Recent Research and Various Techniques Available for Efficiency Improvement of IGCC Power Plants

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Abstract This paper mainly focuses on the various technological improvements that need to be made for the current-integrated gasification combined cycle (IGCC)-based power plants in the near future through which efficiency of above 50 % would be achievable. This paper also elaborates about the working and the parts of an IGCC-based power plant. A discussion on the premier technologies that make IGCC the foremost prominent and promising technology for power generation today and tomorrow has been done, such as the advanced turbine technology, hot-gas cleanup technology, and the efficiency enhancement of the process, while taking into account the various aspects of each of these. If all of these novel technologies are adopted, then not only this will make the process very efficient, but also will be a promising solution for the years to come.

Keywords IGCC · SGS and CO

1 Introduction to an IGCC Plant

In an integrated combustion combined cycle power plant, the heating and partial oxidation of coal is done, such as synthesis gas or syngas (primarily hydrogen and carbon monoxide) is produced, which is subjected to the mechanisms of cooling and cleaning and then it is fired in a gas turbine generator. Whatever exhaust gases are produced, they are led through a heat recovery steam generator (HRSG), which

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forms steam that is sent to a steam turbine generator. The Oxygen that is required for the gasifier section is produced in an air separation unit (ASU). And from both the gas and steam turbines, while working in a combined cycle, power is produced. Given above is the block schematic of an integrated gasification combined cycle (IGCC). And the description of the above has been given below, while illustrating the functions of all of the above.

Slurry Preparation Unit Initially, the feed material, slag and fines water, viscosity modifier, and grinding water are ground into slurry. Additional large particles are removed. Further slurry is heated in order to reduce the amount of fuel necessary for gasification of the coal. The slurry so produced is led to the gasifier.

Air Separation Unit The air feed to the ASU is supplied from a stand-alone main air compressor and supplemented by pressurized air extracted from the gas turbine. The air separation plant is designed to produce 95 mol.% O_2 for use in the gasifier and Claus Plants. Inside the distillation column, the air is separated into oxygen and nitrogen products.

Gasifiers The gasifier vessel is a refractory-lined, high-pressure reaction chamber. The coal slurry feedstock and oxygen are fed through a fuel injector at the top of the gasifier vessel. The coal slurry and the oxygen react in the gasifier at 5.6 MPa (815 psia) and approximately 1,316 °C (2,400 °F) to produce syngas.

Syngas Scrubbers The purpose of the syngas scrubbers is to clean the syngas by separating the solids and entrained liquids from the syngas. The syngas scrubber system also collects and recycles the quench water used in the gasifier quench ring and dip tube. In addition, it controls the level of chlorides and other contaminants in the scrubber water system by bleeding some of the water off to the vacuum flash system.

Shift Reactors The conversion of CO to CO_2 for this plant is achieved by sour gas shift (SGS), where the water–gas (CO–) shift reaction occurs prior to removal of the acid gas from the synthesis gas. The shift reactors also serve to hydrolyze COS, which eliminates the need for a separate COS hydrolysis reactor. They also decompose metal carbonyls, formic acid, and hydrogen cyanide.

Gas Cooling and MP and LP Steam Generation Syngas is sent to a two-stage heat exchanger, wherein the first stage of cooling lowers the temperature by 70 °F and in the second stage the temperature of the syngas is lowered by 115 °F. The syngas is further sent to a knockout drum to collect any remaining liquid.

Mercury Removal Syngas is now heated by 5 °F in a preheater to prevent condensation within the activated carbon beds, wherein the Mercury is removed, removal of which is necessarily important so as to avoid the corrosion of heat exchangers.

Selexol Acid Gas Removal The shifted raw syngas stream is sent to a removal chamber which removes the Hydrogen Sulfide (H_2S) and Carbon Dioxide (CO_2) which results in the formation of three product streams, namely clean syngas for the combustion turbine, H_2S rich acid gas for use in the Claus Plant, and CO_2 for sequestration. The Syngas is flashed off at high temperatures for CO_2 stripping. Further in order to remove the H_2S, reboiling and recirculation actions are used.

CO_2 Compression The compressor raises the pressure level of CO_2 to about 2200 psi during which it becomes a supercritical fluid. Also CO_2 is dried by mixing with Tri-ethylene Glycol, thereby minimizing the possibility of corrosion in the transport piping due to moisture being present.

Syngas Reheat and Expansion This stage involves the heating of a mixture of clean syngas from AGR system and clean gas from the CO_2 compression process to about 465 °F and then passing the above to an expansion turbine.

Claus Plant This stage involves the conversion of H_2S to elemental Sulphur using an exothermic reaction.

$$H_2S + 3/2O_2 \leftrightarrow H_2O + SO_2$$
$$2H_2S + SO_2 \leftrightarrow 2H_2O + 3S$$

The Claus reaction:

$$3H_2S + 3/2O_2 \leftrightarrow 3H_2O + 3S$$

Hydrogenation Reactor and Gas Cooler The following hydrogenation and hydrolysis reactions occur in the hydrogenation reactor:

$$S + H_2 \rightarrow H_2S$$
$$SO_2 + 3H_2 \rightarrow H_2S + 2H_2O$$
$$CS_2 + 2H_2O \rightarrow 2H_2S + CO_2$$
$$COS + H_2O \rightarrow H_2S + CO_2$$

The reactions are exothermic, and heat is removed from the gas in the gas cooler, which produces LP steam.

Combustion Turbine and Generators The combustion turbine is often coupled to a generator via a compressor shaft. Further, the combustion turbine utilizes Hydrogen-rich syngas derived from coal gasification in the aforesaid stages. Also a HRSG recovers the energy from the exhaust gas of the combustion turbine.

HRSGs and the Steam Turbine Generator The exhaust gas from the Combustion Turbine is fed to a HRSG where the heat transfer takes place across a heat transfer surface which reduces the exhaust gas temperature and raises the temperature of the steam and water inside the heat transfer surfaces.

Steam Turbine Generator The function of turbine models is to convert the thermodynamic energy of main and reheat steam into mechanical energy used to drive the generator rotor.

2 Next Generation IGCC Technology

Technological developments which are expected to be achieved by the next generation of IGCC projects and contribute to such cost reductions include:

1. Utilization of dry coal feed system instead of slurry;
2. "Warm" or hot-gas cleanup systems; warm gas cleaning processes are important to the overall IGCC system because at higher temperatures the gas maintains moisture content and some sensible heat.
3. Improvement of gasifier refractory properties, resulting in longer life cycle;
4. Ion transport membranes for air separation;
5. Gas turbine inlet chilling where appropriate and effective;
6. Advanced syngas turbines to increase efficiency and reduce NO_x emissions;
7. Improved reliability of key components and the overall system in general; and
8. Reduced use of water.

Advanced technologies are also being developed to improve the IGCC performance: new technologies for air separation and oxygen production, high-temperature gas cleaning methods, advanced gas turbines, and fuel cells. These technologies are being developed with the goal of raising thermal efficiency (higher heating value) to 50–60 %. An important new system developed incorporates the latest GT improvements for a high-efficiency quench (HEQ) design [1].

3 Advanced Turbines

The advanced syngas turbines provide the greatest performance improvements as the result of air integration, increased turbine firing temperature and pressure ratio, and increased inlet temperature. For example, the advanced "F" frame, 2010-AST, and 2015-AST syngas turbines result in the most significant capital cost reductions of all technologies (by $304/kW, $382/kW, and $429/kW, respectively). These reductions are due to more increased net power generated than from any change in turbine equipment cost. The turbine section itself contributes only $28/kW, $32/kW, and $44/kW reduction to the total plant cost, respectively.

The efficiency of a gas turbine depends on inlet temperature to the turbine. Turbines are designed for high inlet temperature by making improvements in coatings, film, and materials capabilities. Optimization between cooling air consumption and aerodynamic efficiency is an iterative process and thus the best designs need to be put into operation such that economy and efficiency are at their best.

When syngas is combusted in the gas turbine compressor, a pollutant namely NO_x is produced due to the high temperature and pressure, which is not a desirable feature. Thus No_x emissions need to be controlled in the following ways:

1. Premixed combustion improvement by employing dry low NO_x burners and catalytic combustion. This technology holds importance as it creates a uniform air to fuel ratio to avoid localized high temperatures. Also catalytic combustion mechanism is employed so as to allow the fuel to burn at low temperatures, which also directly affects the reduction in the NO_x formation.
2. Addition of inerts to gas turbine flame to reduce flame temperature such as steam, water, and N_2 helps reduce NO_x to 9–25 ppm. This is done because the aforesaid technique is not very effective for syngas containing high amounts of H_2 which has a high reaction rate. Thus fuel dilution is further required for NO_x control.
3. Further NO_x reduction to 5–9 ppm is possible by selective catalytic reduction (SCR), wherein Ammonia is injected into the exhaust gas so that NO_x after chemical reactions with Ammonia and Oxygen forms Nitrogen and Water.

The major components of a gas turbine are the compressor, combustor, and the turbine. The materials of an entire gas turbine unit are under the influence of various operating conditions, and thus the materials to be used for an advanced turbine need lot of thoughts. The blades of the compressor are made from hardenable stainless steels generally. Coatings are also done on the compressor sections so as to reduce the surface roughness and thus the friction losses, which can be abradable and abrasive coatings. In the combustor section, coatings are provided for an insulation barrier from the hot-gas stream and the combustor parts. The materials for combustors must be easily formed and welded, should have resistance to high-temperature oxidation, good compatibility with thermal barrier coatings, and must have fatigue strength. The material for the combustor liner and transition piece can be a Nickel-based alloy such as Alloy X. For the advanced turbine materials, it is an extensive research and development area to find the optimum mix between mechanical properties, environmental resistance, and manufacturability. For that the options that are generally considered are Nickel-based alloys and single-crystal superalloys.

By making use of high temperature, high strength materials, new and novel approaches in sealing and cooling, advanced aerodynamic flow path optimization may help increase the efficiency of IGCC process to more than 50 %, which will reduce fuel consumption, reduce emissions, and will meet future ever-increasing energy demands.

In the present scenario, even H Class turbines are being preferred taking into account the advantages like

1. Increase of combined cycle net efficiency to over 60 %
2. Reduced emissions per produced kWh
3. High efficiency and low emissions also in part-load operation
4. Fast startup capability and operational flexibility
5. Reduced investment costs per kW
6. High reliability and availability
7. Lowest in lowest life cycle costs

The F-class gas turbine and combined cycle technology have been into successful operation for about two decades, but the new advanced H-class represents the most advanced and modern technology for economic and environmental friendly gas fired power generation.

The new generation H-class turbine provides a mix of environmental protection and economic effectiveness and is an advanced turbine technology while making use of innovative design, enhancement of process of manufacturing, and materials of high class. For the objective of high output and high efficiency, certain parameters namely compressor mass flow, firing temperature, exhaust temperature, and corresponding combined cycle parameters such as steam temperatures and pressure levels are used. In the present era of industrialization and power generation requirements, another issue that has been addressed is the choice of the engine cooling method so that the components in the turbine which have to withstand the massively high temperatures do not undergo any harm. And for this, making use of certain optimization methods, it has been realized that completely air-cooled method is the best.

Taking into account the above, the expectations from the H Class turbines are given as follows:

1. Combined cycle net efficiency over 60 %, resulting in approximately 3 % of fuel savings for improved operating expense.
2. Significantly reduced emissions per kWh produced combined with the lower heat rate and 25 ppm NO_x, 10 ppm CO.
3. Increased turn-down for achievement of high efficiency and low emissions also in part-load operation from 100 to 50 % load.
4. Quick startup capability of less than 15 min and operational flexibility to meet immediate needs in power grids.
5. Lower specific investment costs (EUR/kW) for reduced specific capital expenditure.
6. Reliability of over 99 %, availability of over 94 % and serviceability comparable to today's proven F-class technology.
7. Minimized life cycle costs for increased net present value for the owner of at least 7–8 %.

4 Hot-Gas Cleanup Technology

Basically, when it comes to the efficiency improvement of IGCC, there is requirement of the cleanup of the syngas that is produced at the gasifier, and thus there are two major techniques employed for the gas cleanup namely the cold gas cleanup at temperatures below 300 °C for the removal of particulate matter and Sulphur species, but the major limiting factor is that this process is very energy intensive and thus it reduces the overall process efficiency of IGCC.

Before the steps of particulate removal and desulphurization, a hot-gas cleanup is done of the syngas so produced in the gasifier section of an IGCC Power plant, such that the process can be done without the heat exchangers and the process condensate systems.

Since we know that in an IGCC plant, air is directly used as the oxidant, thus there is no need of an oxygen plant. Also, in this method, for the particulate removal, it is possible to use high-efficiency cyclones. There are two approaches to desulphurization, when inside the gasifier itself, limestone is used, which results in about 90 % Sulphur removal; and when done outside the gasifier, a high-temperature removal process is done using the Zinc Ferrite desulphurization process and this helps in reducing the levels of sulphur to about 10 ppmv, which not only helps reduce the SO_2 emissions from the gas turbine, but also the sulphur captured is recycled, and due to which additional sulphur recovery mechanism does not need to be set up. Also the Zinc Ferrite sorbent is recycled and reprocessed. The syngas that is available at the gasifier outlet needs to be cooled and for that water quench is made use of and thus no knockout drum is required for removal of process condensate.

Hot-gas cleanup offers the potential for higher plant thermal efficiencies and lower cost. A key subsystem of hot-gas cleanup is hot-gas desulfurization using regenerable sorbents. Sorbents based on zinc oxide are currently the leading candidates and are being developed for moving- and fluidized-bed reactor applications. Zinc oxide sorbents can effectively reduce the H_2S in coal gas to around 10 ppm levels and can be regenerated for multicycle operation. Advanced IGCC power plants require advanced particle filters and hot-gas desulfurization (HGD) following gasification in order to achieve high thermal efficiency (Figs. 1 and 2, Tables 1 and 2).

Some of the major factors affecting the performance of desulphurization are pressure and temperature of the gas, syngas composition, contaminants, and particulate matter in the gas [2].

5 Efficiency Optimization of IGCC Power Plants

Another improvement that can be made is the efficiency improvement of the IGCC power plants which can be done in a manner as to increase the efficiency of the individual gas and steam turbine efficiencies which is quite possible taking into account the various research and development efforts in progression and achieved till date. Another aspect that needs to be addressed is the increase in the temperature of the syngas reaching the gas turbine. This hike in temperature is required so as to control the presence of alkali metals in the syngas such that the corrosion of the turbine blades does not occur. A hike in temperature also increases the process efficiency. Again there is another limit to the high range of the temperature because the Indian coals are high in ash content such as Silica or Alumina, whose sintering occurs at temperatures beyond a certain limit and that again is not a desirable feature. Thus, it is of utmost importance that the efficiency improvement with the

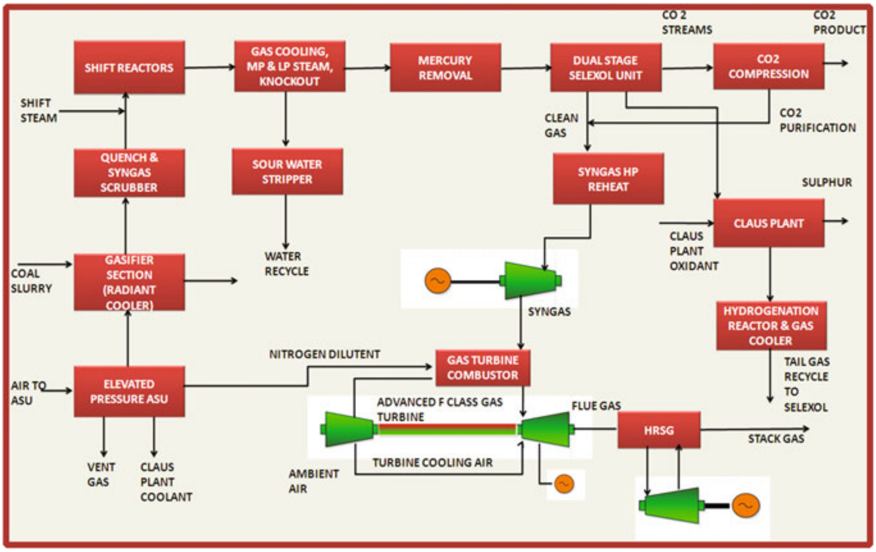

Fig. 1 Schematic of an IGCC power plant. *Source* Volume 2: IGCC Process Descriptions, NETL, 2008

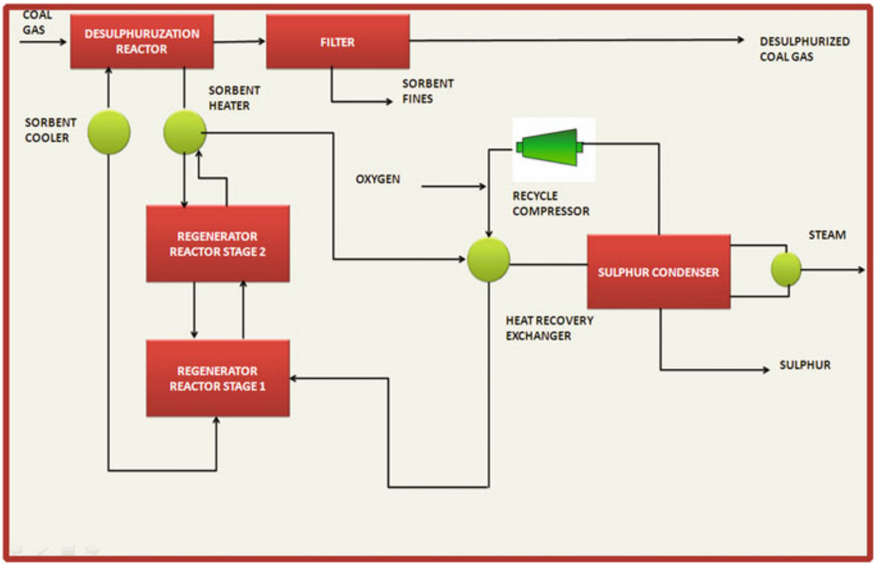

Fig. 2 Schematic of a hot-gas desulphurization plant. *Source* Volume 2: Hot-Gas Desulfurization With Sulfur Recovery, Research Triangle Park

Table 1 Performance comparison between GE 7FA turbine for syngas and natural gas as a fuel

Manufacturer model	General electric frame 7FA	
Fuel: type heating value (LHV)	Syngas 115 BTU/SCF	Natural gas 910 BTU/SCF
Power output @ 59 °F	197 MWe	172 MWe
Heat rate, LHV	8,840 BTU/kW-h	9,420 BTU/kW-h
Efficiency	37.5 %	35.2 %
Exhaust temperature	1091 °F	1116 °F
NO_x control	Nitrogen injection	Dry low NO_x burner
NO_x(@ 15 % O_2 dry)	9 ppmv	9 ppmv
CO (dry)	25 ppmv	9 ppmv

Source Gasification, Gasification Workshop, September 11–13, 2001 Indianapolis, Indiana

Table 2 General electric H class turbine performance rating

Performance rating	SGT5-8000H	SGT6-8000H
Gas turbine power output	375 MW	274 MW
Gas turbine efficiency	40 %	40 %
Combined cycle (1 × 1) power output	570 MW	410 MW
Combined cycle (1 × 1) efficiency	>60 %	>60 %

Source http://www.Ge-Energy.Com

hike in temperature does not yield issues which cause an increase in the maintenance costs. Another factor of concern is the efficiency of fuel conversion.

Controlling the temperature of the syngas reaching the gas turbine is of utmost importance, and this is carried out by making use of a radiant syngas cooler stage just after the gasifier, wherein the raw syngas is cooled down to various temperatures as per the process requirement. When the outlet temperature of the radiant syngas cooler is varied, the efficiency increases, with increase in temperature; but after certain temperature range the electrical power output decreases, thus, creating the need of an optimization mechanism, which finds the optimum temperature range of operation which yields maximum efficiency and maximum power output from the IGCC.

6 Conclusions

1. Though IGCC present efficiency is up to 40 %, still if the further improvements in the process are made, then the efficiencies can reach up to and more than 50 % in the near future.
2. Out of the various improvements that can work, one of the major technological advancements is the advanced gas turbines, wherein the major factors that can help are reduction in flame temperature, increase in turbine inlet temperature, and fuel dilution.

3. Warm gas cleanup systems are beneficial, as before the steps of particulate removal and desulphurization, a hot-gas cleanup is done of the syngas so produced in the gasifier section, such that the process can be done without the heat exchangers and the process condensate systems. This increases the overall efficiency of the system.
4. As far as the improvement in efficiency is concerned, apart from the efficiency of the gas and the steam turbine cycles, another factor that needs focus is that alkali metals in the syngas may corrode the turbine blades; so the temperature needs to be kept beyond a specific temperature and also there is a limit to the higher range of temperature as it can cause sintering of the Silica, which is present in huge quantities in Indian coal.
5. The outlet temperature of the syngas exiting from the radiant syngas cooler stage, after the gasifier section needs to be controlled in a manner as to find the optimum temperature at which the power and efficiency of the IGCC is maximum.

References

1. Todd DM. Gas turbine improvements. In: Enchance IGCC Viability 2000. Gasification Technologies Conference.
2. Atimtay AT, Harrison DP. Desulfurization of hot coal gas. Nato Asi Series G.