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A NOVEL APPROACH FOR "CLEAN" POWER GENERATION USING COAL LIQUIDS AND THE LPP COMBUSTION PROCESS IN AN INTEGRATED GASIFICATION COMBINED CYCLE (IGCC) SYSTEM

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Abstract

The Integrated Gasification Combined Cycle (IGCC) technology, as currently defined, couples a complex coal gasification process plant with a syngas-fired combustion turbine combined cycle power plant. The IGCC process is a two-stage combustion operation with cleanup between the stages. The first stage employs a gasifier where partial oxidation of the coal (or other carbon-based feedstock) occurs. The second stage utilizes the gas turbine combustor to complete the combustion with the gas turbine/combined cycle (GT/CC) technology.

Due to the impracticality of storing significant quantities of the coal syngas, it is necessary to ensure that the combustion turbine remains operational whenever the gasification plant is in operation. The shutdown of the combustion turbine requires immediate shutdown of the gasification plant, or the combustion of the syngas in a flare. In addition, it is difficult to operate the gasification plant at part load; hence it is necessary to run the combustion turbine in a base load configuration. These are significant operating limitations.

The process described herein proposes to combine the gas-to-liquid technology (GTL), e.g. Fischer-Tropsch synthesis or similar, and the Lean, Premixed and Prevaporized (LPP) combustion technology with the coal gasification technology to create a much more robust power generation system. The GTL process is a method whereby syngas is transformed into one or more forms of liquid fuel. These liquids (generically referred to as coal liquids or F-T liquids) can include diesel fuel, kerosene and naphtha, among others.

The conversion of syngas to liquids is a well-known process and has been utilized for many years. The LPP process transforms a wide variety of liquid fuels into a synthetic natural gas (or LPP Gas™) which may be burned in conventional natural gas dry low emissions combustion hardware, precluding the use of water or steam to achieve natural gas level criteria pollutants (NOx, CO, SO_2 and PM) emissions levels, and hence the penalties discussed above are avoided.

By combining the LPP combustion technology with the GTL process, IGCC operation is made much more flexible, dependable, and the overall economics is improved.

Introduction

Developed well over twenty years ago, the Integrated Gasification Combined Cycle (IGCC) technology has long been recognized as an efficient and clean method of converting coal (or other carbon-based feedstock) into electricity, process heat, high-value fuels and other chemicals. Several IGCC plants are now operating commercially in the United States and around the world.

Widespread adoption of coal gasification and the IGCC technology have been hindered by overall plant economics, and by the inherent complexity associated with building and operating such facilities.

The gasifier in a commercial IGCC plant is a very large device which generates syngas at high temperature and pressure (approx. 400 psia and 2600 F), and the gasifier has a large thermal mass. Hence, it is desirable operate the plant at a stable base-load condition over a long period of time. Unfortunately, reduced demand for electrical power (at night and on weekends) leads to inefficient and less economical IGCC plant operation during these low-load time periods, due to decreased part-load performance of both the gasification block and the gas turbine power block.

A typical coal-based IGCC plant is shown diagrammatically in Figure 1 below. Coal is partially oxidized by oxygen (or air) at high pressure and temperature, and the resulting syngas stream is cooled, cleaned of impurities (and potentially CO_2) and burned in a combustion gas turbine.

As shown in Figure 1, gas turbine modifications are normally required to accommodate the increased volumetric flow rate for the syngas, which occurs because of the reduced heating value of the syngas (125-250 BTU/scf LHV) as compared to the heating value of natural gas (800-1,000 BTU/scf LHV). These custom hardware changes increase the gas turbine capital and maintenance costs.

As part of an overall effort to improve reliability, operability, and plant economics, a broad range of IGCC design and optimization studies have been conducted by the Electric Power Research Institute[1] (EPRI) and by the United States Department of Energy[2] (DOE), under the auspices of the *Vision 21* program[3,4].

Common to all of the above studies, and common to the existing commercial IGCC facilities, is the requirement that the combustion turbine be fueled by the syngas produced in the gasification block. This design constraint couples the operation of the gasification block and the gas turbine power block, due to the

[1] http://www.epri.com/portfolio/product.aspx?id=3415

[2] http://www.fossil.energy.gov/programs/powersystems/vision21/

[3] "Topical Report – Task 1 Topical Report, IGCC Plant Cost Optimization," Gasification Plant Cost and Performance Optimization, United States Department of Energy, National Energy Technology Laboratory, Contract No. DE-AC26-99FT40342, May 2002.

[4] "Topical Report – Task 2 Topical Report, IGCC Plant Cost Optimization," Gasification Plant Cost and Performance Optimization, United States Department of Energy, National Energy Technology Laboratory, Contract No. DE-AC26-99FT40342, September 2003.

impracticality of storing large quantities of syngas, and decreases the overall plant availability and reliability. Practical considerations of a large power generation facility, such as load following and part load operation, become much more difficult with the added complexity and operational requirements of the gasification plant.

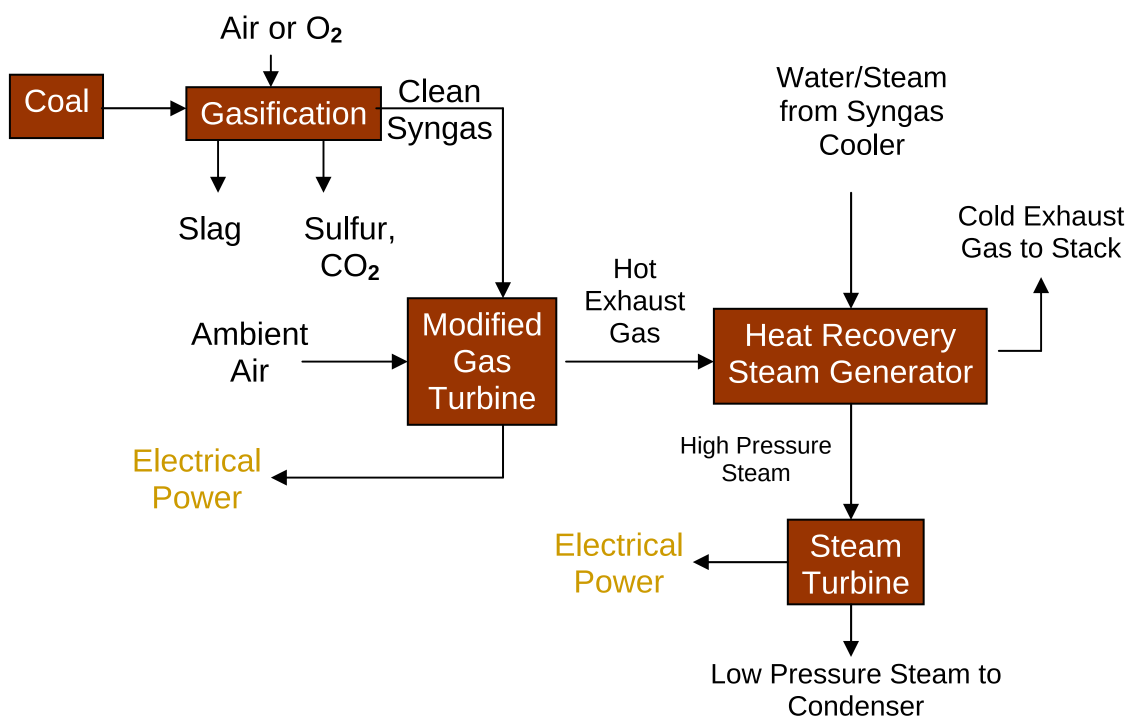

Figure 1: Simplified Typical Coal-based IGCC Plant Process Flow Diagram

IGCC Plant Performance Enhancement Using the LPP Technology

The process described herein proposes to combine the gas-to-liquid technology (GTL), e.g. Fischer-Tropsch synthesis or similar, and the Lean, Premixed Prevaporized (LPP) combustion technology with the coal gasification technology to create a much more robust power generation and co-production system. This combination would burn the coal-derived liquids using the same sophisticated combustor hardware used today that has dramatically lowered the pollutant emission levels from natural gas power plants over the last 20 years. The emissions using the coal-derived fuels would be similar to those of natural gas.

The GTL process is a method whereby syngas is transformed into one or more forms of liquid fuel. These liquid fuels, known generically as coal liquids or F-T liquids, may include diesel fuel, kerosene and naphtha, among others. The conversion of syngas to liquids is a proven technology that has been in commercial use around the world for many years[5,6,7]. The recently invented LPP process transforms a wide variety of liquid fuels into a vaporized fuel stream (or LPP Gas™) which may be burned in conventional, natural gas, dry low emissions combustion hardware, precluding the use of water or steam to achieve low criteria pollutant (NOx, CO and PM) emissions levels, and hence the penalties discussed above are avoided.

By combining the LPP combustion technology with the GTL process, IGCC operation is made much more flexible, dependable, and the overall economics is improved.

LPP Technology Overview

Traditionally, spray diffusion combustors have been employed in gas turbines that operate on liquid fuels such as fuel oil #1 and fuel oil #2. However, this diffusion mode of operation tends to produce unacceptable levels of NOx emissions. The current technology for burning liquid fuels in gas turbines is to use water and/or steam injection with conventional diffusion burners. Emissions levels for a typical "state of the art" gas turbine, such as a GE 7FA burning fuel oil #2 in diffusion mode with water/steam injection, are 42 ppm NOx and 20 ppm CO[8]. Water/steam injection has a dilution and cooling effect, lowering the combustion temperature and thus lowering NOx emissions. But at the same time, water/steam injection is likely to increase CO emissions as a result of local quenching effects. Thus, the "wet" diffusion type of combustion system for liquid fuels must trade off NOx emissions for CO emissions.

In recent years, stringent emissions standards have made lean, premixed combustion more desirable in power generation and industrial applications than ever before, since this combustion mode provides low NOx and low CO emissions without water addition. Lean, premixed combustion of natural gas avoids the problems associated with diffusion combustion and water addition. Thus, lean, premixed combustion is the foundation for modern Dry Low Emissions (DLE) gas turbine combustion systems. When operated on natural gas, DLE combustion systems provide NOx and CO emissions of 25 ppm or less with no water addition. However, these systems cannot currently operate in premixed mode on liquid fuels because of autoignition and flashback within the premixing section.

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[5] "Topical Report – Volume I, Process Design – Illinois No. 6 Coal Case with Conventional Refining", Baseline Design/Economics for Advanced Fischer-Tropsch Technology, U.S. Department of Energy, Contract Number DE-AC22-91PC90027, October, 1994.

[6] "Topical Report – Volume IV, Process Flowsheet (PFS) Models", Baseline Design/Economics for Advanced Fischer-Tropsch Technology, U.S. Department of Energy, Contract Number DE-AC22-91PC90027, October, 1994.

[7] "Topical Report VI – Natural Gas Fischer-Tropsch Case, Volume II, Plant Design and ASPEN Process Simulation Model", Baseline Design/Economics for Advanced Fischer-Tropsch Technology, U.S. Department of Energy, Contract Number DE-AC22-91PC90027, August, 1996.

[8] Davis, L. B. and Black, S. H., 2000, "Dry Low NOx Combustion Systems for GE Heavy-Duty Gas Turbines", GER 3568G.

Plee and Mellor[9] characterized autoignition of the fuel/air mixture in the premixer as an important factor that causes flashback in practical combustion devices. Autoignition of the fuel/air mixture occurs before the main combustion zone, when the ignition delay time of the fuel/air mixture is shorter than the mean residence time of the fuel in the premixer. Autoignition especially occurs with the higher-order hydrocarbon fuels, such as fuel oils, which have shorter ignition delay times compared to natural gas[10]. The short ignition delay times of vaporized higher hydrocarbons have proven difficult to overcome when burning in lean, premixed mode.

Nevertheless, in order to overcome high NOx levels produced by spray combustion, gas turbine designers still desire to use lean, premixed, prevaporized (LPP) combustion. Several approaches have been reported in the literature[11,12,13,14,15,16,17,18] to overcome flashback and autoignition in the premixers of LPP combustors. These approaches attempt to achieve low NOx emissions by designing premixers and combustors that permit rapid mixing and combustion before spontaneous ignition of the fuel can occur. In most of the work reported on LPP combustion systems in the literature, the fuel is sprayed directly into the premixer so that the liquid fuel droplets vaporize and mix with air at lean conditions. Typically, swirlers with multi-port liquid fuel injection systems are

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[9] Plee, S. L. and Mellor, A. M., 1978, "Review of Flashback Term Reported in Prevaporizing/Premixing Combustors", Combust. Flame, 32. pp. 193-203.

[10] Oumejjoud, K., Stuttaford, P., Jennings, S., Rizkalla, H., Henriquez, J., Chen, Y., 2005, "Emission, LBO and Combustion Characterization for Several Alternative Fuels", Proc. ASME Turbo Expo 2005, Paper# GT2005-68561.

[11] Maier, G. and Wiitig, S., 1999, "Fuel Preparation and Emission Characteristics of a Pressure Loaded LPP Combustor", 30th AMA Fluid Dynamics Conference, AIAA- 99-3774.

[12] Imamura, A., Yoshida, M., Kawano, M., Aruga, N., Nagata, Y. and Kawagishi, M., 2001, "Research and Development of a LPP Combustor with Swirling Flow for Low NOx", 37th Joint Propulsion Conference & Exhibit, AIAA-2001-3311.

[13] Ikezaki, T., Hosoi, J. and Hidemi, T., 2001, "The Performance of the Low NOx Aero Gas Turbine Combustor Under High Pressure", ASME paper 2001 -GT-0084.

[14] Lin, Y., Peng, Y. and Liu, G., 2004, "Investigation on NOx of a Low Emission Combustor Design with Multihole Premixer-Prevaporizer", Proc. ASME Turbo Expo 2004, Paper# GT2004- 53203.

[15] Lee, C., Chun, K. S., Locke and R. J., 1995, "Fuel-Air Mixing Effect on NO X Emissions for a Lean Premixed-Prevaporized Combustion System", 33rd AIAA Aerospace Sciences Meeting and Exhibit, Paper# AIAA-95-0729.

[16] Michou, Y., Chauveau, C., Gijkalp, I. and Carvalho, I. S., 1999, "Experimental Study of Lean Premixed and Prevaporized Turbulent Spray Combustion", 37th AIAA Aerospace Sciences Meeting and Exhibit, AIAA 99–0332.

[17] Hoffmann, S., Judith, H. and Holm, C., 1998, "Further Development of the Siemens LPP Hybrid Burner", ASME International Gas Turbine & Aeroengine Congress & Exhibition, ASME 98-GT-552.

[18] Mansour, A., Benjamin, M., Straub, D. L. and Richards, G. A., 2001, "Application of Macrolamination Technology to Lean, Premixed Combustion", ASME J. of Eng. Gas Turb. Power, 123, pp. 796–802.

employed for better fuel/air mixing[19]. However, unlike these attempts to alter hardware, there has been no reported work on altering fuel combustion characteristics in order to delay the onset of ignition in lean, premixed combustion systems.

In the present solution, vaporization of the liquid fuel in an inert environment has been shown to be a technically viable approach for LPP combustion. As described by Roby et al.[20], a fuel vaporization and conditioning process has been developed and tested[21] to achieve low emissions (NOx and CO) comparable to those of natural gas while operating on liquid fuels, without water or steam addition. In this approach, liquid fuel is vaporized in an inert environment to create a fuel vapor/inert gas mixture, LPP Gas™, with combustion properties similar to those of natural gas. Premature autoignition of the LPP Gas™ was controlled by the level of inert gas in the vaporization process. Tests conducted in both atmospheric and high pressure test rigs utilizing typical swirl-stabilized burners (designed for natural gas) found operation similar to that achieved when burning natural gas. Emissions levels were similar for both the LPP Gas™ fuels (fuel oil #1 and #2, Biodiesel and F-T synthetic JP-8) and natural gas, with any differences in NOx emissions ascribed to fuel-bound nitrogen present in the liquid fuel. Also, tests showed that the LPP combustion system helps to reduce the NOx emissions by facilitating stable combustion even at very lean conditions when using liquid fuels. Extended lean operation was observed for the liquid fuels due to the wider lean flammability range for these fuels compared with natural gas.

An added advantage of the fuel vaporization and conditioning process is the ability to switch between LPP Gas™ and natural gas 'on-the-fly' in the same combustor, without significantly affecting the flame stability.

Elevated pressure tests were conducted on a full temperature, full pressure combustor test stand capable of supplying combustor air at typical compressor discharge temperatures and pressures. During these high pressure gas turbine burner tests, the liquid fuel was supplied in gaseous form from the LPP liquid fuel vaporizer skid shown in Figure 2.

The testing involved a study of emissions and combustion characteristics, such as flame stability and lean blow-out limits. The tests were performed at typical compressor discharge temperatures. For the high pressure tests, typical compressor discharge pressures were also used. The same fuel nozzle used for

[19] Lin, Y., Peng, Y. and Liu, G., 2004, "Investigation on NOx of a Low Emission Combustor Design with Multihole Premixer-Prevaporizer", Proc. ASME Turbo Expo 2004, Paper# GT2004- 53203.

[20] Roby, R. J., Klassen, M. S. and C. F. Schemel, 2006, "System for Vaporization of Liquid Fuels for Combustion and Method of Use", U.S. Patent, #7,089,745 B2.

[21] P. Gokulakrishnan, M. J. Ramotowski, G. Gaines, C. Fuller, R. Joklik, L. D. Eskin, M. S. Klassen and R. J. Roby, "Experimental Study of NOx Formation in Lean, Premixed, Prevaporized Combustion of Fuel Oils at Elevated Pressures", Paper GT2007-27552, ASME/IGTI Turbo Expo, Montreal, Canada, May 2007.

natural gas testing was also used for liquid fuel testing on LPP Gas™ without any modifications.

Figure 2: LPP liquid fuel vaporizer skid used for gas turbine burner testing at elevated pressures.

Figure 3 shows NOx and CO emissions at full load conditions for both natural gas and fuel oil #2. During the testing, emissions and dynamics data were taken over a range of lean equivalence ratios from approximately 0.75 to the lean blow-off (LBO) limit. However, the emissions data is plotted against measured exhaust gas temperature in order to provide a common temperature reference. The lowest temperature data points shown in Figure 3 reflect the experimentally observed LBO limit. Figure 3 shows that fuel oil #2 LPP Gas™ has an extended LBO limit compared to natural gas and thus can achieve NOx emissions nearly as low as natural gas despite the fuel-bound nitrogen.

Figure 3 also shows that the crossover point between NOx and CO emissions extends to lower temperatures (and therefore lower equivalence ratios) for fuel oil #2 LPP Gas™ as compared to natural gas. As can be seen from the figure, fuel oil #2 LPP Gas™ showed increased flame stability and an extended LBO limit at lower temperatures (equivalence ratio) compared to natural gas. Figures 4 and 5 show similar results (in an atmospheric-pressure burner) for a variety of fuels, including a F-T derived jet fuel (S-8).

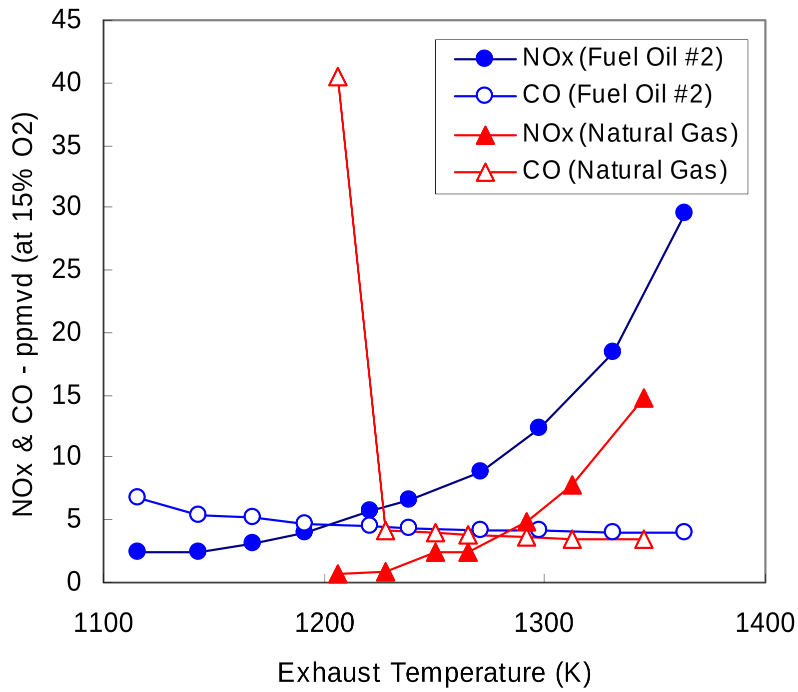

Figure 3: Comparison of NOx & CO emissions measurements for fuel oil #2 and natural gas as a function of measured exhaust gas temperature for a single fuel nozzle at Solar Turbines Taurus 60 full load conditions (100%). Combustion air temperature was 648 K, combustor pressure was 12.6 atm, and fuel dilution was 5:1 (molar basis).

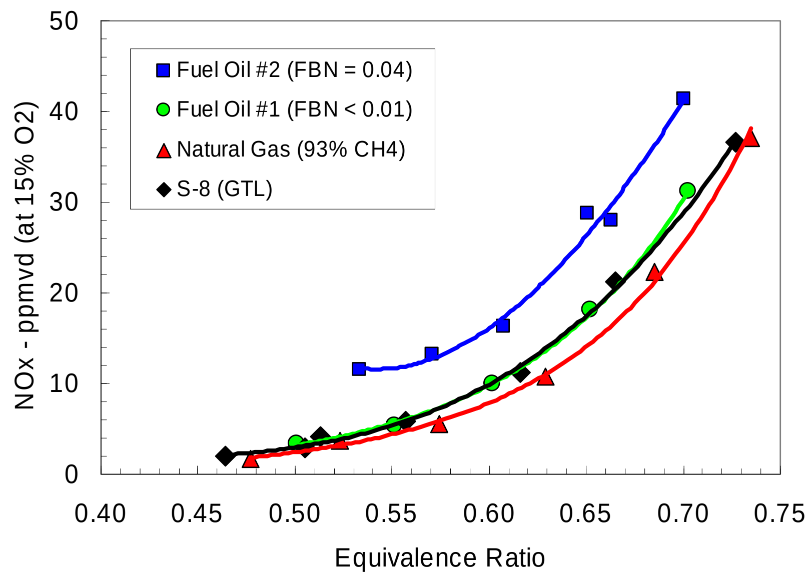

Figure 4: Comparison of NOx emissions measurements for fuel oil #2, fuel oil #1, synthetic JP-8 (S-8) and natural gas as a function of equivalence ratio for a single fuel nozzle at Centaur 50 full load conditions (100%). Combustion air temperature was 627 K, combustor pressure was 1 atm, and fuel dilution was 5:1 (molar basis).

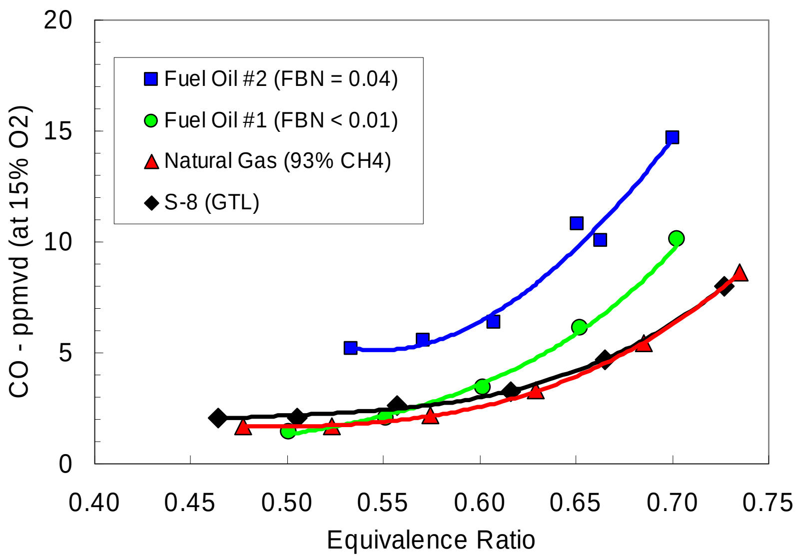

Figure 5: Comparison of CO emissions measurements for fuel oil #2, fuel oil #1, synthetic JP-8 (S-8) and natural gas as a function of measured exhaust gas temperature for a single fuel nozzle at Centaur 50 full load conditions (100%). Combustion air temperature was 627 K, combustor pressure was 1 atm, and fuel dilution was 5:1 (molar basis).

LPP/IGCC Integration Scenarios

Integration of the LPP and IGCC technologies can take place through several potential scenarios, as described below.

In Scenario #1 (shown in Figure 6), it is proposed to enhance the coal gasification portion of the IGCC process plant with a GTL process plant to transform the coal syngas into coal liquids. These coal liquids could then be readily stored in tanks, for use as necessary. In this scenario, it is further proposed to replace the syngas-fired combustion turbine used in a typical IGCC design with a conventional natural-gas fired combustion turbine, combined with an LPP skid to transform the coal liquid fuels into LPP Gas™ which will be burned by the conventional dry low emissions combustion turbine.

By creating coal liquids, the gasification block would no longer require continuous operation of the combustion turbine, and the gasification block could maintain full base load operation, regardless of the power generated by the power block. If the combustion turbine load is reduced or removed altogether, the excess coal liquids produced would be stored as necessary in nearby tanks, or would be distributed via pipeline, truck or train. This configuration provides the widest load-following capability for the power block, with no minimum power generation requirement.

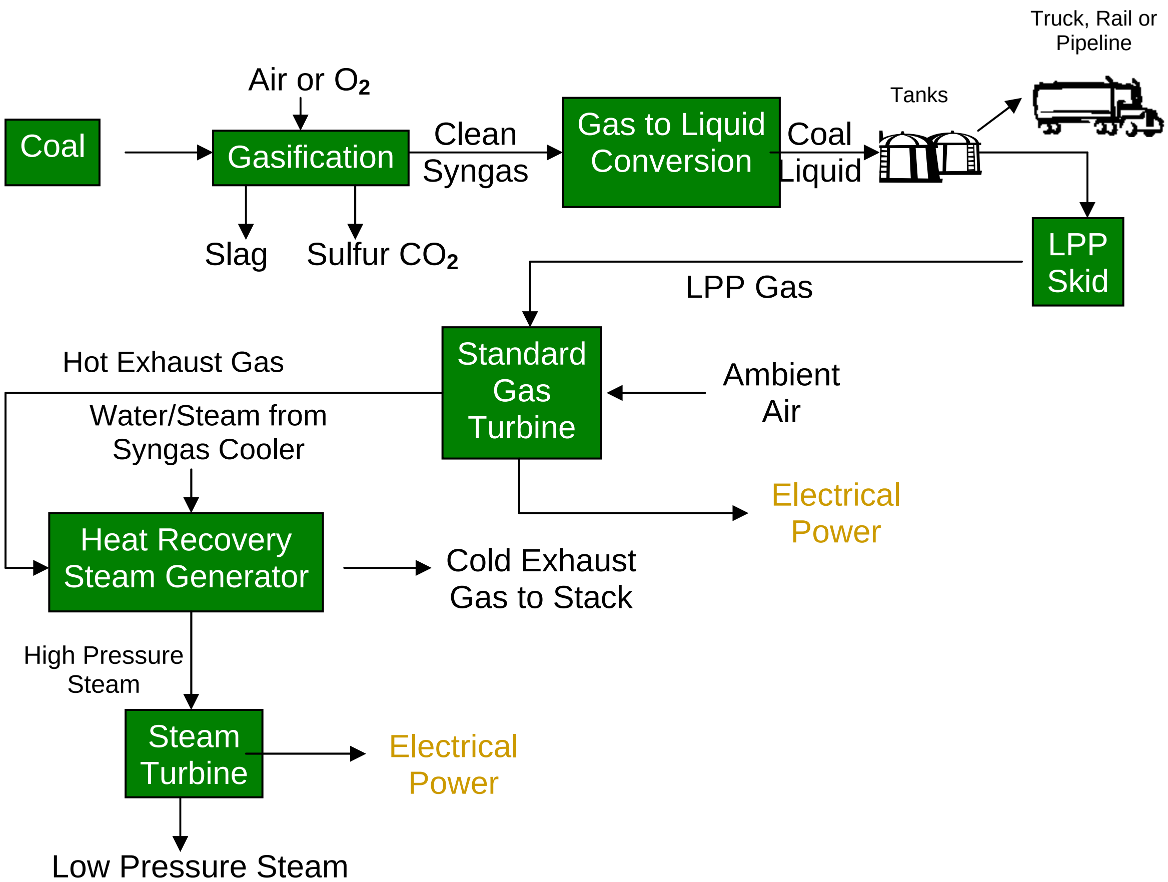

Figure 6: Scenario #1: Integrated LPP Gas™ IGCC Plant

In Scenario #2 (shown in Figure 7), the coal gasification portion of the IGCC process plant is enhanced with a GTL process plant to transform a portion (but not all) of the coal syngas into coal liquids. The syngas stream that was not converted to liquid would be burned in one or more syngas-fired combustion turbines, sized for base load operation during low plant load conditions (at night, etc.). The coal liquids would be consumed by standard combustion turbine hardware burning LPP Gas™, which would operate in "peaking mode" as necessary, and would allow the overall plant to respond to electrical load changes without having to change the rate of production of the syngas.

In Scenario #3 (shown in Figure 8), it is proposed to completely decouple the gasification/GTL plant and the power plant. The coal liquids would be produced at the gasification/GTL plant and would be shipped to stand-alone combustion turbines that are equipped with the LPP technology. This would provide the added benefit of allowing the gasification/GTL plant to be sited at any location, including a location in close proximity to the coal (or other feedstock) source. A site within close proximity to the coal source would reduce the transportation cost for the coal, and would facilitate disposal of the slag waste product resulting from the gasification plant.

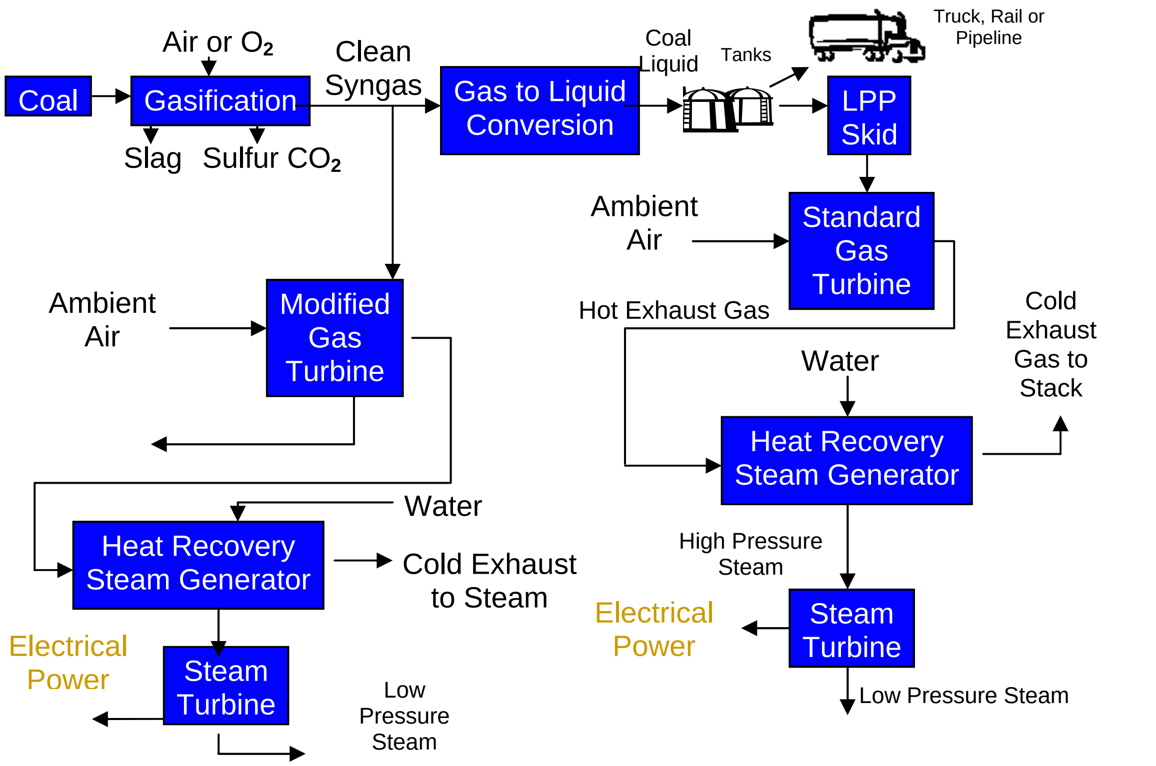

Figure 7: Scenario #2: Integrated LPP Gas™/Syngas IGCC Plant

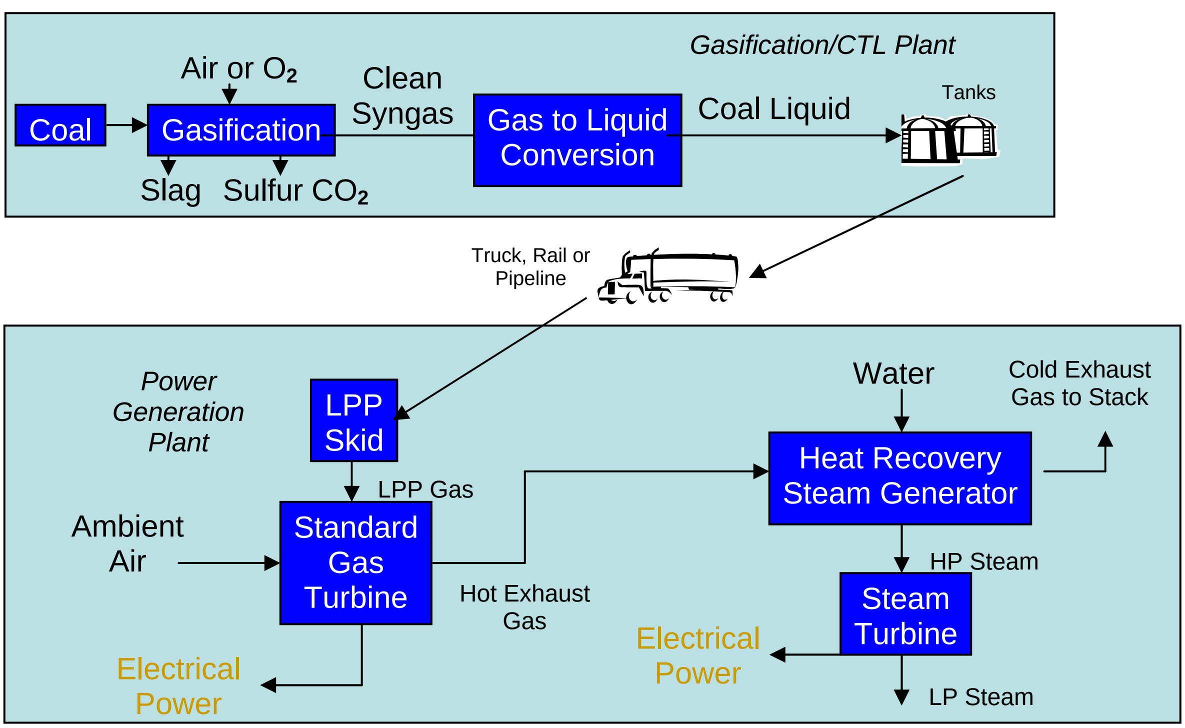

Figure 8: Scenario #3: Non-Integrated LPP Gas™ IGCC Plant

Additional Benefits and Synergies of the LPP/IGCC Integration

The combination of the coal gasification process with the LPP process also offers the following advantages, in addition to those described above:

1. *Beneficial use of waste Nitrogen (N2) produced by the air separation unit portion of the coal gasification plant:* Most coal gasifiers use nearly pure oxygen (O2) to partially oxidize the coal and create coal syngas. This oxygen is produced by an air separation unit (ASU) that separates the oxygen and nitrogen from ambient air. The nitrogen produced by the ASU is considered to be a waste product stream, and is injected into the clean syngas burned by the combustion turbine in an attempt to reduce NOx emissions by the combustion turbine. However, nitrogen gas can be used by the LPP process to create the LPP Gas™. Hence, by using the waste nitrogen already available from the ASU, the energy requirements of the LPP process are substantially reduced. Note that the low NOx combustion hardware present in natural gas combustion turbines does not require the use of supplemental nitrogen as is the case for syngas combustion hardware.

2. *Significant improvement in the IGCC value proposition may be realized by using sidestream products (such as naphtha) as a feedstock for the LPP process, in place of the higher value coal liquid product streams such as kerosene or diesel fuel:* Naphtha comprises sizable portion (approximately 30-45%) of the total output stream of a Fischer-Tropsch based coal liquids plant. Unsuitable for use as a transportation fuel, the monetary value of naphtha is expected to significantly decline as commercial production of coal liquids increases in the future. Since naphtha represents a very good feedstock for the LPP process, the LPP technology will be able to convert the low value liquid stream into a high value LPP Gas™ stream, significantly improving overall plant economics.

3. *It may be possible to significantly reduce the plant capital cost if a spare gasifier is not needed for the coal gasification plant:* As noted, the gasifier hardware portion of a coal gasification plant operates at a very high temperature and pressure. It has been found that the reliability of the gasifier hardware is such that traditional IGCC plant economics may require that a spare gasifier be built as a "hot standby" in case the primary gasifier fails or requires maintenance. The standby gasifier is needed because 1) there is a long lead time required to repair a gasifier, and 2) the syngas produced cannot be stored for use while the gasifier is being repaired. The gasifier hardware can cost tens or hundreds of millions of dollars in a typical IGCC plant. In the event of a gasifier failure, the integrated LPP/IGCC plant could continue to produce electricity by converting the stored coal liquid to LPP Gas™ and burning it in the gas turbine at the plant.

4. *Ownership and operation of the CTL and power blocks may be separated:* One of the operational issues of concern to IGCC plant owners is the fact that the coal gasification process is a complex chemical process for which the power industry does not have extensive experience. Scenarios #1 and #3 decouple the coal gasification/CTL plant from the power generation plant. This would allow, for example, a process plant company to own and operate the gasification/CTL plant, while a utility or independent power producer would operate a standard combustion turbine plant, along with the LPP skid.

Summary and Conclusions

The flexibility and economics of an IGCC plant can be considerably improved with the introduction of a novel technology for cleanly burning coal-derived liquids as part of the plant configuration. An enhanced IGCC plant configuration had been proposed, which integrates the novel LPP technology with traditional gasification technology. The combined LPP/IGCC concept overcomes several notable challenges associated with the operation and profitability of existing Integrated Gasification Combined Cycle facilities.

The LPP technology allows for the clean combustion of coal-derived liquids, producing pollutant levels similar to those currently achievable only with natural gas. By extending the IGCC plant to include a CTL process, the resulting plant has much more flexibility to handle turn-down due to reduced power demand. The resulting coal liquids are more readily stored than syngas, allowing the coal gasification block to continue to operate at design capacity even when the power production needs are reduced. The LPP technology also allows for the decoupling of the gasification and power plants, allowing the gasification to take place at locations that may be more advantageous from an economic or environmental point of view. Numerous other benefits include use of waste nitrogen for the LPP process, use of sidestream products such as naphtha as a feedstock for the LPP process and elimination of the need for a spare gasifier.

It is anticipated that these enhanced configurations will significantly advance the acceptance and implementation of the IGCC concept in the future.