

Carbon emissions puts focus on oxy cycle with “built-in” CO₂ capture

By Harry Jaeger

Oxy-fuel combustion, along with its array of advanced-design turbo machinery, takes aim at a truly innovative approach to coal-based power generation with near-zero emissions.

Restructuring of the US DOE FutureGen project and its expected refocusing to tackle carbon emissions from current state-of-the-art IGCC plants is placing new emphasis on alternative advanced technologies aimed at coal-based power plants of the future.

One of those technologies is an oxy-fuel gas generator and associated ultra-high temperature turbines which will permit “near-zero emissions” power generation:

Efficiency. Goal is operate at around 40% net overall HHV efficiency including fuel processing and full carbon dioxide removal.

Emissions. Ultra-low NO_x and CO emissions with over 99% carbon dioxide capture integrated into the power cycle for sequestration.

Fuel. Flexibility to operate on syngas made from coal, refinery residues and biomass as well as oil, natural gas or liquefied natural gas.

Design studies to develop enabling technologies are being carried out as a collaborative effort by Clean Energy Systems, Inc (CES), developer of the oxy-fuel gas generator, and Siemens Energy under the DOE Office of Fossil Energy’s ‘Advanced Turbines’ program.

This work parallels hydrogen gas turbine work for advanced IGCC plants with pre-combustion carbon capture. Quite recently, DOE launched a comparative technical and economic assessment study to evaluate the relative merits of IGCC versus oxy-fuel

for future development.

Separate R&D projects under the DOE clean coal program to develop external parts of an advanced gasification-based oxy-fuel plant include advanced gasification technologies, warm gas cleanup, ion transport membrane air separation -- all of which will directly benefit advanced IGCC plants as well.

Rivalry is healthy

Rivalry between these alternative technologies for zero-emissions coal power is healthy, says a DOE spokesman: “This way we are able to take a good look at advanced systems for both pre-combustion carbon dioxide capture (IGCC) and post-combustion capture (oxy-fuel), and we may find that there is a future for both of them.”

The key to success for the oxy-

fuel program will be the scale-up of the CES gas generator and development of enabling turbine technologies for achieving high thermal cycle efficiency, says Keith Pronske, CEO, president and co-founder of CES.

Unlike oxy-fuel boiler and pulverized coal cycle plants, where oxygen is blended with CO₂ to replace air in a conventional boiler, the CES approach is to combust a hydrocarbon fuel in oxygen at high pressure and stoichiometric conditions in a gas generator that produces a working fluid consisting of steam and carbon dioxide.

Recycled water is added downstream of the combustion zone to moderate the temperature of the working fluid. The result is a high pressure, high temperature drive gas, typically consisting of about 85% steam and 15% carbon dioxide (for natural gas fuel).



Kimberlina oxy-fuel power plant. Testing at Kimberlina this year will be conducted at up to 40% full load for “factory acceptance” of the first operational gas generator coupled to a modified turbine. After the completion of tests this summer, the equipment will be moved to a permanent location for installation in a 50 MW plant.

Key to high efficiency

The key to high efficiency is the ability to use this steam and CO₂ mixture at 3000°F temperatures or higher, similar to advanced gas turbine technology, rather than adding more water to reduce the temperature to a range acceptable by conventional steam turbines.

The goal is to achieve a net HHV efficiency of around 40% including the "power cost" for fuel processing, oxygen, and with full carbon dioxide removal. According to NETL study results (see GTW Jul-Aug 2007) this compares with about 32% for current technology coal-based IGCC plants with 90% carbon dioxide capture.

Future IGCC plants incorporating advanced hydrogen gas turbines and other plant improvements are expected to add another 3 to 5 percentage points. So the incentive for the development of oxy-fuel combustion would appear to be on the order of 3-5 percentage points in efficiency over advanced IGCC technology.

Next generation oxy-fuel cycle design studies incorporate an oxy-fuel reheater as a second stage of combustion to improve efficiency. Envisioned for the long term is a gas-turbine-like IP turbine operating at inlet temperatures on the order of 3200°F.

First generation demo

Initial "proof of principle" lab-scale testing by CES was supported mainly by the California Energy Commission during 1999-2000.

Continued interest on the part of CEC and DOE resulted in the successful fabrication and testing, during 2005-2006, of a 20 MWt natural-gas fired oxy-combustion unit (4-inch inside diameter) used to drive a 5 MWe steam turbine.

CES reports that scale-up to a "first-generation" commercial size combustion unit design is now well underway. They have already completed design and fabrication of a 170 MWt oxy-fuel combustion system (12-inch inside diameter) to be commissioned during June of 2008 at the company's Kimberlina oxy-fuel test facility near Bakersfield, California.

Later this year, following initial testing of the gas generator on its own, the hardware will be integrated with a modified General Electric J79 aircraft engine to assemble the first oxy-fuel combustion gas turbine power generating module.

As described by CES in a joint paper with Siemens and Florida Turbine Technologies, Inc. to be presented in June at the Berlin ASME Turbo-Expo, this will be accomplished by using a modified commercial LMA-1500 aeroderivative power package based on the J79 engine. This unit is the product of Land and Marine Alternatives, Inc. of Fontana, California, which has a large inventory of these aero engines.

1960s technology

"The turbine makes a good fit with our 170 MWt gas generator," Pronske points out, "and even though J79

technology dates back to the 1960s, it will become the world's most 'advanced steam turbine' at temperatures in excess of 1400°F when driven by the oxy-fuel gas generator.

To adapt the J79 to oxy-fuel operation, the compressor and combustion sections of the engine will be removed. Another critical modification is a low-leakage shaft sealing arrangement that will be used to compensate for approximately 30,000 lbs of compressor forward thrust, say CES project engineers.

In operation, hot pressurized exhaust gases (at 1400°F and 168 psia) produced by the oxy-combustor will be ducted through a specially designed cast Inconel volute and turning-vane assembly to power the turbine.

The input fuel for the demonstration will be natural gas, and the drive gas mixture will be about 85% steam and 15% carbon dioxide.

Near-zero emissions oxy-fuel combustion technology

Oxy-fuel combustion involves the burning of fuel in pure oxygen rather than in air. It first became of serious interest during the pre-1980s era of cheap natural gas as a means of producing a concentrated stream of carbon dioxide for enhanced oil recovery injection.

When any hydrocarbon fuel, or, for that matter any combination of carbon and hydrogen (coal-derived syngas, for example) is burned in a pure oxygen atmosphere, the resulting products of combustion are essentially, pure water vapor and carbon dioxide – without the nitrogen component normally carried over when fuel is burned in air.

By condensing the water vapor out of the exhaust gases (for recycling in the system), the remaining exhaust gas stream is highly concentrated CO₂, which can be compressed and injected on site, or transported by pipeline, for sequestration.

In this way, over 99% of the carbon dioxide produced by combustion is captured in the exhaust. It leapfrogs all of the costly and energy intensive CO₂ absorption and solvent recovery processes that coal-based IGCC and PC power plants need for pre- and post-combustion carbon capture.

In the CES oxy-fuel combustion system, the process takes place at high pressure and temperature, much as it would in a rocket engine combustion chamber.

The exhaust energy from the combustor (or gas generator) is recovered by expansion through a series of turbo-expanders to drive an electric generator.

The combustion zone exit temperature is moderated to acceptable turbine inlet temperatures by injecting recycle water into the gas generator as a diluent. In this way, the final gas mixture is high in water vapor content (up to 90% by weight).

For the Kimberlina test program, the turbine will consist only of the 3-stage primary HP turbine running at reduced inlet pressure and about 40% of rated power output.

A double-suction centrifugal compressor, to be supplied by Concepts NREC of Woburn, Massachusetts will be attached to the primary turbine output flange as a power-absorbing air-brake/dynamometer.

Kimberlina test program

The J79 turbine will operate at design speed and temperatures, according to Vic Viterie, Fellow for Systems at CES, but at lower pressure levels. Rapid start and overspeed fault testing will be included in the demonstration test program to evaluate system control response capability in addition to startup, steady state and throttling tests.

In commercial operation, the main turbine would be followed by either

a single-stage 5500 rpm free turbine (exhaust turbine) driving an electric generator through a gearbox or by a pressurized HRSG to raise low pressure steam for a conventional steam turbine.

The HRSG and steam turbine configuration is planned for the recently announced WestCarb pilot demonstration project (see editorial box). In this application, the gas generator will operate at higher pressure and a high pressure turbine will be installed upstream of the modified J79 – much like a “second generation” plant concept under design study.

“For this initial demonstration, we selected rather conservative low-risk operating parameters relative to the original J79 firing temperature of 1700°F,” says CES.

“We wanted to take into account the effect of the steam-rich working fluid on gas turbine operating characteristics. It also greatly simplifies mat-

ters by eliminating the need for blade cooling.”

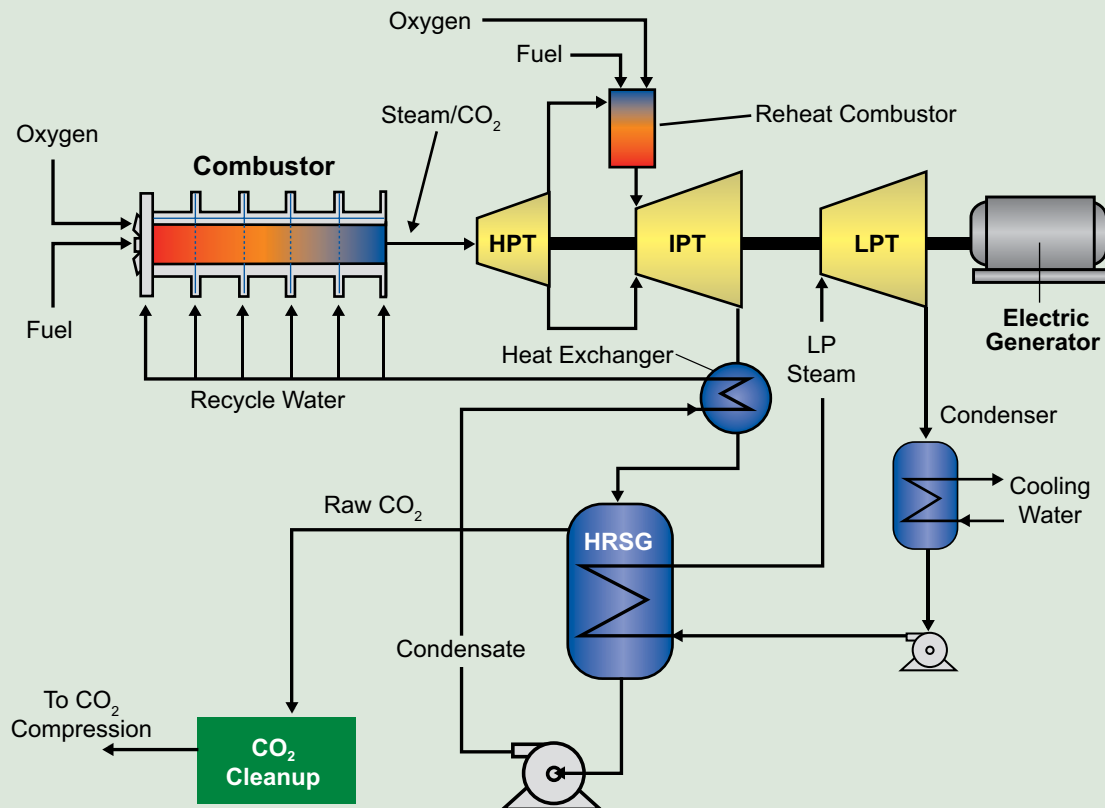
“For future applications we can move to higher temperatures to achieve higher plant efficiencies. We are also considering a design with multiple oxy-fuel combustors to replace the original cannular burners. This will allow us to operate the unit at up to 1700°F, approaching its original design inlet temperature as an air-breathing machine,” CES adds.

Significantly, the selected 1400°F turbine inlet temperature closely parallels that of advanced ultra-supercritical steam turbines, for which there are active design and materials development programs underway.

Second generation design

CES and Siemens are already looking well beyond the near-term first generation design, with an eye toward completing a competitive commercial-scale oxy-fuel plant design in the next

Second generation design. Project team is looking to complete a second generation commercial scale oxy-fuel plant design in the next 2-3 years based on this cycle arrangement, for construction in 2012-2013. Operation at higher pressures and temperatures relative to first generation plants will enhance power output and efficiency.



2-3 years for construction and commercialization in the 2012-13 time-frame.

“Primary objective of the second generation plant is to achieve improved performance by operating at higher pressure and temperature relative to the first generation plants,” say project engineers.

Proposed cycle and equipment arrangement for this plant (see block diagram) shows that the design incorporates both HP and IP oxy-fuel turbines.

This is followed by a conventional steam bottoming cycle to utilize the recoverable heat from the IP turbine exhaust.

The LP turbine operates on pure steam produced by the single-pressure HRSG, which operates at a low enough temperature that it can also serve to condense out the water vapor from the oxy-fuel working fluid.

While this water is collected for recycling to the oxy-fuel combustor, the condensing process acts to separate and deliver the raw CO₂ for cleanup and compression for pipeline transport to off-site sequestration.

High-pressure turbine output will be fed directly by the main oxy-fuel combustor where the exhaust temperature will be moderated by water and/or steam injection down to around 1000°F-1100°F.

The combustor pressure will be upwards of 100 atmospheres (about 1500 psia), and HP turbine pressure ratio about 5 to 1. These operating conditions are similar to those of current steam turbine HP steam turbines.

The IP turbine is located downstream of an oxy-fuel reheat combustor that raises the temperature of the HP turbine exhaust from about 650°F to a nominal 2150°F turbine inlet temperature.

Although considered modest relative to current state of the art gas turbine technology, this elevated inlet temperature level dictates that cooling be provided for the IP turbine airfoils. For this purpose, a portion of the HP exhaust flow is bypassed around the reheat combustor and fed to the turbine cooling circuits.



Oxy-fuel gas generator. Production unit is being readied for commissioning tests at the Kimberlina facility in preparation for the 50-MW WestCarb project installation. This oxy-fuel gas generator has a rated power level of 170 MWt on natural gas. It is about 100 inches long and 12 inches in diameter.

From rocket science to power generation

A group of California-based ex-rocket engineers formed Clean Energy Systems Inc. in the early 1990s to develop a new concept for burning clean fuel in oxygen and water to produce a mixture of clean steam and CO₂ at high temperatures and pressures to drive a high temperature turbine in an advanced power cycle. .

In 1999, CES was funded by the California Energy Commission to build a lab-scale combustor for proof-of-principle demonstration and test on mixtures of oxygen, methane and water at temperatures up to 2700°F and pressures up to 300 psia.

NETL awarded the company a development contract in late 2000 to build and test a 20 MWt combustor (oxy-fuel gas generator) tested in 2002-2003 at 600°F to 3000°F temperatures and 1100 to 1540 psia pressures over a load range of 20% to 100% rated output.

In 2005, again with CEC support, the oxy-fuel gas generator was coupled with a 5 MW steam turbine generator at the company's test facility in Kimberlina to supply up to 3 MW of export power to the grid.. During this time, the unit logged close to 300 starts and more than 1300 hours of operation.

Last September, CES announced near-term commercial applications for oxy-fuel gas generators to power 50-MW power projects in The Netherlands, Norway and Canada that will burn natural gas fuel.

Each plant is designed around an oxy-fuel gas generator operating at 500-750 psia to power an HP turbine which will exhaust into a pressurized HRSG to produce steam for expansion in a separate steam turbine generator.

In each case, captured carbon dioxide from the plant is to be used for either enhanced oil or gas recovery injection, which qualifies the European projects (at least) for substantial government agency financial support.

E-class IP turbine

In selecting a suitable existing design to serve as the IP turbine for the second generation oxy-fuel plant, the development team took a hard look at alternatives, taking into account such criteria as power rating and rated temperature and pressure conditions relative to the cycle conditions of interest.

“We were looking for a cooled turbine of around 100-150 MW rating (turbine only) and for which we would have plenty of technical data and design information available for necessary design work for the adaptation to the oxy-fuel cycle,” say project engineers.

After considering a number of candidate gas turbine models, including different manufacturers, sizes and mechanical arrangement (aero and heavy frame) the team selected a 50 MW class Siemens SGT-900 (formerly known as the W251B) which has a 3-stage turbine with a 5400-rpm output speed and two stages of cooling.

After removing the axial compressor (as would be the case for the oxy-fuel application) the turbine power output will be about 150 MWe when

operating at rated temperature and pressure.

Overall the nominal power output of this plant design, based on using this IP turbine and including the HP and LP turbines, would be 200 MW (net), with an LHV efficiency of 40% when using natural gas as the fuel.

This plant performance takes into account the air separation unit for the oxy-fuel combustors, power required for CO₂ capture, and the power needed for its compression to 2200 psia.

But it does not include the negative impact on efficiency that would be due to fuel processing such as gasification to provide coal- or petcoke-derived syngas for the main oxy-fuel combustor and reheater. Typically, this would mean a reduction of 4-6 percentage points in plant efficiency.

According to information presented at the ASME Turbo-Expo conference, this cycle is being analyzed at the full turbine inlet temperature of 2300°F, where it is expected that performance will improve considerably.

Adapting to oxy-fuel cycle

As in the case of the J79 turbine be-

ing used for the first generation oxy-fuel plant, adaptation of the SGT-900 for the second-generation plant will require that the turbine section operate without a functioning compressor section.

“We are evaluating a wide range of impacts and ramifications of the oxy-fuel cycle on the turbine design and materials, and there are a number of options,” say engineers working on the project.

For example, the compressor can be eliminated by removing the entire compressor section from the machine or by routing the HP turbine exhaust gases through the compressor flow path without airfoils.

In either case, they indicate that it will be necessary to provide some means of balancing the turbine rotor axial thrust load, which is normally offset by the compressor axial thrust. Options here include the use of a thrust piston or increasing the capacity of the existing thrust bearing.

Present configuration of the cycle is such that it will operate at pressure levels similar to those of the original gas turbine, so there is no impact in that regard. Also, a direct replacement of current can-type combustors with oxy-fuel combustors is being considered to minimize impact on gas turbine structural arrangement.

Gas composition impacts

Operating pressure and temperature conditions are similar. However, the substantial change in the working fluid composition will affect the aerodynamic and thermodynamic performance of the turbine and could have an impact on existing materials and coatings.

While products of combustion in a gas-fired gas turbine are heavily diluted with excess air, and thereby high in nitrogen content, oxy-fuel combustor products are diluted with steam and contain high levels of water vapor.

“The oxy-fuel working fluid will consist of 60-90% water vapor (by weight) depending on the fuel used and operating temperature,” say CES engineers, “the remainder is mostly carbon dioxide plus some residual ex-

Modified vs. Original J79 Operating Parameters. Original 1960s vintage J79 jet engine has been modified for oxy-fuel operation. To simplify plant design, the inlet temperature has been reduced to 1400°F (from 1700°F) to eliminate turbine cooling. For the Kimberlina tests, the inlet pressure also has been reduced to operate the turbine at about 40% of its rated output. Test configuration does not include an exhaust turbine.

Main Turbine (MT)	Modified J79 Design	Original J79 Design
Turbine inlet temp	760°C (1400°F)	927°C (1700°F)
Inlet pressure	11.59 bar (168 psia)	12.34 bar (179 psia)
Exhaust temperature	489°C (913°F)	636°C (1176°F)
Exhaust pressure	2.14 bar (31.0 psia)	2.28 bar (33.1 psia)
Mass flow per sec	62.6 kg (138 lb)	73.5 kg (162 lb)
Shaft speed	7460 rpm	7460 rpm
Shaft power	32,490 kW	32,500 kW
Exhaust Turbine (ET)	Modified J79 Design	Original J79 Design
Turbine inlet temp	489°C (913°F)	636°C (1176°F)
Inlet pressure	2.14 bar (31.0 psia)	2.28 bar (33.1 psia)
Exhaust temperature	401°C (754°F)	465°C (869°F)
Exhaust pressure	1.10 bar (16.0 psia)	1.07 bar (15.5 psia)
Mass flow per second	62.6 kg (138 lb)	73.5 kg (162 lb)
Shaft speed	5500 rpm	5500 rpm
Shaft power	10,854 kW	10,500 kW

cess oxygen.”

This change in gas composition from original gas turbine design values impacts on both expansion characteristics and heat transfer rates from the hot gases to the cooled turbine parts.

Most significantly, the specific heat of the steam/and carbon dioxide mixture is approximately 1.5 to 1.9 times that of typical gas turbine products of combustion. One result is a considerable increase in turbine exit temperature (by some 180°F) which may require modifying the last row turbine blade and exhaust casing, both of which are currently uncooled.

In addition, the molecular weight of the oxy-fuel combustion products is slightly lower, resulting in lower density. This means reduced mass flow capacity in a fixed geometry turbine with given inlet pressure and temperature. In spite of this, project engineers note, the overall effect of the higher specific heat of the gas mixture is a net increase of 15 to 20% in power output.

Aerodynamic factors

Another impact is evident from detailed row-by-row aerodynamic analysis, which indicates that the change in gas properties results in higher velocities and generally higher airfoil incidence angles than for the original design

Project engineers continue to evaluate the effect on airfoil efficiencies so they can determine whether a change in operating conditions is warranted for performance optimization on oxy-fuel gases.

Options include reducing inlet temperature and increasing rotor speed – in which case, however, their respective impacts on plant efficiency and power output must be considered. Adjustments to blade and vane manufacturing drawings are also an option.

With respect to turbine cooling, the higher thermal conductivity of the oxy-fuel gas mixture means higher convective heat transfer rates. Associated higher heat flux rates will cause steeper temperature gradients and higher thermally induced stresses in

the cooled parts. The impact of this on airfoil structural design must also be evaluated.

Another factor in the evaluation of the SGT-900 turbine for the oxy-fuel application is the impact of the change in gas composition on materials. Engineers report that the high water vapor and carbon dioxide content may introduce new corrosive effects. If so, the behavior of existing materials and thermal barrier coatings need to be studied in this environment.

There may be a need for some material substitutions and design application of oxidation and corrosion resistant coatings both on external and internal surfaces. To check this out, tests at Kimberlina will evaluate the impact on of oxy-fuel exhaust gases on different materials and coatings.

What does future hold?

GTW has learned that real potential exists for the first application of the 200-MW SGT-900 based oxy-fuel

plant concept to find a home in the UK, where an active competition is underway to select a post-combustion CO₂ capture technology for a government-supported demonstration.

A decision on that competition is expected in the next few months. In the meantime, Phase II work under the DOE program is supporting the intermediate-term technology developments needed to commercialize this second generation plant design.

They are also looking into what it will take to realize the ultimate potential of the oxy-fuel cycle. “Our ultimate goal is the advanced ‘third generation cycle’ with targeted IP turbine inlet temperature in excess of 3000°F,” says project leaders.

This calls for full-speed ahead to attack the full slate of technical challenges that lie ahead. But, under currently reduced levels of DOE funding, they are looking at commercial deployment of this plant in the 2017-2018 timeframe. ■

CES technology to anchor large-scale carbon capture and storage project

On May 8 the US DOE announced that it had selected Clean Energy Systems (CES) oxy-fuel zero-emissions power plant technology to supply carbon dioxide for a large-scale carbon capture and storage pilot project.

The project will be managed and executed by the California Energy Commission (CEC) under the oversight of the West Coast Regional Carbon Sequestration Partnership (WestCarb).

The CEC is to receive \$65.6 million in funding from DOE towards the estimated \$90.6 million cost of the geologic CO₂ storage pilot project. The balance of the funding will be provided by a group of project partners that includes Clean Energy Systems and the Commission.

CES and partners will build, own, and operate a nominal 50 MW gas-fueled plant with 100% carbon capture using technology already demonstrated at the company's Kimberlina test site where it is testing a 170 MWt gas generator that will also be used for the WestCarb project.

Entire exhaust stream of the 50 MW plant is to be injected for underground storage over a period of four years from 2011-2015. This should see the injection of one million tons of compressed CO₂ into subterranean storage formations 7,000 feet beneath the surface.

WestCarb is a collaborative research project bringing together dedicated scientists and engineers at 70 public agencies, private companies and non-profits to identify and validate the best regional opportunities for keeping CO₂ out of the atmosphere.