high-pressure experiments, resolving mechanical and operational issues to allow detailed characterization of the fundamental AGC chemical processes.

The bench-scale experimental testing has included validation of the fluidization flow rate calculations, successful gasification of coal, upgrading of the system setup, and testing of the Reactor 1 process of coal gasification in the presence of an inert or CAM bed. Preliminary results show that the use of a CAM bed significantly impacts the performance of the system relative to gasification in an inert bed, and that these results are reproducible over several tests.

Details of the AGC system's mass and energy balance have been documented for the preliminary economic evaluation. A framework has been developed for the estimation of capital and operating costs, including identification of specific cost categories that will require estimates.

The pilot-scale design effort has continued with detailed literature reviews and development of a spreadsheet-based tool for calculation of reasonable operating parameter ranges. The assumptions made at this stage of the design effort will be updated as work proceeds.

FUTURE WORK

Future work will focus on testing and analysis of results from both the lab-scale and bench-scale systems. 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 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.

Task 1 Lab-Scale Experiments – Fundamentals

Task 1 activities will include experimental testing of the lab-scale high-temperature, high-pressure reactor and furnace. Kinetic tests involving coal, char, steam, air and combinations of oxygen-transfer material and CO_2 absorber material will be conducted. Cycling tests will also be conducted. These experimental efforts will be closely coupled with the ongoing modeling efforts to ensure that the experiments will provide information useful in model validation.

Task 3 Bench-Scale Testing

Activities will focus on parametric testing to identify optimized operating conditions and specific tests to characterize material performance. Results of these tests will be used along with lab-scale results to modify and validate kinetic and process models, as well as provide inputs for economic evaluation efforts.

Task 4 Engineering and Modeling Studies

Kinetic and process models will be further developed and validated using results from testing activities. These models will also be used to provide information for pilot plant design efforts. The preliminary economic assessment will continue, as additional information is available about the AGC process and its operating constraints.

Task 5 Pilot Plant Design and Engineering

Future work on the pilot plant design will focus on the design of the entire system, including design of the reactors, specification of subsystem components, documentation of the P&ID, and planning for testing that will be conducted on the pilot plant.

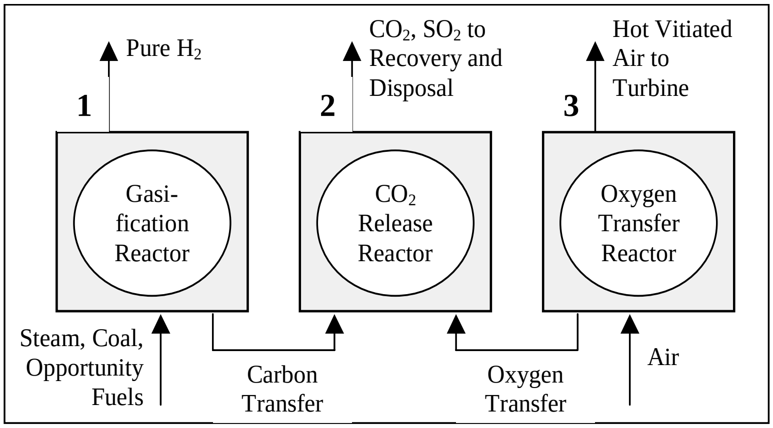


Figure 1. Conceptual design of the AGC technology.

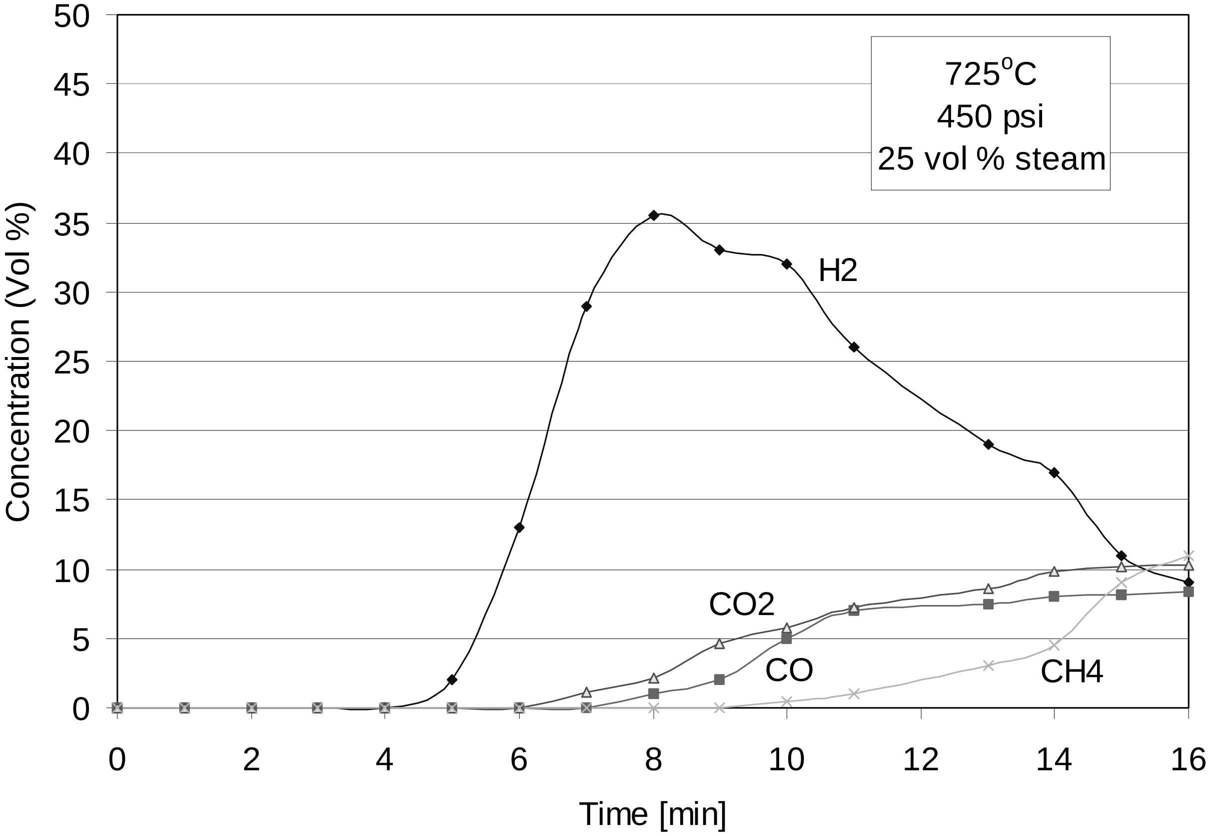


Figure 2. Lab-scale experimental coal gasification results.

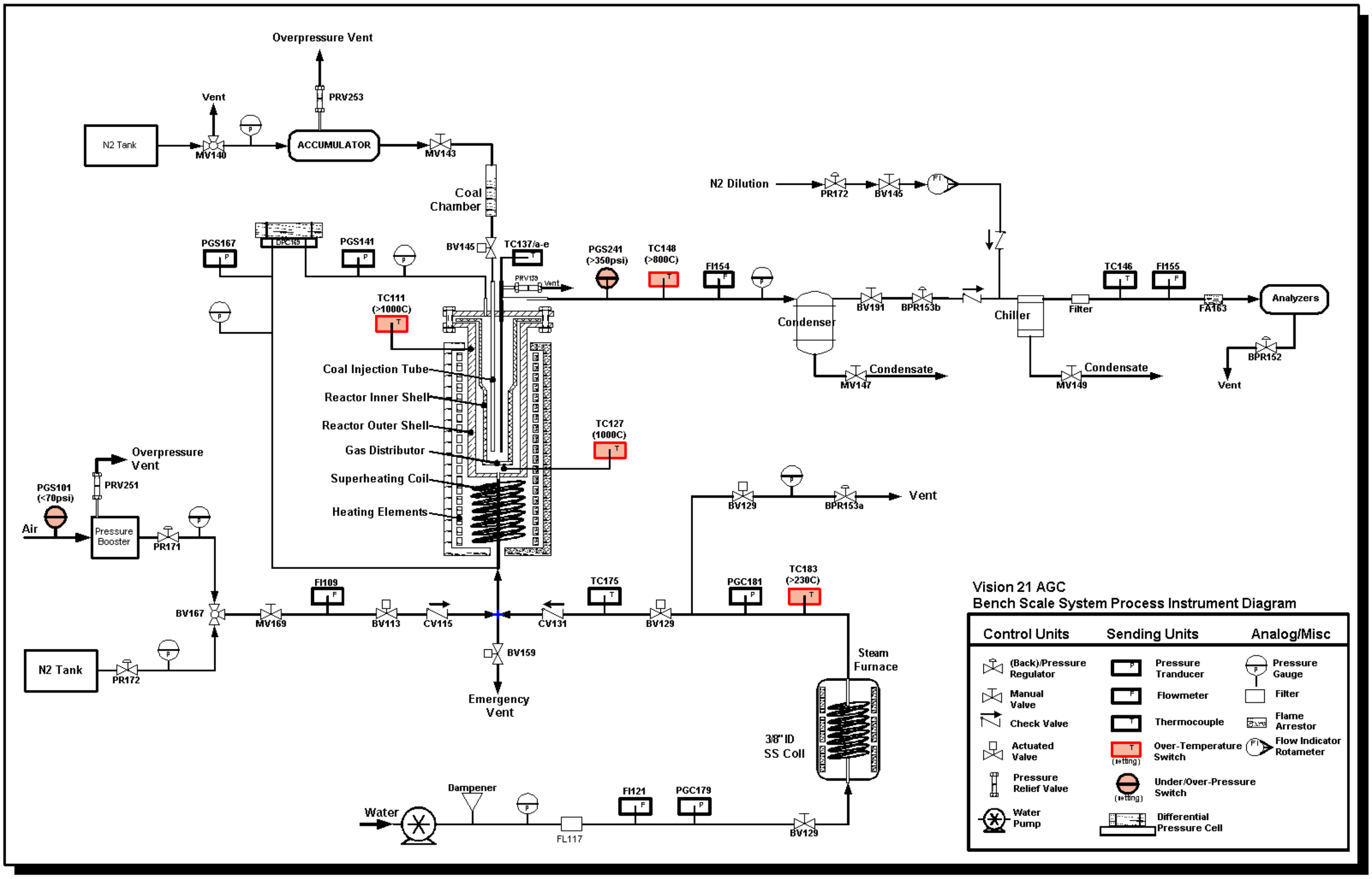


Figure 3. Process and instrumentation diagram for the bench-scale experimental system.

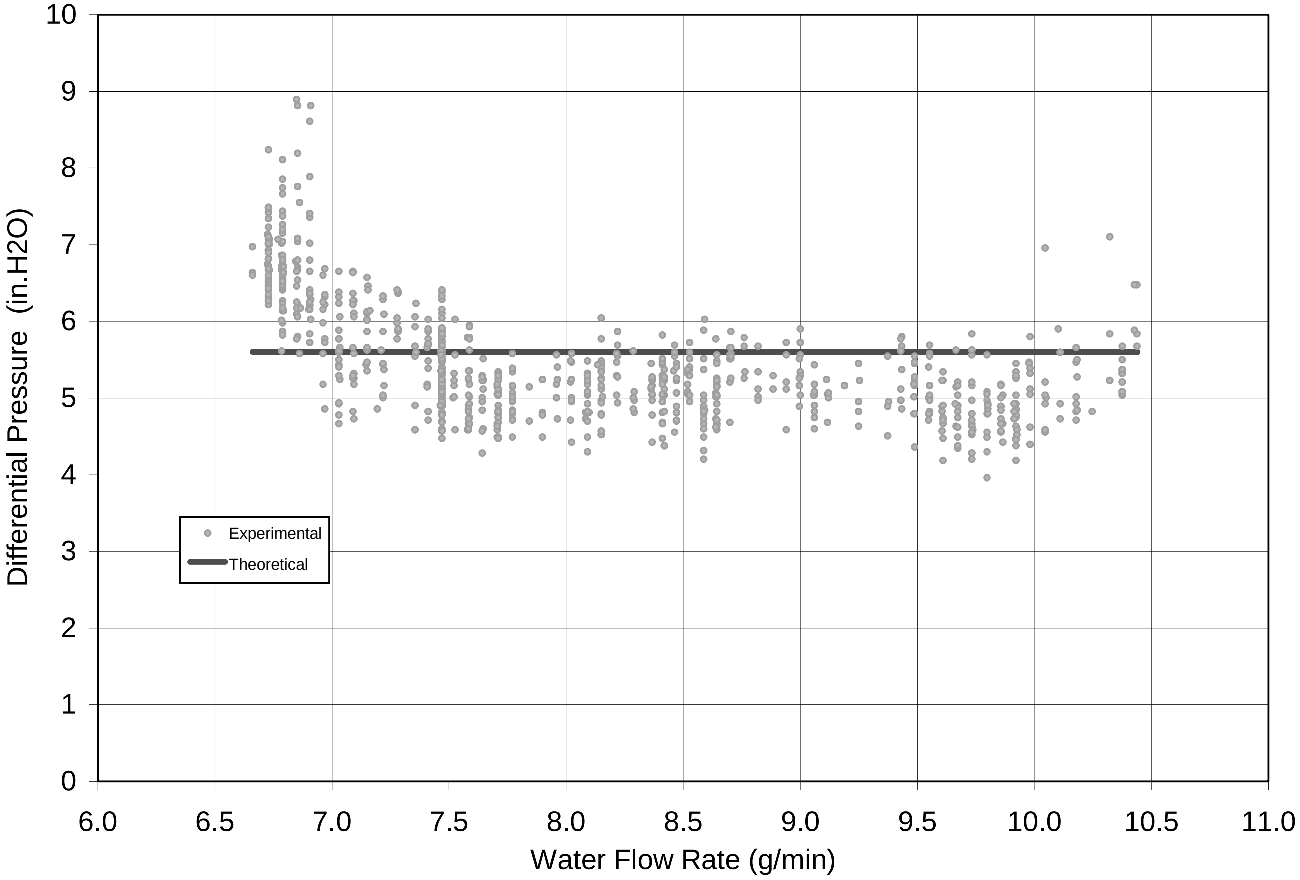


Figure 4. Pressure drop through the reactor bed as a function of fluidization flow rate: a comparison of experimental results with theoretical values.

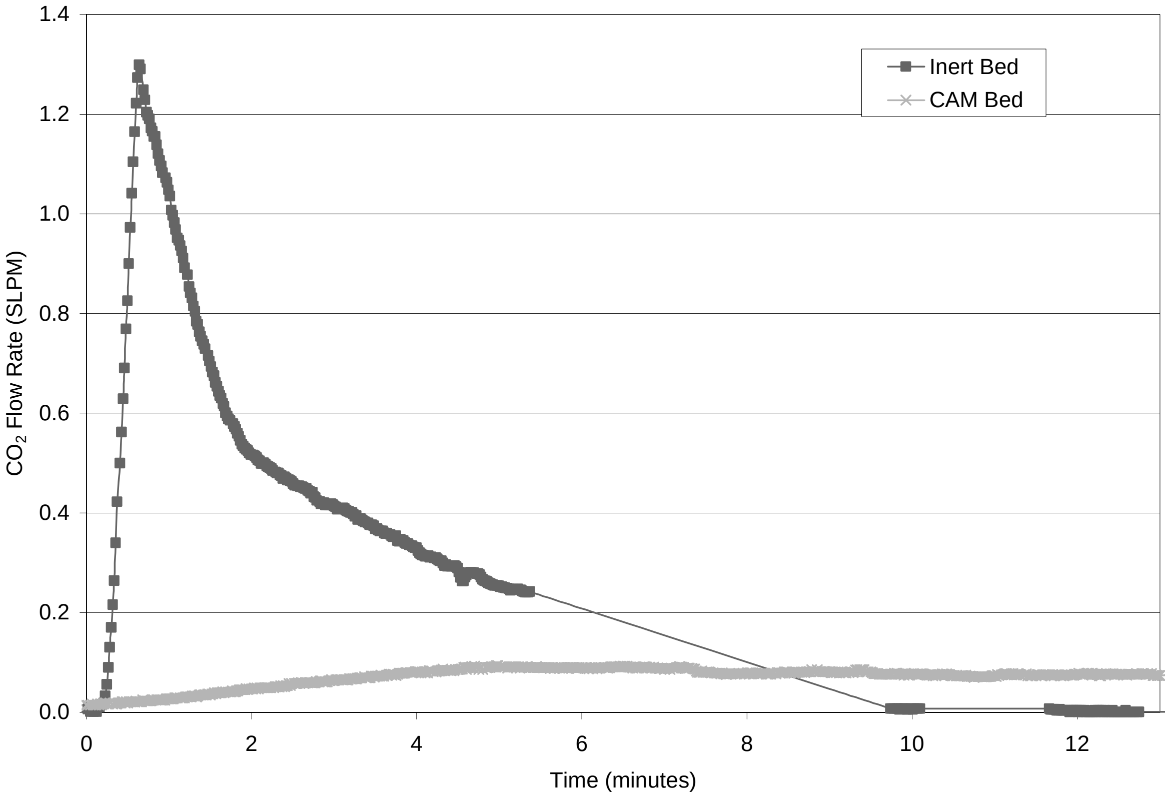


Figure 5. CO_2 concentration in gasification product gas for tests conducted with inert bed and CAM (CO_2-absorbing material) bed.

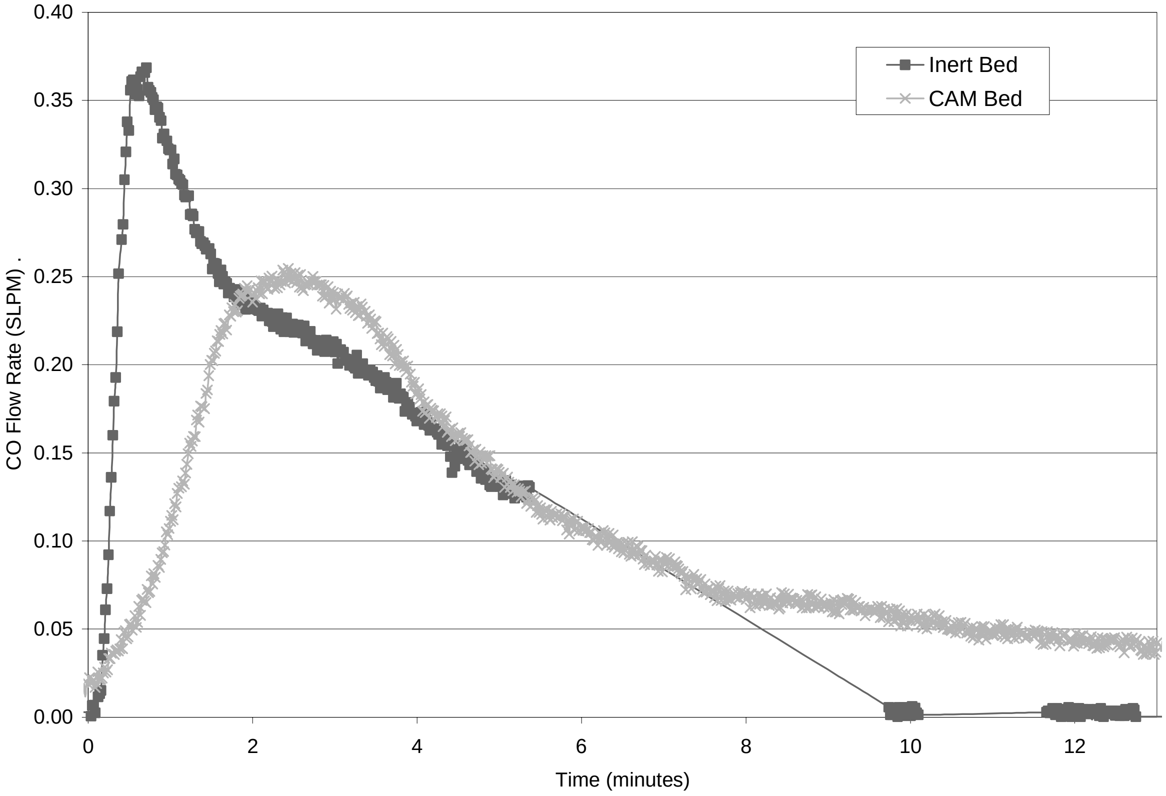


Figure 6. CO concentration in gasification product gas for tests conducted with inert bed and CAM (CO_2-absorbing material) bed.

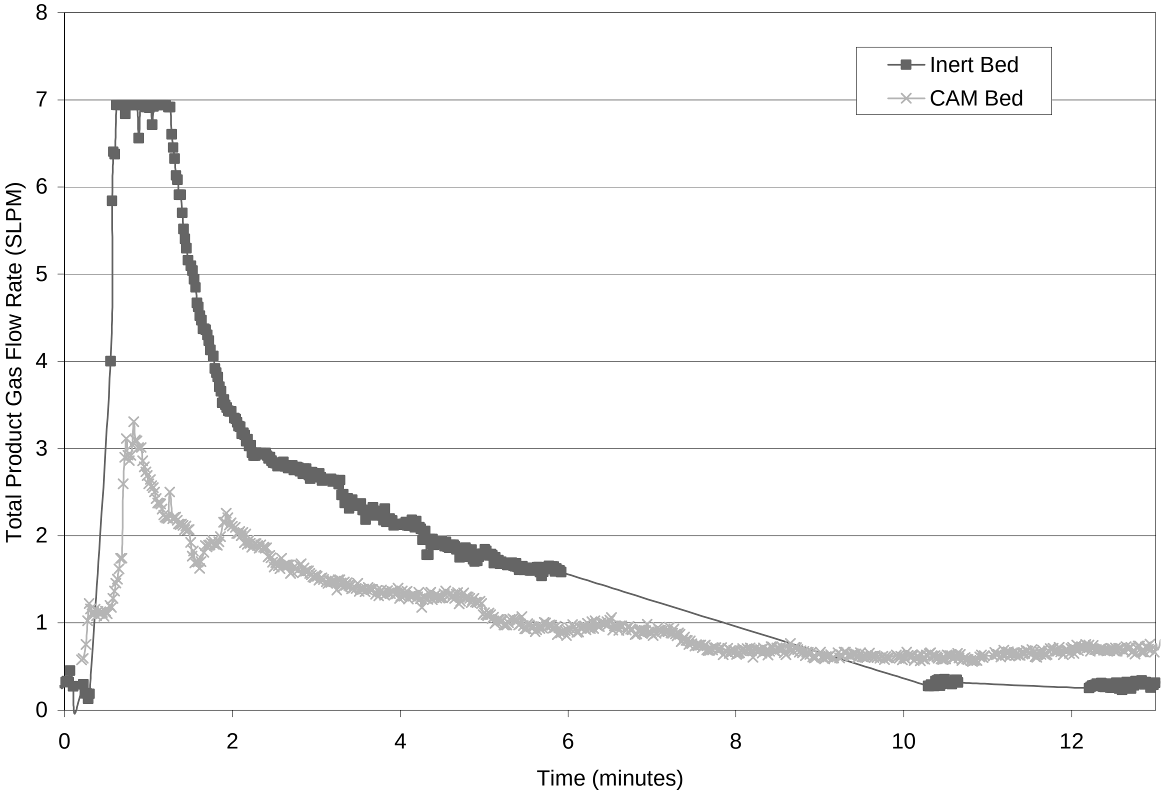


Figure 7. Product gas flow rate during gasification for tests conducted with inert bed and CAM (CO_2-absorbing material) bed.

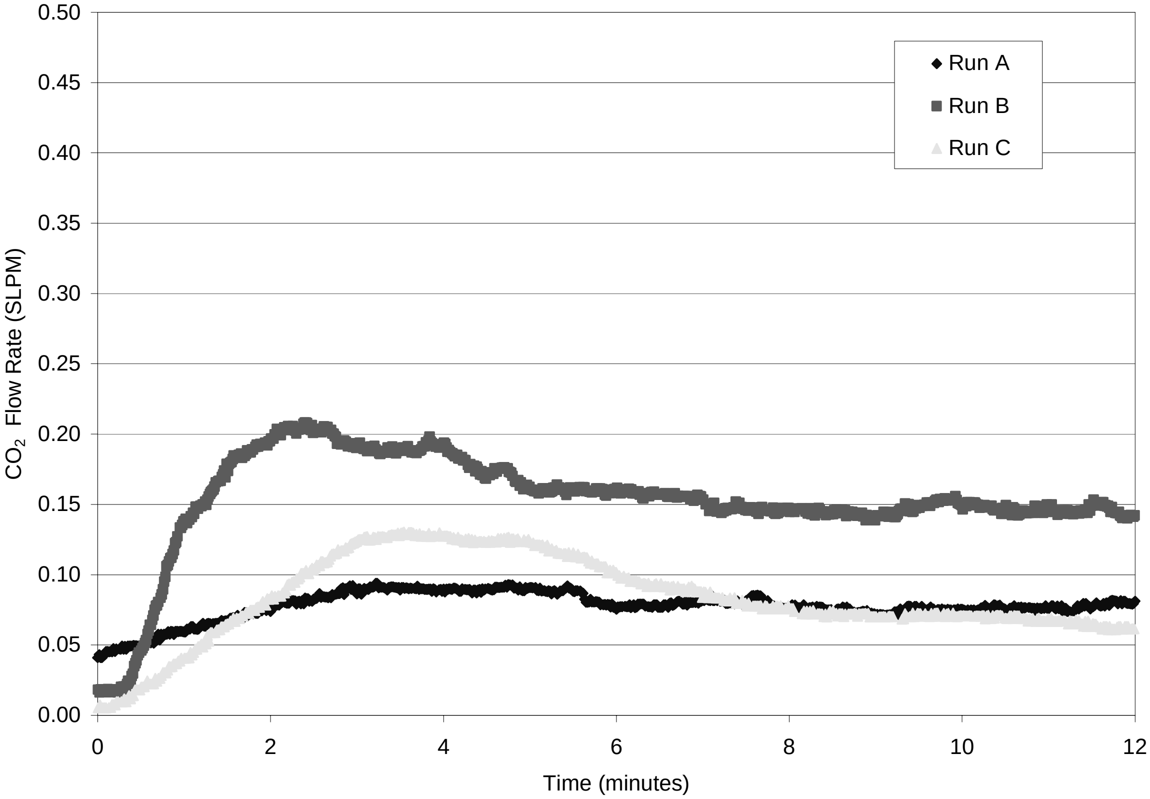


Figure 8. CO_2 measurements during coal gasification with a CAM (CO_2-absorbing material) bed for three different test runs.

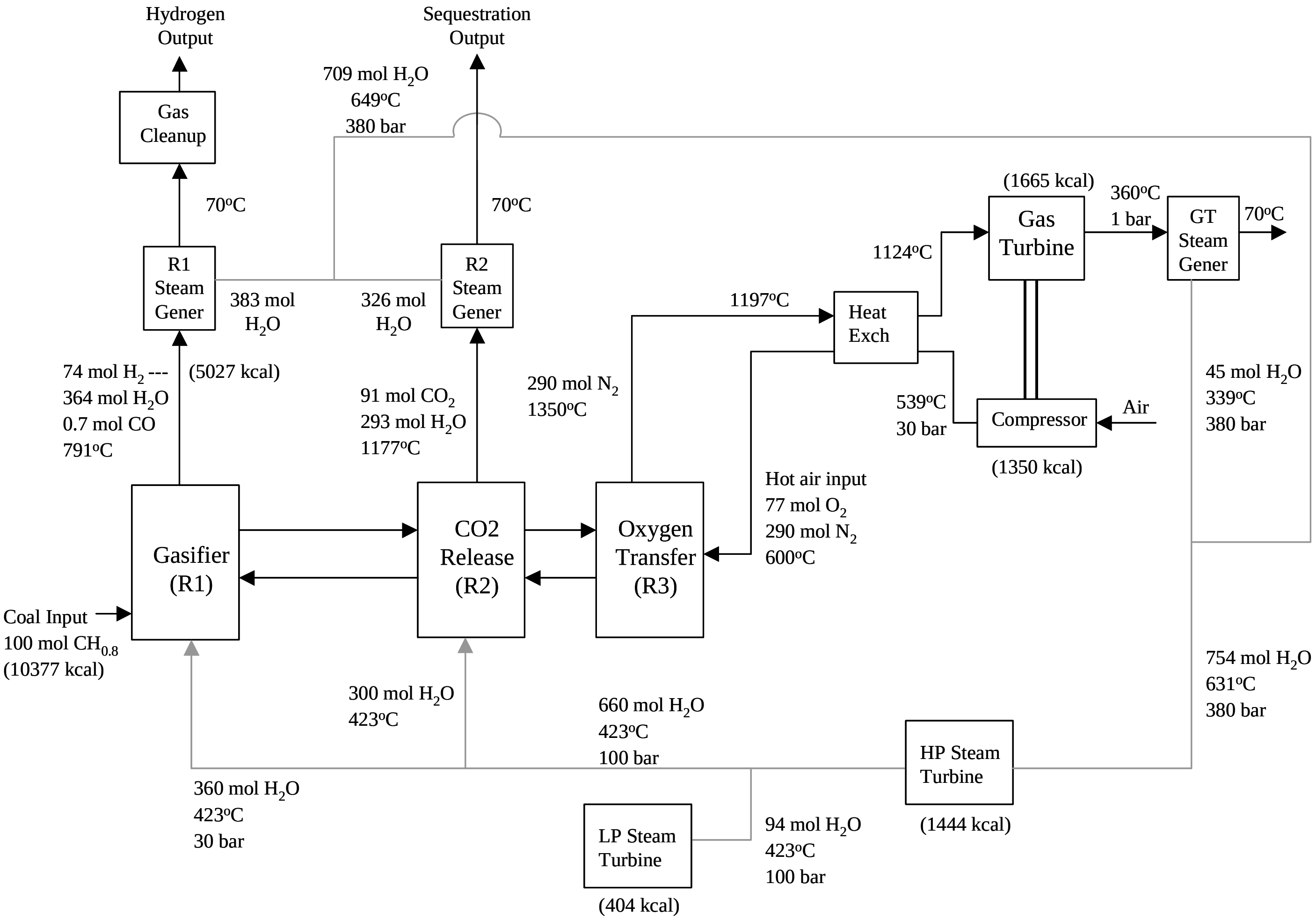


Figure 9. AGC baseline case process heat and mass balance.

APPENDIX A

Template for preliminary estimate of dimensions and critical operating parameters in Reactor 1 of the AGC pilot-scale unit.

DESIGN SPREADSHEET FOR THE FLUIDIZED GASIFICATION REACTOR, PILOT-SCALE

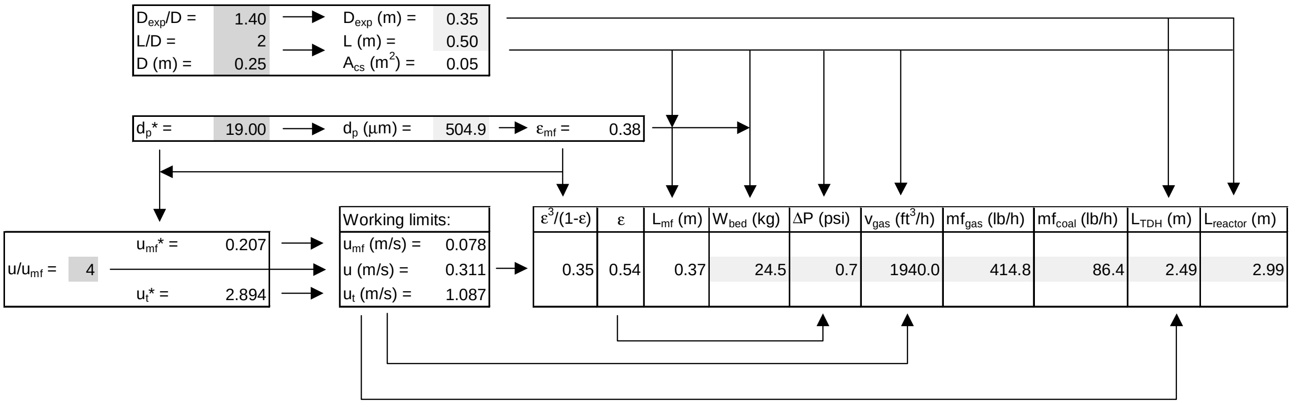
Operating regime, according to Kunii, D. and Levenspiel, O., Chem.Eng.Sci. 52(15), pp.2471-2482 (1997).
Contact model in the region of Bubbling Fluidized Bed, i.e. between the curves of minimum fluidization and terminal velocities.

=> non-dimensional particle diameter, d_p* : (recommended for bubbling fluidization)	LSL =	1
	HSL =	20
=> non-dimensional linear velocity, u* :	LSL =	u_{mf}*
	HSL =	u_t*

Operating pressure, P (MPa) =	2
Operating temperature, T (K) =	1073

Solid properties:	ρ_s (kg/m^3) =	2200	Fluid properties:	ρ_g (kg/m^3) =	4.0528
	ϕ_s =	0.6		μ (μPa.s) =	40.4587
				MW_g (g/mol) =	18
Process data:	H_2O/C =	4			
	MW_{coal} (g/mol) =	15			
Other parameters:	g (m/s^2) =	9.8			
	R (J/mol.K) =	8.315			

☐ **This is your input data**



D_{exp}/D =	1.40	D_{exp} (m) =	0.35
L/D =	2	L (m) =	0.50
D (m) =	0.25	A_{cs} (m^2) =	0.05

d_p* = 19.00 → d_p (μm) = 504.9 → ε_{mf} = 0.38

	u_{mf}* =	0.207
u/u_{mf} = 4		
	u_t* =	2.894

Working limits:	
u_{mf} (m/s) =	0.078
u (m/s) =	0.311
u_t (m/s) =	1.087

$\varepsilon^3/(1-\varepsilon)$	ε	L_{mf} (m)	W_{bed} (kg)	ΔP (psi)	v_{gas} (ft^3/h)	mf_{gas} (lb/h)	mf_{coal} (lb/h)	L_{TDH} (m)	$L_{reactor}$ (m)
0.35	0.54	0.37	24.5	0.7	1940.0	414.8	86.4	2.49	2.99

▨ **This is your input data**

☐ **This is your critical output data**