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Ways to Further Improve Efficiency for Ultra-supercritical Coal-fired Power Plants in China

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Abstract

The character of China ‘s structure of energy resources is “Deficient Oil, Lean Gas and Rich Coal", which makes coal be the dominant energy in China. Now coal accounts for about 72% of total primary energy consumption, 3.57 billion tons of coal were consumed in 2011, in which 54.8% was for power generation. Total installed power capacity was 1,056 GWe in 2011, in which coal fired power capacity was 765GWe, accounting for 72.5% of the total. Now China has been the largest energy consumer and CO_2 emitter in the world, therefore, low energy efficiency and high CO_2 emissions are the biggest challenges for China’s energy.

Now more than 130,000MWe SC/USC units were in operation in 2010 in China, in which 82 units with the total capacity of 70,000MWe were USC, China has been a country with the largest number and installed capacity of USC units in the world. This paper will introduce China’s energy strategy and focus on the ways to further improve efficiency for USC coal-fired power plants in China, which includes:

(1) The policy of “Large Substitutes For Small ” to improve nationwide average power efficiency;
(2) To innovate and create new technologies and systems to further improve the efficiency of existing USC coal-fired power plants as high as possible, specially, the best USC coal-fired power plant, Shanghai Waigaoqiao NO.3 Power Plant will be introduced in details.
(3) To develop an innovative design of ultra-supercritical (USC) coal-fired power plant to use 600^{o}C material to achieve close to 700° C USC efficiency, which will also be beneficial for the 700° C ultra-supercritical technology in the future.

Keywords: ultra-supercritical (USC), efficiency, innovation

1. Background

The special character of China ‘s structure of energy resources is “Deficient Oil, Lean Gas and Rich Coal", which makes coal be the dominant energy in China. Today, coal accounts for 71.66% of total energy consumption. much higher than that of 28.6% of world average. In 2011,China’s coal production was 3.52 billion tons and coal consumption was 3.578 billion tons, in which 54.8% was for power generation, therefore, coal-fired power plants are the largest coal consumer in China. China’s total installed power capacity in 2011 was 1,056 GW, in which coal capacity accounted for 72.5% and generated electricity was 4,277 TWh, ranking the first in the world, in which electricity generated by coal power accounted for 82.5%. It is believed that coal will remain the backbone of global electricity

generation, especially for China, a drop in coal –fired power generation in the OECD countries in the next 20 years will be offset by the big increase of China, where 600GWe of new capacity exceeds the current total capacity of the US,EU, & Japan.

In 2007 , China exceeded the USA becoming the largest CO_2 emitter in the world. In July 2010, IEA announced that China's total energy consumption was 2.252 billion toe, 4% higher than that of the USA (2.170 billion toe), becoming the largest energy consumer in the world. To be the largest energy consumer and CO_2 emitter in the world, China is facing an unprecedented challenge for energy saving and emission reduction.

Based on the conditions and challenges of China's energy and environment, China's energy strategy is:

(1) To improve energy efficiency and energy structure to reduce coal proportion from energy structure;
(2) To strive development of renewable and nuclear energy;
(3) Clean and efficient development and utilization of coal.

The Chinese government promised：

(1) Non-fossil energy will account for 15% of total primary energy by 2020;
(2) CO_2 emissions of per unit of GDP will reduce 40~45% on the basis of 2005 value by 2020.

2. Ways to reduce CO_2 emissions from coal-fired power plants

There are three ways to reduce CO_2 emissions from coal-fired power plants, which are:(1) CO_2 capture and storage (CCS); (2) Co-firing with biomass and (3) Improvement of efficiency for power generation

(1) CCS is a high energy consumption system with high investment and now is still under development, the penalty of efficiency loss caused by CCS can be higher than 10%, therefore, now it is still very much uncertain whether CCS can finally be accepted or not, especially in China.
(2) As for co-firing with biomass for coal fired power plants, for such a big coal power Capacity in China, biomass can only reduce very small portion of coal for power generation.
(3) The best, economic and practical way to reduce CO_2 emissions from coal-fired power plants today is to improve the net efficiency.

Table 1 Plant Efficiency VS Specific CO_2 Emissions

Types of Coal fired power units	Net efficiency %	Specific CO_2 emissions g CO_2/kWh
Low efficiency units	28	1193
Current world average level	30	1116
Current China's average level	37	900

Current China's USC average level	43	777
Future 700 ^{o}C USC level	52	643

As can be seen from Table 1, the higher the plant net efficiency, the lower the CO_2 emissions. How to Improve the efficiency of coal fired power plants in China, there are 3 main approaches:

(1) To continuously implement the policy of "Large Substitutes For Small " ;

(2) To innovate and create new technologies and systems to improve the efficiency of existing coal fired power plants as high as possible. Shanghai Waigaoqiao (WGQ) No.3 Power Plant is the outstanding representative for efficiency improvement;

(3) To develop and promote 700^{o}C USC technology to reach 52% of net efficiency for coal fired power generation in the future.

3. **The policy of "Large Substitutes For Small (LSS)"**

The policy of "Large Substitutes For Small (LSS) was implemented in 2006, during 5 Years implementation until 2010, LSS had achieved tremendous success as follows:

(1) 76,830MWe of small capacity with low efficiency units were decommissioned during China's "11th 5 Year Plan" and over 200,000MWe high efficient large capacity units installed by 2010;

(2) The policy of LSS is a strong driven force to much promote the development and application of high efficiency coal-fired power units, which is supercritical (SC) and ultra-critical technology(USC). Before 2004, there were imported 22 SC units with total capacity of 12,680MWe in China. Since the implementation of the policy of LSS, the first 600MWe SC unit and 1000MWe USC unit designed and made in China were in operation in 2004 and 2007, respectively, since then the ordering capacity of SC/USC units in 2007-2010 was 317,360MWe, accounting for 85% of total ordering thermal power capacity in China. According to a statistics, by the end of 2010, more than 100 of 600MWe SC units, 35 of 660MWe USC units and 47 of 1000MWe USC units had been in operation, respectively, China became the country with the largest number and capacity of SC/USC units in operation in the world.

(3) Nationwide average coal consumption for power generation reduced from 370 gce/kwh in 2005 to 335 gce/kwh in 2010, net reduction of average coal consumption was 35 gce/kwh in 5 years;

(4) Annual coal saving of 81 million tons of standard coal and reduction of 220 million tons of CO_2 emissions have been achieved since the implementation of the policy of LSS:

(5) There is still some 100,000MWe of inefficient small/medium capacity (12%of total capacity) including the unit size of 200-300MWe which will be decommissioned in the next few years.

4. Shanghai Waigaoqiao No.3 Power Plant Is the outstanding example to further improve the efficiency for existing USC units

Figure 1 Shanghai Waigaoqiao (WGQ) No.3 power plant

(1) Efficiency improvement for power generation

Shanghai Waigaoqiao (WGQ) No.3 power plant has 2 1000MWe USC units, which were put into operation in March and June 2008 , respectively. The design performances of the units are:

1) Steam flow rate：2733t/h

2) Steam parameters: 25.86MPa / 600 ^{o}C/ 600 ^{o}C

3) Design heat rate: ： 7320kJ/kWh

4) Design net coal consumption: 292 gce/kWh

5) Design net efficiency：42% (including FGD and SCR; cooling water temperature is 20 ^{o}C)

By the end of 2011, the actual operation performances were:

(1) Annual average load rate: 81%

(2) Annual average net coal consumption (including FGD & SCR)：276 gce/kWh

(3) Annual average net efficiency (including FGD & SCR)：44.5%

(4) If the average net efficiency is converted into design conditions (full load), the net efficiency is: 46.5%

WGQ No.3 power plant paid great attention to improve the net efficiency of pow er generation from the beginning of the design and construction to the commercial operation of the plant by technical innovation and system optimization, which included 12 innovations of the world's first, 6 of the domestic initiative and 12 patents. Figure 1 is Shanghai Waigaoqiao (WGQ) No.3 power plant and Figure 2 is the parts of the innovative

technologies and the net efficiency increment of Waigaoqiao No.3 Power Plant. These innovative efforts have made great achievements, during less than 4 years operation, the net efficiency (including FGD and SCR) of WGQ No.3 power plant increased from 42.73% in 2008 to 44.5% in 2011 and the specific coal consumption for power generation reduced from 287.44 gce/kWh in 2008 to 276.02 gce/kWh in 2011 as shown in Table 2.

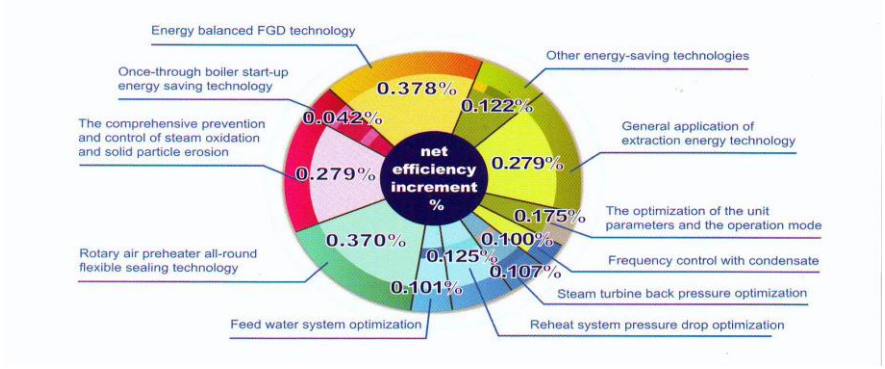

Figure 2 Parts of the innovative technologies and the net efficiency increment of WGQ No.3 Plant.

Table 2 Improvement of net efficiency and specific coal consumption by innovation and optimization

Year	2008	2009	2010	2011
Actual net efficiency*, %	42.73	43.53	43.97	44.50
Actual specific net coal consumption* , gce/kWh	287.44	282.16	279.39	276.02
Note: * (1) actual operation load rate was 75%; (2) Including FGD & SCR				

Above achievements were achieved at annual average operation load rate of 75% (2008-2010) and 81%(2011), if converted the net efficiency to the design conditions (full load), the net efficiency would be 46.5%.

(2) High efficient emission control systems with low energy consumption

The efficiency improvement helps the reduction of emissions, in addition to this, a series of innovations for emission control technology also help the huge reduction of emissions and energy saving for emission control systems. Table 3 is New emission limits for coal fired power plants in the priority regions of China [GB13223-2011](MEP, 2011c)

Table 3 New emission limits for coal fired power plants in the priority regions* of China [GB13223-2011]

Pollutant	Conditions for application	Permitted emission levels, mg/m^3	Location for Monitoring emissions
Particulates	All	20	Stack or flue duct
SO_2	All	50	
NOx (as NO_2)	All	100	
Hg and compounds	All	0.03	
Stack opacity (Lingeman blackness)	All	1	Exit of stack

Note: * Beijing, Shanghai (Yangtze River Delta) and Guangzhou (Pearl River Delta), and six areas around the cities of Shenyang, Changsha, Wuhan, Chengdu-Chongqing, the Shandong peninsula, and the coastal area west of the Taiwan strait.

The new emission limits became effective on 1/1/2012 which is the most serious emission limits in China. Usually, the more strict the emission limits, the higher the cost and the lower the efficiency for power generation. The challenge is: “Can we develop emission control systems with high efficiency and low energy consumption”? Shanghai WGQ No.3 power plant found the solution through technical innovations.

1) For SO_2 emission control, a new heat recovery system was developed and applied, which makes the energy consumption for FGD system being balanced.

2) For dust emission control, ESP was retrofitted by using high-frequency power technology, electricity power of ESP reduced from 871KW to 266KW, annual reduction of power consumption was 9.07 million kWh, the dust emission reduced from 25 mg/m^3 to 12 mg/m^3 .the reduction of dust emissions was 1147 tons in 2011.

3) For NOx emission control, by using adjustable steam extraction top heater for the feed water system to maintain an optimized flue gas temperature at SCR catalyst reactor during boiler low load for the best NOx reduction, which can also reduce 57kJ/kW of heat rate for steam turbine at 50% of unit load and specific coal consumption for 2.18 gce/kWh. A series of innovations for SCR system make the NOx emissions always keep around 30 mg/m^3, much lower than that of the requirement of 100 mg/m^3 by new emission limits.

5. Further Improvements of Efficiency: from 600 ^oC USC to 700^oC USC

According to WGQ No.3 power plant’s experiences, even for modern high efficiency 600 ^oC 1000MWe Ultra-supercritical units, there are still a big potential to further improve the efficiency by improved thermodynamic innovation.

Table 4 Comparison of Net Efficiency Between Different Types of Units

Type of units	Steam parameters	Reheat	Temperature of feed water	Net efficiency
Sub-critical	17MPa/540^{o}C/540^{o}C	1	275 ^{o}C	35%
Supercritical	24MPa/538^{o}C/566^{o}C	1	275 ^{o}C	40%
Ultra-supercritical	25MPa/600^{o}C/600^{o}C	1	290 ^{o}C	44%
Ultra-supercritical	35MPa/700^{o}C/720^{o}C	1	310 ^{o}C	47%
Ultra-supercritical	30MPa/700^{o}C/720^{o}C/720^{o}C	2	310 ^{o}C	49%
Ultra-supercritical	35MPa/700^{o}C/720^{o}C/720^{o}C	2	320 ^{o}C	51%
Ultra-supercritical	37.5MPa/700^{o}C/720^{o}C/720^{o}C	2	335 ^{o}C	52 %

It can be seen from Table 4 that the higher the steam parameters, the higher the efficiency for power generation. Therefore, higher efficiency can be also reached by higher steam parameters, especially steam temperature. For example, if steam temperature is increased from 600^{o}C to 700^{o}C, the net efficiency will increase for 2.2%, but if the steam pressure is increased from 25MPa to 35MPa, the net efficiency will increase for 0.8% only.

But the challenge is: the high steam temperature requires high temperature new material with higher cost. For example, the material used for steam temperature of 600^{o}C is austenitic alloy, but nickel based alloy must be used for steam temperature of 700^{o}C and the cost of nickel based alloy will be much higher than that of austenitic alloy as shown in Table 5.

Table 5 Cost Comparison of Main Steam and Reheat Piping for Different Steam Temperature

Steam temperature (^{o}C)	Cost of main steam and reheat piping	Ratio
566^{o}C Supercritical units (SC)	11,041USD/ton (P91)	1
600^{o}C ultra-supercritical (USC)	56,780USD/ton (P92)	5
700^{o}C ultra-supercritical (USC)	473,000USD/ton (Inconel 617)	43

Table 5 shows that the main bottleneck for 700^{o}C ultra-supercritical technology is the high cost of high temperature alloy for the main steam and reheat piping which the steam temperature in the piping is 700^{o}C. At present in China, the capital cost for a 2×1000MW 600 ^{o}C USC plant with single reheat is 8 billion RMB(1.23billion USD), in which the cost of piping is 400 million RMB (63 million USD). But for a 2×1000MW 700 ^{o}C USC plant with double reheat, the cost for piping only will be at least 2.5 billion RMB (390 million USD)..In this case, the high cost of high temperature material will restrict the use of 700 ^{o}C USC unit. The increase of 3% efficiency will not fill up the cost of high temperature material, which may be resulted in that the 700 ^{o}C USC unit cannot be accepted by the market. Therefore, the key to solve this problem is to much shorten the length of the main steam and reheat piping. For this purpose, the General Manager Mr. Feng, Weizhong of WGQ No.3 power plant developed a patent innovative design for the arrangement of steam turbines, which can be used as the next generation of power plant and is called “cross-compound at high/low position arrangement (CCHLPA) of steam turbine /generator as shown in Figure 3. The aim of the new design is to locate the high pressure turbine as close as possible to the final superheater- and hot reheater outlet headers. By using this design, HP & IP1 turbine/generator is installed near the boiler outlet headers, the IP2 & LP turbine/ generator and the condenser are still installed at the conventional turbine house. This design has been reviewed and evaluated by Siemens, ALSTOM and Chinese local manufacturers, power research institutes with very positive results.

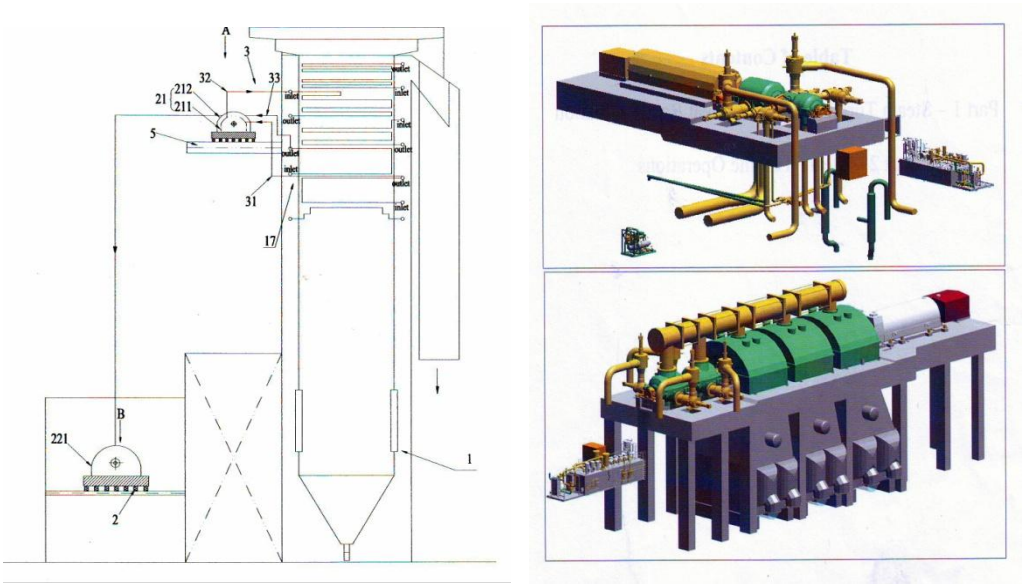

Figure 3 USC Unit of cross-compound arrangement at high/low position

Based on this new design concept, a project of 600^{o}C double reheat USC with CCHLPA design has been proposed as follows:

(1) Capacity: 1,350MWe
(2) Reheat: Double reheat
(3) Unit arrangement: Cross-compound with high/low position arrangement of steam turbine/generator
(4) Steam parameters: 30MPa/600^{o}C/620^{o}C/610^{o}C
(5) Feed water temperature: 310^{o}C
(6) Back pressure of steam turbine: 4,000Pa
(7) Heat rate of steam turbine: 6,996 kJ/kWh (without calculating WGQ3's existing innovated benefits)
(8) Design net efficiency: 48.92% (including part of WGQ No.3's innovative technology)

It can be seen from Table 6 that if the new innovative design of 1350MWe 600^{o}C USC unit with double reheat/CCHLPA design and combination of all the innovative technologies developed and confirmed by Shanghai Waigaoqiao No.3 Power Plant, even through the steam temperature is still 600^{o}C with 600^{o}C material, the net efficiency of this design can reach 48.92%, which is very close to the future efficiency of 700^{o}C USC. The singnificance of this new design is not only the high net efficiency of 48.92%, which can be realized by using 600 ^{o}C material, but also the new design of cross-compound with high/low position arrangement of steam turbine/generator can be demonstrated. Once the new materials for 700^{o}C USC is ready, the 700^{o}C USC with 52% of net efficiency and low cost will be realized

Table 6 Performance Comparison of 600^{o}C USC Between Different Designs

Item	China's typical coventional 1000MWe 600^{o}C single	WGQ No.3 1000MWe 600^{o}C single reheat	Conventional design of 1350MWe 600^{o}C double	WGQ No.3 1350MWe 600^{o}C double Reheat

	reheat USC	innovative USC	Reheat USC	innovative USC
Heat rate (kJ/kWh)	7,320	7,140	6,996	Plus the existing WGQ No.3 plant's innovative technologies
Power consumption rate (%)	4.5	3.5	4.0	
Boiler efficiency (%)	93.6	95.5	94	
Piping efficiency (%)	99	99	99	
Plant net efficiency (%)	43.4	46	46	48.92

6. Conclusions

(1) For a country like China with such a big coal-fired power capacity, the best and ecomnomic way to reduce CO_2 emissions today is to install high efficiency USC units and improve the efficiency as high as possible by innovation technologies.

(2) The experiences of efficiency improvement made by Shanghai Waigaoqiao No.3 Power Plant give us a great inspiration that even through the efficiency of modern 1000MWe 600^{o}C USC units has been high enough, there is still a big potential for further improvement of efficiency.

(3) It is believed that these innovative technologies for efficiency improvement, which will not only benefit to existing 600^{o}C USC units, but also benefit future 700^{o}C USC units.

(4) China should widely disseminate WGQ No.3 plant's experiences and develop innovative technologies for further efficiency improvement and emission reduction. We believe this is the way that China's coal-fired power sector should continue to go.

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