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Power Generation from Coal-A review

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Abstract

Power generation from coal is an essential need to meet world's energy demand. There are two major challenges in coal-based power generation: improving the efficiency and reducing the emissions level. In fact, these challenges have been under research for a long time. This article focuses on the recent developments of process technologies and coal treatment to improve the performance of coal-based power plant. Barriers to the adoptions of modern developments and additional needs in research are also addressed.

1. INTRODUCTION

Coal is the world's most abundant and widely distributed fossil fuel, with global proven reserves totaling nearly 1000 billion tons. Given these characteristics, coal has been a key component of the electricity generation mix worldwide. Coal fuels more than 40% of the world's electricity, though this figure is much higher in many countries, such as South Africa (93%), Poland (92%), China (79%), India (69%) and the United States (49%). Moreover, the growing energy needs of the developing world are likely to ensure that coal remains a key component of the power generation mix in the foreseeable future, regardless of climate change policy. The main objective of this article is to review the major ongoing developments in process technology, barriers to the adoption of technology, and further research requirement relevant to power generation from coal on the basis of the most recent (2011) report from International Energy Agency (IEA).

2. DEVELOPMENTS IN PROCESS TECHNOLOGY

Employing the combustion of pulverized coal in air to raise steam has been the mainstay of coal-based power generation worldwide for almost 100 years. The efficiency of a pulverized coal combustion unit depends on a variety of factors: steam conditions, the quality of coal used, ambient conditions, plant design, and operational and maintenance practice. A number of advanced coal-fired power generation technologies, cleaner coal technologies (CCTs), as they are often called, have been or are being developed to improve thermal efficiency, to reduce and capture CO_2 emissions, and to reduce other emissions (*e.g.* NOx, SO_2 and particulates). The major coal-based power generation technologies available today, and/or under development, include supercritical (SC) and ultra-supercritical (USC) pulverized coal combustion, circulating fluidized bed combustion (CFBC), and Integrated gasification combined cycle (IGCC).

2.1 Supercritical and Ultra-Supercritical Pulverized Coal-Fired Technology

Supercritical is a thermodynamic expression where there is no difference between the liquid and gaseous phase. Water/steam reaches this state at about 22.1 MPa (221 bar) pressure. Above this operating pressure of the steam, the cycle is supercritical and its cycle medium is a single-phase fluid; as a result there is no need to separate water from steam as in the boiler of a sub-critical cycle.

Typical sub-critical steam cycle operating parameters are from 150 to 180 bar pressure and between 540^oC and 565^oC temperature for superheated steam, with reheat to similar temperatures. Steam cycle operating parameters for super critical plants typically are 245 bar pressure and 540 to 570^oC for superheated steam, with reheat to similar temperatures. Ultra-supercritical units operating at temperatures of 700^o C and higher, and pressure in excess of 300 bar are in the development phase. Once-through boilers are therefore used in a supercritical cycle. A switch from sub-critical to current USC steam conditions would raise efficiency by around 4 to 6 percentage-points. USC plants will reduce fuel consumption and emissions by 25 to 30% compared to the current state-of-the-art sub-critical cycle[3]. Boiler and steam turbine costs can be as much as 40 to 50% higher for a USC plant than for a sub-critical plant.

Ultra-supercritical units use nickel-based super-alloys for some components in the boiler, turbine and piping. Such materials are used in gas turbines. However, the balance-of-plant cost can be 13 to 16% lower, because of reductions in coal consumption, coal handling and flue gas handling. The total investment cost for USC steam cycle plants can be 12 to 15% higher than the cost of a subcritical steam cycle. Adding CO_2 capture to a power plant results in a substantial energy penalty. As large volumes of absorbent are required to treat the flue gas, its subsequent regeneration uses considerable quantities of low pressure steam that would otherwise

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be available for power generation. Maximizing plant efficiency is, therefore, highly desirable when employing carbon capture and storage: the higher the net efficiency of the base plant, the higher will be the net efficiency of that plant with carbon capture and storage. However, the operating environment with flue gas from coal is different so international programs are seeking to develop the necessary materials and fabrication methods for use with these materials.

Difficulties for adaptation of supercritical and ultra-supercritical units: Supercritical and ultra-supercritical technology is sometimes rejected or overlooked because of misguided perceptions that they are costly, unproven and unsuitable for use with local coals. Consequently, many countries have preferred conventional sub-critical technology despite evidence that demonstrates that SC and USC designs are commercially proven and competitive, especially when coal prices are high. Experience is lacking only in the case of high-ash coals; but even for such coals, there should be a gradual switch from sub-critical to SC and then to USC as operational experience grows. The major barriers to advances in SC and USC steam cycles are therefore technical, *i.e.* metallurgical and material fabrication issues. Apart from the continued development of materials, fabrication methods and long-duration testing of materials, there is clearly a need to accelerate the development and full-scale demonstration of advanced USC conditions.

Location of SC and USC units: Supercritical plants are currently located in eighteen countries. Globally between 2004 and mid-2007, the share of SC plants increased from approximately 18 to 20% (~ 265 GW) of coal-fired capacity. This rose to over 25% in 2009 and increased further as new SC units were built in China, India, South Africa and Russia.

USC plants are in operation in Denmark, Germany, Japan and Italy; however their share of global power generation is under 1%. A number of USC plants are also being constructed in China. An example is the Huaneng Group’s Yuhuan Power plant in Zhejiang Province, which is a USC plant with two 1000 MWe units and steam parameters of 26.25 MPa/600^{o}C/600^{o}C. Chinese manufacturers are also offering USC at up to 605^{o}C, *i.e.* at or near state-of-the-art conditions (Minchener, 2010).

While the first generation of supercritical units was under 400 MWe in size, larger units of up to 1100 MWe are progressively being built. The major units, built under construction or under planning in different countries, clearly demonstrate the progression to larger unit sizes (Table 1).

2.2 Circulating Fluidized Bed Combustion Technology

There are two major categories of fluidized bed combustion units: those operating with bubbling fluidized bed combustion (BFBC) and those with circulating fluidized bed combustion (CFBC). Almost all of the recent plant additions have been CFBC units. CFBC units can tolerate a wide variety of coals and particle sizes and, because of their low operating temperatures and staged combustion, produce low levels of NOx relative to pulverized coal boilers. The lower operating temperature is also ideally suitable for the in situ capture of sulphur dioxide (SO_2). The efficiency of CFBC units is similar to that of pulverized coal units. CFBC units can demonstrate significant operating experience. They have the ability to accept a variety of fuels, including a range of coals: from lignite to anthracite, waste coal and biomass. They exhibit low emissions of conventional pollutants and show potential to be designed for oxy-firing. Though there is a need for research, development and demonstration (RD&D) to progress to higher steam conditions over time, there are no obvious difficulties to CFBC other than the size of the market.

Barriers to wider adoption CFBC technology: With around 20 GW operating worldwide, CFBC units can demonstrate significant operating experience. They have the ability to accept a variety of fuels, including a range of coals: from lignites to anthracite, waste coal and biomass. They exhibit low emissions of conventional pollutants and show potential to be designed for oxy-firing. Though there is a need for research, development and demonstration (RD&D) to progress to higher steam conditions over time, there are no obvious barriers to CFBC other than the size of the market. The major development needs for supercritical CFBC technology are mostly similar to those for SC and USC pulverised coal-fired technology. These are to develop materials with higher temperature and pressure resistances, to improve fabrication technology using these materials; and to accelerate demonstration of large SC units.

2.3 Integrated Gasification Combined Cycle

Coal-based integrated gasification combined cycle (IGCC) uses a combination of gas and steam turbines to produce electricity. The gas used to fire the gas turbine is first made by “gasifying” or partially oxidizing the coal to produce a fuel gas, which is then followed by gas cleaning as shown in fig.1

Table 1. Major supercritical units – recently commissioned, under construction or planned.

Australia	❖ Kogan Creek, 2007, 750 MWe	Netherlands	❖ Eemshaven, under construction, 2013, 2x800 MWe
Canada	❖ Genesee Unit 3, 2005, 450 MWe	South Africa	❖ 2011-15, 6×800 MWe
China	❖ Waigaoqiao, 2008, 2×1 000 MWe ❖ Yuhuan, 2007-08, 4×1 000 MWe ❖ Under construction, ~50 000 MWe Planned by 2015 - >110 000 MWe	Russia	❖ Berezovskya, 2011, 800 MWe ❖ Novocherkasskaya, 2012, 330 MWe,CFB ❖ Petrovskaya, 2012-14, 3×800 MW
India	❖ Sipat, 2007-09, 3×660 MWe ❖ Barh, 2009, 3x660 MWe ❖ UltraMega Projects – 2012, ❖ 5×4 000 MWe plants; unit size 660 MWe or 800 MWe	Germany	❖ Niederaussem, 2003, 1 000 MWe, ❖ Lignite ❖ Walsum, 2010, 750 MWe ❖ Neurath, under construction, 2011, ❖ 2×1100 MWe, largest lignite-fired ❖ USC units ❖ Hamm, Under construction, 2012
United States	❖ 2008, 545 MWe, 890 MWe ❖ Oak Grove, Texas, 2009, 800 MWe ❖ Oak Grove, Texas, 2010, 800 MWe ❖ Under construction, 2009-12,	Poland	❖ Lagisza, 2009, 460 MWe, CFB ❖ Belchatow, 2010, 833 MWe
Italy	❖ Torrevaldaliga Nord, 2010, 3×660 MWe ❖ Planned by 2015, 3×660 MWe	Korea	❖ Tangjin, 2006, 2x519 MWe ❖ 2008-10, 5×500 MWe, 2× 870 MWe
Mexico	❖ Pacifico, 2010, 700 MWe		

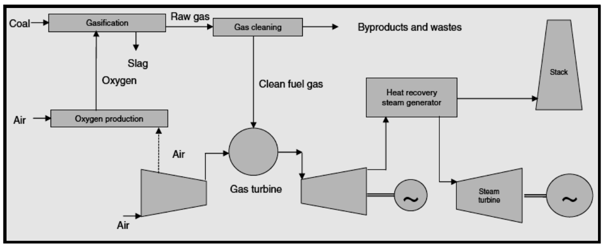

Fig. 1: Major components of an IGCC system without CO_2 capture.

The major subsystems within IGCC that have the potential to influence the overall efficiency, cost and reliability, are:

(i) Gasifier – this affects the conversion of carbon in coal to fuel gas
(ii) Gas cleaning system – this affects the emission of pollutant gases and gases harmful to either the environment, the gas turbine or both;
(iii) Oxygen production;
(iv) Gas turbine;
(v) Syngas cooler, heat recovery steam generator, steam turbine cycle.
For details on subsystems, the IEA-2011 report is recommended.

Outlook for coal-based IGCC: Aided by climate change mitigation pressures and technical and cost improvements, IGCC has the potential, in the longer term, to compete with PC combustion technology, the current system of choice for utilities. However, the immediate future of the technology is less certain.

As indicated in Table 2, several IGCC projects have been proposed in Australia, China, the European Union and the United States, with a number of other countries showing interest. Of around 25 500 MW IGCC projects proposed worldwide in 2007, the majority were later cancelled, citing cost escalations and uncertainty in emission regulations. Of note is that 60% of the projects were in the United States, greatly helped by the provisions of the 2005 Energy Policy Act.

Immediate concerns must be addressed if IGCC is to be more widely deployed. Though proponents of IGCC may point to particular benefits, such as emissions performance or potential for polygeneration, it is still perceived to have as of yet unquantified operating risks. Operation and maintenance costs are less certain as there are few reference plants and little power industry operating experience. Other issues include improving the capital cost and availability of IGCC on all coals.

3. DEVELOPMENTS IN COAL TREATMENT

Coal treatment can bring considerable environmental benefits, including reduced emissions of SO_2, NOx, particulates and CO_2, through the supply of clean coal of consistent quality to downstream utilization processes.

Coals are extremely heterogeneous, varying widely in their content and properties from country to country; mine to mine, and even from seam to seam. The principle impurities are ash-forming minerals and

Table 2. Major Coal-based IGCC projects under consideration

Project	Location	Coal	Gasifier Technology	Gas turbine and model	Net output (MWe)	Year
GreenGen	Tianjin China	Bit	Shanghai boiler; dry fed O2 blown	Siemens and Shanghai Electric	250 - stage 1 400 - stage 2	Late 2011 [Stage 1]
Dongguan Taiyangzhou	Guangdong China	Bit	KBR Transport Integrated Gasification	Unknown	120 - stage 1 800 - stage 2	Late 2011 [Stage 1]
Duke Energy	Indiana US	Bit	GE Slurry-fed O2 blown	GE Frame 7B	618	2012
Nuon Magnum	Eemshaven Netherlands	Bit Biom	Shell	MHI 3xM701F4	2012	[CCGT as 1st phase]
Excelsior Energy	Minnesota US	Lig/PetCoke	ConocoPhillips Slurry-fed O2 blown	Siemens 2xS5000F	620	2014 [No PPA, as yet]
Southern Company	Mississippi US	Lig	KBR Transport Integrated Gasification	2 x 'F' Class	582	2014
Texas Clean Energy Project	Texas US	Sub-bit	Siemens	Siemens	380	2015
Wandoan Power	Queensland Australia	Bit	GE	GE	334	2016
Osaki CoolGen	Japan	Sub-bit	Hitachi	Hitachi	140	2017
Hydrogen Energy California	California US	Bit/pet coke	GE	GE Frame 7F	250	2018
American Electric Power	Ohio US	Bit	GE Slurry-fed O2 blown	GE Frame 7B	630	[Project on hold]
Taylorville Energy Center	Illinois US	Bit	Siemens	GE	600	[Project on hold]

sulphur. Some are interspersed through the coal seam, some are introduced by the mining process, and some -principally organic sulphur, nitrogen and some mineral salts -are bound organically to the coal

These impurities affect the properties of the coal and the combustion process, including the nature of the flue gas emissions and the combustion residues. The coal beneficiation or preparation process, which also often goes by the terms coal cleaning or coal washing, is aimed at separating and removing the impurities to the extent possible and economically feasible. Coal beneficiation aims to separate the coal from the impurities mainly by exploiting differences in density. Physical coal preparation processes target inorganic impurities and do not remove those organically bound to the coal. Sulphur is a prime target to reduce sulphur dioxide emissions following combustion. It is present both as an inorganic component (pyrite particles), and organically bound.

3.1 Coal Beneficiation

A number of countries, notably India, China, Czech Republic, Poland, South Africa, Romania and Turkey use high-ash coals for power generation. During the mining operation, ash and other extraneous matter are also extracted with the coal. Coal beneficiation is a process that improves the quality of coal by reducing the extraneous matter or reducing the associated ash, or both. The two basic processes of beneficiation (Satyamurty, 2007) are dry de-shaling and wet process. In dry de-shaling, the non-coal matter or shaly coal is removed using no liquid media. However, in wet process, coal is crushed and put in a liquid media (usually water) of adjustable specific gravity to separate the lighter coal (with low-ash content) from heavier coal (with high ash content). The rejects from the wet process also contain carbonaceous matter.

Major benefits of coal beneficiation: It results in savings in the capital and operating costs of the power plant, particularly the boiler, coal handling and ash handling systems. The cost of power generation may also be reduced if the washed coal increases the plant load factor and the washery rejects are utilized efficiently in fluidized bed boilers.

R& D needs for coal beneficiation: It is important to develop new technologies to make significant reductions in ash content through coal beneficiation. Increasing the yield of low-ash coal and reducing the consumption of water are the two major challenges to be overcome by the wet process for coal beneficiation.

3.2 Developments in Coal Drying

Low-rank coals containing high-moisture (30 to 70% on as-received weight basis) represent a significant resource worldwide. An estimated 45% of the world's coal reserves are lignites (brown coal). These are inexpensive, low in ash and sulphur reserves, but have a high-moisture content of up to 65% on an as-received basis. Brown coal represents an important source of power generation in several countries, including Australia, Germany, Greece, Poland, Russia, Turkey and the United States.

The needs for coal drying: Coal pre-drying is an important step towards improving the efficiency of both existing and new power plants using high-moisture coals. In general the efficiency of a unit using coal drops by about 4 percentage-points and 9 percentage-points when coal moisture content increases from 10 to 40% and 60% respectively. Apart from efficiency reduction, high moisture increases coal handling feed rate, demands more auxiliary power for coal-handling systems and pulverisers, and leads to higher plant operating and maintenance costs.

4. RECOMMENDATIONS

(i) Large-scale supercritical pulverised coal plants are commercially available and cost effective. Strong consideration should be given to the introduction of policies that markedly reduce the future construction of sub-critical plant for new build.

(ii) Following the successful commissioning of the first supercritical CFBC at Lagisza (Poland), it should serve as an example for future CFBC plants. In fact, both China and Russia now have programmes to construct supercritical CFBC units.

(iii) Maximizing plant efficiency is highly desirable when employing CCS. Efficiency gains from upgrading sub-critical units are limited. To achieve efficiencies higher than 40% (LHV, net), operation with supercritical steam conditions is necessary. If, at some future time, CCS is to be applied to most coal-fired plant, policies will need to address the status of less efficient power generation.

(iv) A significant part of the world's coal reserves comprises brown coal or lignites, often associated with high moisture content. This can lead to a penalty of between 4 and 9 percentage-points in plant efficiency. RWE employs a novel coal-drying process at Niederaussem Unit K, where an efficiency of 43.5% (LHV, net) has been achieved. Improvements under development may lead to an increase of a further 4 percentage-points. This work sets a benchmark for what may be achieved using low-grade coals.

5. CONCLUSIONS

Coal is an important source of energy for the world, particularly for power generation. However, to play its role in a sustainable energy future, its environmental (harmful emissions) footprint needs to be reduced; using coal more efficiently is an important first step. Where economic and regulatory conditions exist which shift this balance consistently in favor of higher efficiency and lower emissions, improvements become a commercial imperative and will become a normal part of operating a competitive business. The development of supercritical steam cycles with progressively higher steam temperatures, combined with modern plant design and automation, provides significant potential for efficiency improvement and mitigation of CO_2 emissions compared to existing coal-fired plant. These improvements will be realized through the progressive replacement of existing assets with reference to leading practice plant designs. Nevertheless, the greatest reduction in specific CO_2 emissions from coal-fired plant will eventually be realized through the application of carbon capture and storage (CCS) technology. Consideration of the basic efficiency of the power plant will be a major factor in the economic viability of CCS. Potential exists for even greater CO_2 reductions where CCS is applied to coal.

6. ACKNOWLEDGEMENT

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7. REFERENCES

[1] International Energy Agency Report 2011.