LATEST DEVELOPMENT IN SUPERCRITICAL STEAM TECHNOLOGY

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INTRODUCTION

The current (2008) global annual coal supply for power generation of about 3 Giga-tons (equivalent to around 80 billions GJ per year) is good to take share of around 40% in the total electric power produced worldwide by all kinds of power generation plants.

The world's economy is growing quickly, especially in Asia. In most parts of Asia the annual growth in demand for electricity is 8-12% and higher.

In PR China, the total power generation capacity is expected to almost double in next 15 years (from 460GW in year 2008 to 875GW in year 2023[1]).

The annual global electricity demand is forecast to double between 2000 and 2030, from 15,000 Billion kWh in year 2000 to above 30,000 Billion kWh in 2030. The global share of electricity in total energy consumed will rise from 15% in 2000 to above 20% in 2030.

Recent extremely increase in price of crude oil, followed by LNG and dry natural gas, coupled with steady growing demand and dwindling reserves causes coal to enjoy its top importance for power generation. Maintaining coal as a generation option in this century will require methods for addressing serious environmental issues.

The worldwide coal-fired power generation capacity of about 1,160GW (2008) is producing electric power with an average net thermal efficiency of around 32 - 35% (at average PLF of 65%), much below any acceptable standards.

It is very important that all new coal fired power plants identify benchmarking parameters against to measure progress in efficiency, economics and environmental controls. It is obvious that most efficient and environmentally friendly, coal-based, power generation units have to be widely commercialized and implemented to enable affordable and reliable electricity production even if environment protection requirements will be tightened up in the future.

The need for high fuel utilization at reasonable power generation costs and acceptable emissions extends application opportunities for wide implementation of supercritical (SC) and ultra-supercritical (USC) steam cycles.

SC and USC technologies provide not only stable and high quality electric power but also contribute to reduction of CO_2 emissions and general adverse impact to the environment.

In this paper a technical review of past, present and future SC/USC technology development is discussed.

BACKGROUND

According to statistical review of EIA / IEO 2007 the worldwide installed pulverized coal fired power generation capacity is 1,160GW (status 2007), and the average power load factor (PLF) is around 65%.

The Asian share in this capacity is around 49% (570 GW), and the average PLF (68%) is slightly above the worldwide level.

[1] **Source EIA / IEO 2007**

The total (worldwide) installed power generation capacity including the individual fuel share with the development projections until year 2030[1] is shown in the following Figure 1.

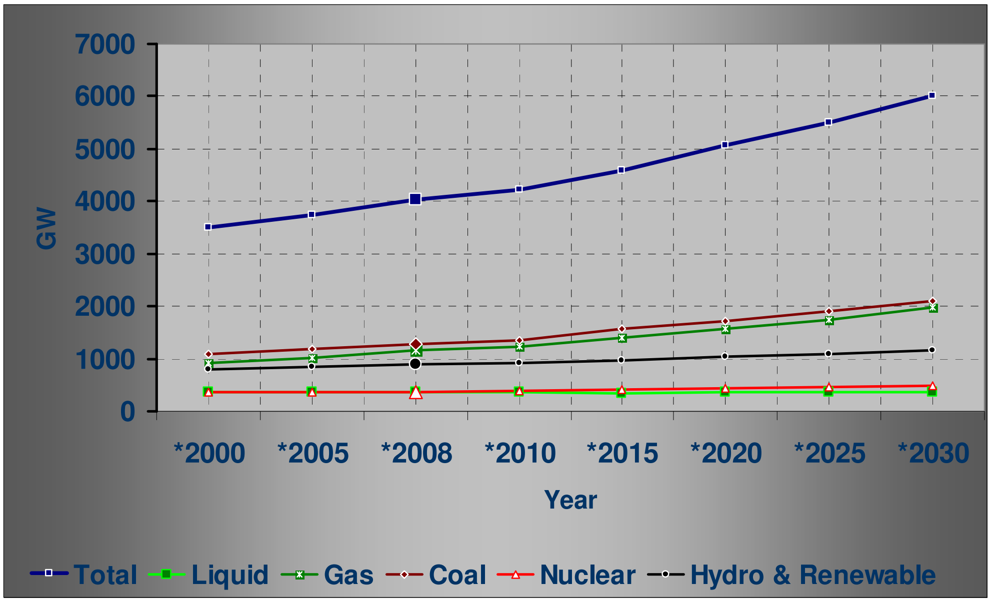


FIGURE 1
WORLD TOTAL INSTALLED POWER GENERATING CAPACITY BY FUEL (2000-2030)

Figure 2 illustrates the installed coal fired power generation capacity (including projection until 2030) in PR China, India and rest of Asia[2] in comparison to global coal fired capacity[3].

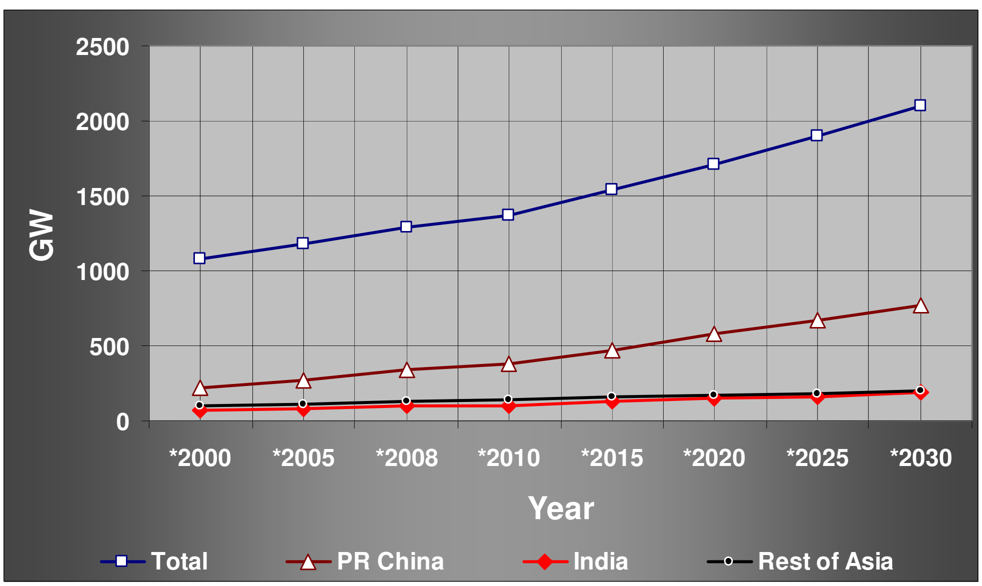


FIGURE 2
TOTAL INSTALLED COAL FIRED POWER GENERATING CAPACITY BY REGION (2000-2030)

[2] Without Middle East, China and India
[3] Source EIA / IEO 2007

The PR China's share in global coal fired power generation capacity which has grown from 20% in year 2000 to 24% in this year (2008) is projected to grow to 30% in 2015 and more than 36% in 2030.

The construction of new coal fired power plants in Japan and South Korea will rather stagnate at the level of around 4-6% (76-82GW) in the future.

The following Figure 3 shows a comparison between the share of global coal fired power production in total global power production (—⁎—) and comparison between the share in total global installed coal fired power capacity in total global installed power capacity with all kind of fuels. (—□—). The share of PR China's, India's and Rest of Asia's coal fired power generation capacity is also shown in this diagram.

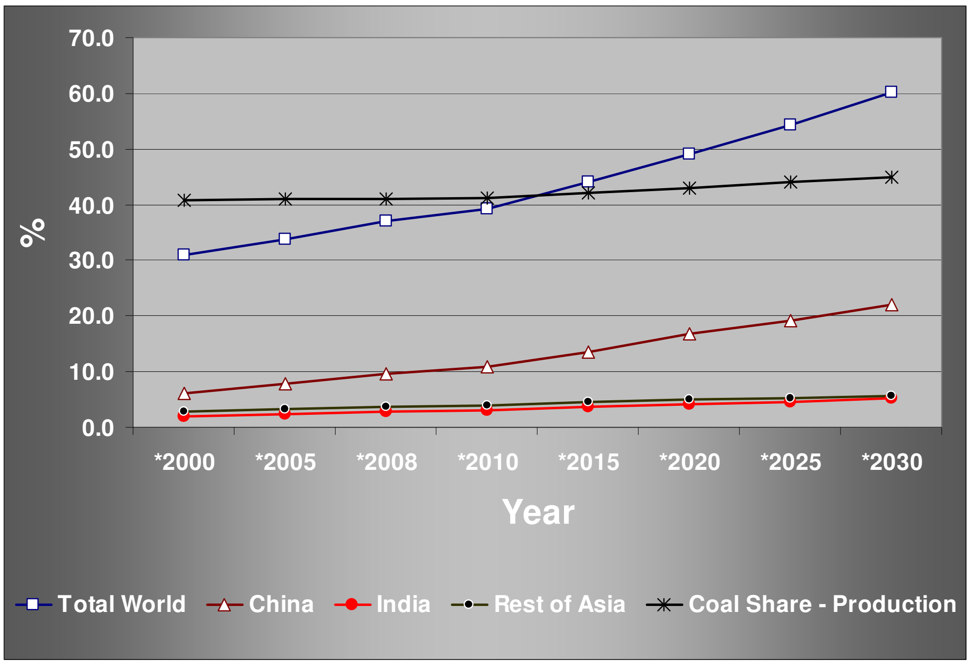


FIGURE 3
SHARE OF COAL FIRED INSTALLED CAPACITY (PRODUCTION) VS WORLD TOTAL POWER GENERATION CAPACITY (PRODUCTION)

The following three interesting phenomena which are shown in this Figure should be highlighted.

First it is the rise in PR China share. In year 2000 the PR China's coal fired power generation capacity was only around 6% from world total capacity. This year (2008) the PR China's share is more than 8% and the prediction for year 2030 is solid 22%.

The another phenomena is the world total coal fired power generation capacity share, which has changed from 31% in 2000 to 35% in 2008 and is predicted to rise to around 60% in 2030.

And the third is the share of coal fired power production in the world total power production which is changing less dramatic comparing to the power generation capacity.

The coal fired power production is maintaining a slightly increasing share between 41% (2000) and 45% (2030).

In PR China, like in some other Asian countries, the coal is the fuel of choice for power generation. Currently (2008) PR China's total power generation capacity is around 460GW, 70% out of it (335GW) is based on coal fuel.

According to serious national and international statistics the expected annual growth in PR China's electricity demand between 2007 and 2020 shall be around 5-6%, representing annually 25GW of new capacity subsequently through to 2020.

PR China's Central Government has undertaken a campaign to close down all small energy inefficient and highly polluting power plants with outdated technologies.

According to the National Development and Reform Commission (NDRC), PR China will close down all its old, inefficient coal-fired power plants that have combined capacity of 50GW and all small oil-fired power plants with total capacity around 10GW.

Additionally there are plans to shut-down thermal power plant units with capacities under 100 MW that have been in operation for more than 20 years.

In order to satisfy modern environmental requirement as well as the growing electricity demand, the nation will encourage the use of large modern and highly efficient (600-800-1000MW) SC/USC units in its new power plants.

SC/USC pulverized coal fired steam power plants with live (main) steam and reheat temperatures above 600℃ and over 45% thermal efficiency will be the preferred route.

Like PR China, India (presently the sixth-greatest electricity generating country which accounts for about 4% -150GW- of the world's total annual electricity generation) is also building large SC/USC thermal power generation plants to realize economies of scale, in addition to retrofitting older thermal power plants.

India's need for power is growing is such that over the next 22 years (until 2030) the total capacity has to be doubled (from present 150GW to 300GW in 2030).

The installation of new coal fired power plants in India will follow this trend (increasing the coal fired capacity from present 95GW to 190GW in year 2030).

As of July 2008, nine Ultra Mega Power Plants (UMPP) are already under construction or have been planned in Karnataka, Chattisgarh, Madhya Pradesh, Andhra Pradesh, Maharashtra, Orissa, Tamil Nadu, Gujarat and Jharkhand (4,000MW Mundra, 4,000MW Akaltara, 4,000MW Tadri, 4,000MW Sasan, 4,000MW Giriye, 4,000MW Krishnapatnam, 4,000MW Sundergarh, 4,000MW Cheyyur and 4,000MW Tilayya).

Four of these power plants will come up at pithead locations (near coal mines) and use cheaper domestic coal, while the rest will come up in coastal locations with easy access to coal unloading ports (or jetties) use more expensive imported coal.

As shown in the Figure 4 the average world PLF is around 5% lower than PR China's PLF. This is because in many developed industrial countries some of the coal fired power plants are kept stand-by or operated at part load as spinning reserve.

This is not the case in some Asian countries (like India, Indonesia, PR China, etc). These countries can't afford the luxury of spinning reserve.

All power plants, mainly in PR China and India, which are not shut down for maintenance (or forced outage) are running at base load.

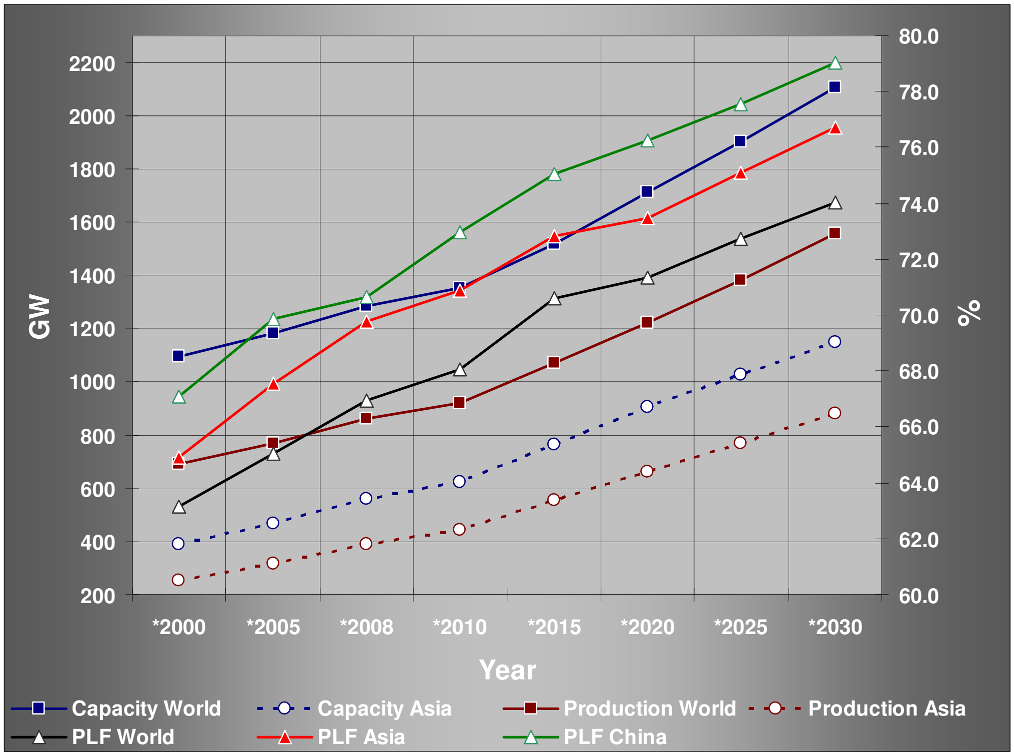


FIGURE 4
COAL FIRED INSTALLED POWER GEBERATION CAPACITY VS COAL FIRED POWER PRODUCTION

World's commercial coal based power generation history started by the end of 19th century, precisely in year 1895, when three 100kW[4] radial flow Parsons steam turbine-generators were installed in UK's Cambridge Power Station to power the first electric street lighting scheme in the city.

Early 20th century commercial coal fired power plants were producing 1.0–5.0MW per unit (using Parsons Turbo-Generators) with main steam pressure of 1.0–1.4MPa and temperatures around 200-260℃ reaching poor net plant overall efficiencies below 8% to 12%.

At the beginning of World War I, 1914-15 military and commercial cargo ships have been driven by 6.0MW/3000rpm – 20.0MW/1000rpm STs with main steam pressure between 1.0-1.6MPa and increased temperatures in the range of 300-350℃.

Improvements in turbine & boiler design parameters (mainly steam pressure & temperature), materials, unit size and introduction of pulverized coal firing technology (late 1920's and early 1930's) contributed to considerable reduction of specific coal consumption by more than 75% in its first thirty years of 20th century.

The middle of 20th century (1950s) was signed by remarkable improvements in boiler and steam turbine technology and rapid growth of ST-generator unit size from 50MW to 200MW within only 5 years).

[4] POWER OUTPUTS & EFFICIENCIES IN THIS PAPER REFER TO NET POWER OUTPUT * NET LHV EFFICIENCY (IF NOT EXPLICITLY DECLARED AS "GROSS", "GROSS LHV" OR GROSS HHV")

During this period the single reheat cycle with operating pressure of 16.5MPa and main steam temperatures in the region of 538℃, with efficiency in the range of 28% to 30%, became commercially well established.

In 1957 the world first SC power plant began operation. This 125MW US Philo Power Plant was in commercial operation at 31MPa and 612℃ until 1979 followed by 325MW Eddystone 1 Power Plant in 1960.

This plant was designed to operate under steam conditions of 34.5MPa and 650/565/565℃, however because mechanical and metallurgical problems the plant has been de-rated to 32.2MPa and 610℃ and has been operating under these conditions for most of its service life (In 2003 honored by ASME as Historic Mechanical Engineering Landmark).

Late 1960s and early 1970s a first double reheat SC units (350 – 1000MW) were implemented be GE in USA (24.2MPa/538/552/566℃).

With the introduction of SC technology for large coal fired power plants during this period, efficiency was boosted to respectable level of 38% - 40%.

Today, operating at advanced SC/USC steam conditions with pressures of above 30.0MPa and main/reheat steam temperatures of about 600/620/620℃, large coal fired power plants are hitting net efficiency level of 44% - 46%.

Asia's growth has been underpinned by coal, the major available fuel in Asia, from the first half 20th century when first coal fired power plants that were built in India, Japan and PR China.

Currently Asia-Pacific region has proved coal reserves of around 250-300 billion metric tons[5], enough coal to last over 100 years at today's level of use.

The growing trend of coal utilization for power generation can be found in most of Asian countries. In relation to this development the following two important questions confront us:-

- What role should coal play in the future power generation projects?
- Which power generation technology must be implemented to ensure stable, clean and affordable supplies of energy in future decades?

In conjunction with the post-world war II high crude oil prices caused by OPEC oil embargo in 1973-1974, the Iranian Revolution in 1979 and the recent immense price escalation of crude oil prices, the use of Fuel Oil (FO) for power generation is stagnating and will definitely decline in the future (refer to Figure 1).

The crude oil price development between 1965 and 2008 is shown in the following Figure 5. LNG and the dry natural gas prices already started (even not as steep as crude oil) to follow the crude oil price trend.

Forecast of a dramatic rise in natural gas prices, due within an outlook of 5 to 10 years, causes coal to enjoy its resurgence once again.

[5] **Source "BP Statistical Review of World Energy 2008"; Status end of 2007; without Eurasia.**

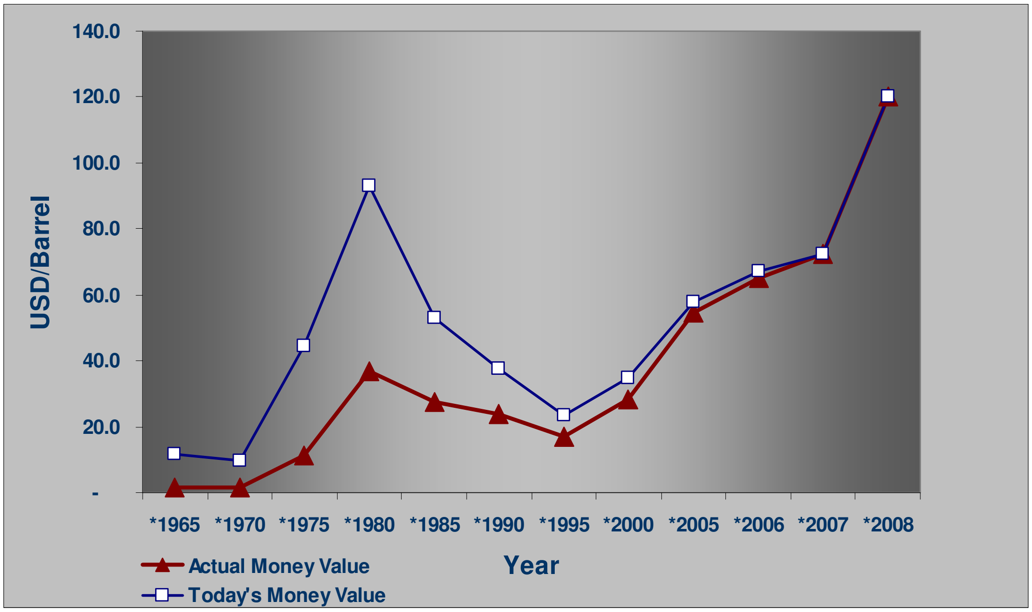


FIGURE 5
CRUDE OIL PRICE DEVELOPMENT[6]

The price development comparison between crude oil, steam coal and natural gas is shown in Figure 6.

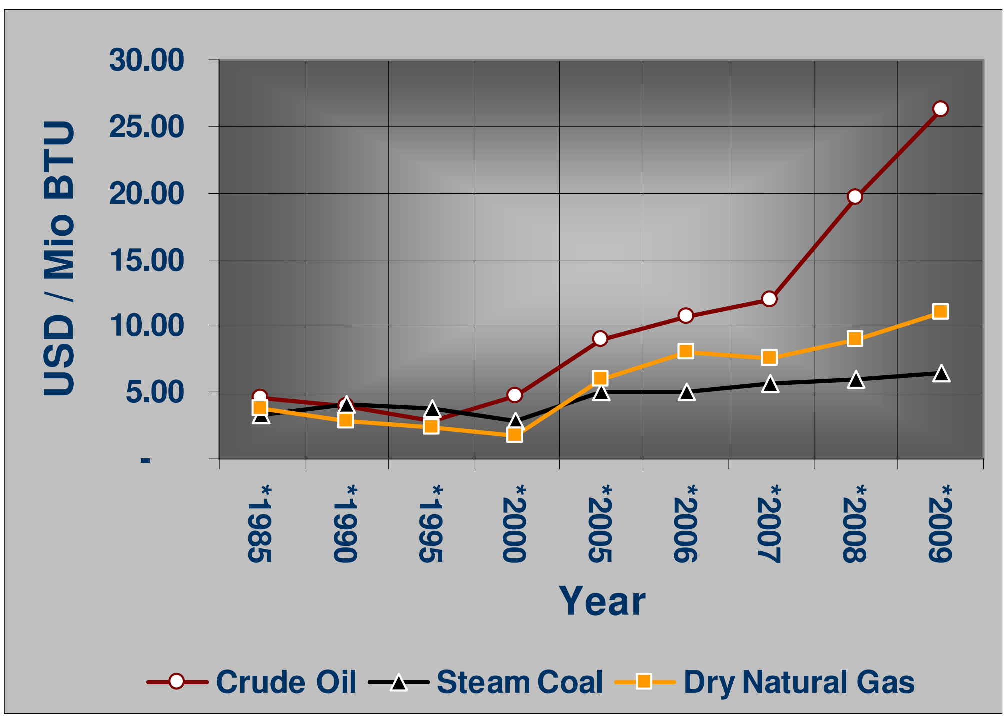


FIGURE 6
PRICE COMPARISON CRUDE OIL – DRY NATURAL GAS – STEAM COAL[7]

[6] 2008 - Status 15th August 2008
[7] 2008 - Status 15th August 2008 (120USD/Barrel)

As shown in Figure 6 the price equilibrium between dry natural gas and coal was reached in year 2002 - 2003. This is a good reason why the large power generators are diverting their power production from natural gas fuel to coal.

Emerging interest in new pulverized coal-fired SC/USC steam power plants has fueled development of new, cutting-edge technologies.

Power plants with record-breaking steam parameters approaching or exceeding levels of 30.0MPa and 600 ℃ have been commissioned during the last ten years in Japan, Korea, PR China, Germany, Russia and other countries. Continuous efforts in R&D are required on advanced materials for boilers and STs to allow use in USC conditions.

Improved and new materials with necessary fabricability and resistance to creep, oxidation, corrosion and fatigue capable of sustaining higher stresses and enabling the design of bigger turbine modules, longer last stage blades, higher creep rupture stress materials for boiler furnace walls and austenitic steels for super-heater pipes plays an important role in further development of SC/USC technology.

The maximum temperatures and pressures for USC application that can be currently economically handled by state of the art ST and boiler design as well as material features are ≤30.0MPa and ≤600-610℃ for main steam and ≤610-620℃ for reheat steam conditions. Further increase in temperature capability of USC ST will certainly require the use of Ni-based super-alloys and system redesign.

The power industry believes that continuing development effort over the next decade will see a steam turbine under USC test operating conditions at 35.0MPa and temperatures of some 720 to 760℃, resulting in a net, LHV, efficiency above 52% (Figure 7).

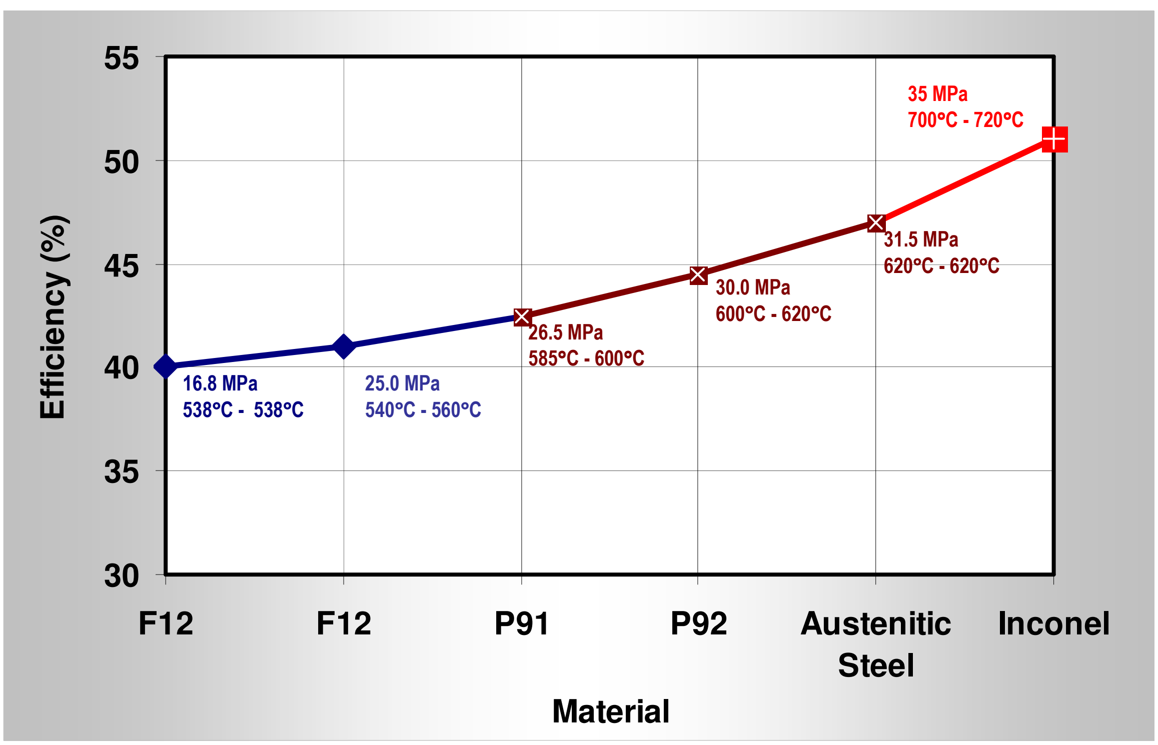


FIGURE 7

POTENTIAL INCREASE IN NET EFFICIENCY

The following properties of selected materials for high temperature and pressure components are very important for further USC development:-

- Good fabricability, castability & weldability;
- Oxidation and corrosion resistance;
- High resistance to thermal fatigue;
- Creep resistance; and
- High cycle fatigue resistance (mainly for HP blades).

More than 570 SC/USC units, installed in more than 430 power plants (status 2008) with rating from 200MW to 1300MW and total capacity of above 330GW, are in operation or under planning & construction worldwide - including Europe, USA, Japan, Russia, PR China, India and number of other countries (Figure 8).

The majority of these units operate at steam pressure / temperature below 24MPa / 595℃ in order to utilize all-ferritic components for thick wall boiler components.

As said above, PR China is now installing SC power plants as standard and Indian Government is also intensively promoting implementation of SC/USC technology for the future pulverized coal based thermal power plants.

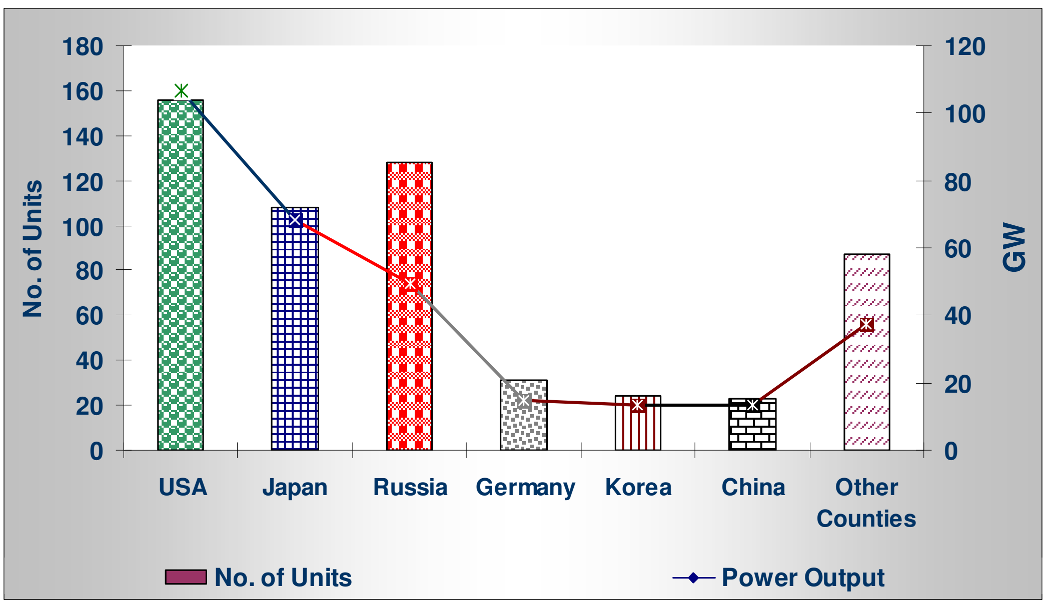


FIGURE 8
NUMBER AND CAPACITY OF SC/USC POWER PLANTS WORLDWIDE[8]

SC/USC industry was suffering more from the bullish expansion and uncontrolled increase in the unit size rather than from extreme pressures and temperatures themselves.

Before this decline, unit size had been gradually increasing from 200MW up to 500MW output within relatively short period between 1960 and 1975.

[8] Source USA DOE Newsletter

SC & USC pulverized coal fired power plants with efficiencies of above 48% and lower specific emissions than sub-critical power plants have a great future in the coal fired power generation industry worldwide.

SUPERCRITICAL & ULTRA-SUPERCRITICAL TECHNOLOGY – PRESENT & FUTURE OPTION

The SC and USC technology are the most-advanced coal based thermal power technologies today. With either technology, a steam generating unit operates under temperatures and pressures above the critical point, at which the boundary of water's liquid state and a vapor state disappears.

By eliminating the transition of water into steam, the power units considerably increase the fuel efficiency.

Historically, it was widely well known that from the traditional 16.5MPa/538°C single reheat cycle, dramatic improvements could be achieved by raising the main steam pressure to levels above 30.0MPa and temperatures to levels in excess of 600/620°C resulting in an improvement of net (LHV) efficiencies from 40% to 46% and above.

The early SC units in commercial operation experienced problems related to the higher maintenance costs as well as to lower operational flexibility, availability and reliability.

Typical problems were linked to the ST control valve wear, to the thermal stress and turbine blade solid particle erosion problems, much more complicated start-up process as well as probability of greater potential for turbine water induction through the main steam system compare to drum-type subcritical units.

SC/USC technology is also more sensitive to feedwater quality. Water chemistry has been perceived to be more complicated in SC/USC plants.

Problems related to turbine stress corrosion cracking experienced in the past were largely due to the use of deoxygenated all-volatile cycle chemistry.

The solution to these problems was the combination of a condensate polishing plant with oxygenated treatment which is a well proven procedure.

Except provision of full-flow condensate polishing plant no additional installations for supercritical power plants (compared to the sub-critical power plants) are required.

There are no operational limitations due to use of SC/USC once-through (OT) boilers compared to sub-critical drum type boilers. In fact OT boiler technology is better suited to frequent load variations than drum type boilers, since the drum is a component with a high wall thickness, requiring controlled heating.

OT technology offers excellent higher loads operational dynamics with ramp rates in the range of 6%-8%/min compared to about 3%-4%/min for sub-critical units. This makes OT boilers more suitable for fast startup as well as for transient conditions.

Limitations on achievable steam parameters are set by creep properties of currently available construction materials for high temperature boiler sections, main steam piping and other components, as well as high temperature corrosion resistance of super-heater and re-heater materials.

Higher steam temperatures make the change from ferritic steel to austenitic steel and inconel unavoidable.

Today's design of a typical advanced, single reheat, ST for USC 1000MW-class applications, takes the form of a modular, tandem-compound, four- to six-cylinders arrangement with a single crossover pipe.

The main steam enters the HP turbine through main steam valves. The HP turbine has usually full arc admission and is designed for the highest steam conditions.

Exhaust steam from the HP stage is reheated and fed to the double-flow IP turbine, being fed subsequently to the two low pressure (LP) double-flow STs via a single crossover pipe, giving a four-flow exhaust arrangement into the condenser.

The last-stage (LS) blades length for full-speed (3,000rpm) 50Hz applications are up to 1140mm (45 inches) for steel and up to 1,400mm (55 inches) for titanium. For 60Hz (3,600rpm) 965mm (38") titanium LS may be used.

WATER-STEAM CYCLE OPTIMIZATION

The efficiency of the coal fired power plant water/steam cycle can be optimized by:-

- Condenser pressure reduction;
- Boiler flue gas temperature reduction;
- Reduction of boiler pressure losses and leakages;
- Minimization of combustion air excess;
- Thermal losses minimization;
- Improvement of boiler & steam-turbine components technical design;
- Main steam parameters optimization;
- Proper reheat or double reheat applications;
- Feed water temperature optimization;

Some of these measures have been taken into account during design & development stage of high efficient USC Power Plants in both Europe and Japan which achieved (or are suppose to achieve) net plant efficiencies of around 46-48%.

The most important step towards the above goal is the optimization of main steam temperature and pressure together with improvement of feed water heating and steam reheating system.

Currently the most efficient coal fired USC power plants are operating with main steam temperatures in the range of 600-610℃. This is an increase of about 60-80℃ during last 35 years. It is expected that steam temperatures will raise another 50-100℃ in the next 20-30 years.

The improvements of steel brought significant progress in increase of main and reheat steam temperatures from the 540-560℃ range to 600-610℃ and above.

Higher main steam temperatures also mean higher efficiencies but on the other side with rising steam temperatures also superheating of the bleed steam for the regenerative feed-water heaters will continue to increase.

This means that in modern water/steam cycles the efficiency gain through higher main and reheat steam temperatures is reduced for that part of the reheat steam that is later on used as superheated bleed steam for the feed-water heaters.

Additionally the replacement of single-reheat by double-reheat cycle is considerably contributing to an improvement of power plant performance.

The benefits of using the double-reheat cycle are further enhanced by implementation of SC/USC pressures and temperatures.

However for any power generation application, the possible power output and efficiency gain with double-reheat must be thorough-fully evaluated against the higher investment costs attributable to greater equipment complexity in the boiler, steam turbine and piping system and at last but not least the fuel costs and environmental requirements.

One of the most important parts of any SC/USC power plant optimization is the selection of final feed water temperature (FWT) and reheat pressure (RP), resulting in possible improvement of relative efficiency of:-

- up to 0.8% for single-reheat; with optimum FWT of 316°C and RP 6.0-7.0MPa; and
- up to 1.5% for double-reheat; with optimum FWT of 327°C and first RP 9.5-10.0MPa and second RP 2.5-3.5MPa.

The single reheat has been the standard water/steam cycle for coal fired units for many years in the past, however the demands for ever higher cycle performances is giving the double reheat cycle the advantage over time.

Another very important factor for cycle optimization is the steam temperature at LP ST inlet. The maximum allowable LP ST inlet temperature is limited by material considerations, mainly the rotor and cross-over hood.

Optimization of reheat pressure (RP), cross-over pressure (COP) and feed water temperature (FWT) plays a very important role in the cycle optimization.

Typical recommended guideline values for double-reheat cycle 31.0MPa/ 600/610/610°C:

FWT=327°C ⇒ 1st RP=9.5MPa ⇒ 2nd RP=3.5MPa ⇒ COP=1.0MPa

A good example from the past is the joint research project for a coal Reference Power Plant (RPP) in Germany with net efficiencies between 46% (basic design) and 48%[9] (final option with optimized pre-heating and condensing plant) which was worked out in respect to optimize the economic and ecological aspects as described in this paper.

This project is a very important milestone for a safe, environmentally friendly and economically justifiable power generation and supply not only in Europe but also in other countries worldwide.

The main data and parameters are summarized in the following Table 1.

[9] **These values are based on inland conditions using cooling towers. Achievable net (LHV) efficiency with once-through cooling may be above 48%.**

Plant Gross Capacity	600 MW
Plant Net Capacity	552 MW
Auxiliary Consumption	8%
Plant Load Factor (PLF)	85%
ST Speed / Frequency)	3000rpm / 50Hz
Average Coal LHV	25,000 kJ/kg (5971 kcal/kg)
Net Heat Rate / Efficiency	7843.1 kJ/kWh / 45.9 %
Steam Conditions	28.5MPa / 600°C / 600°C
Reheat Steam	6.0MPa / 620°C
Feed Water Temperature	303ºC
ST Type	3-Casing, Single Reheat
Condenser Pressure	45 mbar
Boiler Type	Benson Tower with Vertical Tubing
Cooling System	Natural Draft Wet Cooling Tower (11ºC$_{\text{Ambient}}$ - 18ºC$_{\text{Cooling Water Temp.}}$
Steam Preheating	8-Preheter + External De-superheater
Last LP Blade	Titanium 1400 mm (55")

TABLE 1
RPP-MAIN PARAMETERS

Project partners of this project have been German manufacturers, operators and scientific institutes, namely VGB PowerTech as coordinator, Babcock Borsing Power Systems GmbH for the boiler, Siemens AG Power Generation for the STG and power plant design planning and construction.

RPP single reheat water-steam cycle as shown in Figure 9 was chosen for this project. It mainly consists of USC OT Boiler, three casing (HP-IP-LP) ST, condenser with main condensate pumps, feed-water tank with pumps and LP & HP preheating lines.

Siemens and Mitsui have also embarked on a joint development program to take the RPP 50Hz design as the basis for 60Hz applications.

The resulting 60Hz USC RPP has been designed with the nominal rating of 800MW$_{\text{GROSS}}$ (725MW$_{\text{NET}}$).

The steam parameters of 28.5MPa/600/610ºC were selected to incorporate good experience with large SC/USC coal fired power plants which are in operation mainly in Europe and Japan (e.g. 600MW$_{\text{GROSS}}$ Isogo, 1027$_{\text{GROSS}}$ Niedersaussen, and others; Refer also to Table 4).

Based on results of this project and under consideration of process optimization, cycle analysis as well as design aspects of the ST and boiler and steam generator a net efficiency between 49% and 51% can be achieved with the 700ºC USC steam power plant. This is a target of European AD700 research project.

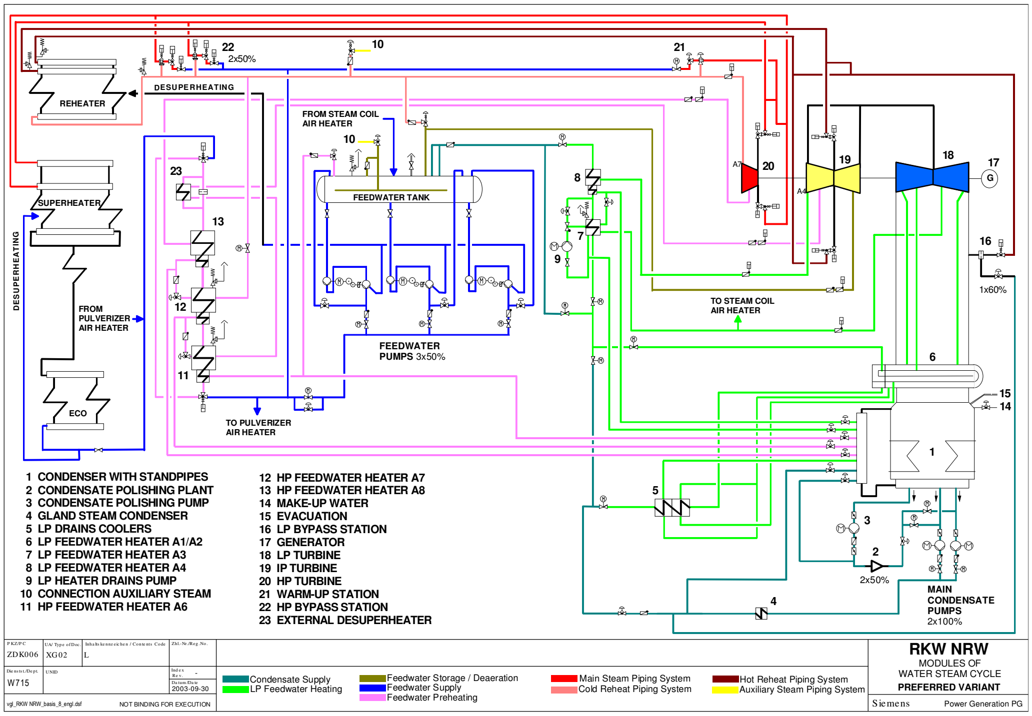


FIGURE 9
RPP WATER-STEAM CYCLE DIAGRAM[10]

We expect (IMTE AG) that Continuing development effort over the next two decades will see a USC equipment under test, operating at main steam conditions up to 37.5MPa/700/720ºC with a net power generation heat rate of below 7,000 kJ/kWh (<51%).

MATERIALS

A major challenge in designing and constructing SC/USC power plant has been area of material technology. The main goal of search for- and develop new- materials is enhancement of SC/USC performances by raising the steam pressure and temperatures. In order to achieve these goals materials with acceptable creep rupture strength at design temperatures and pressures must be used.

While materials suitable for operation with metal temperatures up to 565°C were available even 25 years ago, further development were needed to achieve 600°C and above. To allow the increase of steam pressures and temperatures to higher levels the development of high strength materials including nickel-based super-alloys for the most severely exposed boiler and ST components is considered a top material design engineering challenge.

It is important that the criteria for fabricable and weldable material creep rupture strength, steam oxidation resistance, flue gas corrosion resistance, and thermo-mechanical cycling resistance must be set up for the design and development of ferritic, austenitic and nickel-based materials to meet the targeted requirements.

[10] Courtesy of Siemens

STEAM GENERATOR (BOILER)

Unlike a drum-type boiler which has been used in sub-critical conventional power plants for many centuries, the OT boiler does not have a large steam drum to store energy.

Because there is no energy reserve, the OT boiler control system must supervise and control, continuously and very exactly, the feed-water flow and boiler firing rate (both fuel and air) to deliver the steam to the ST according to ST-generator and consequentially the network requirements.

In OT type boiler, the steam-flow rate is established by boiler's feed-water pump and the superheated steam temperature is controlled by the fuel-firing and air delivering rate. The accuracy and resolution of the power plant's (using OT boilers) distributed control system (DCS) is more important than in drum boiler units.

A well-designed control system that provides smooth regulation and the ability to hit and maintain all set-points most precisely and exactly can help utilities capitalize on the economic and environmental potential which these units offer.

OT boiler control is usually performed by boiler's load signal to the feed-water, fuel and the air control system. In this way primary feed-water flow, the fuel flow and the air flow are controlled according to built-in set values which are given as a function of the load signal.

In some cases the direct feed-water control is replaced by the measurement of the steam condition in the different parts of the boiler. In such way the set values of the feed-water flow are determined directly from the measurement of the steam conditions.

The determination of feed-water flow set values from the measurement of steam conditions eliminates uncertainty in connection with disturbances in the process because the measurement of steam conditions states exactly how much water it needs independently from other systems.

To avoid any delays caused by inertia phenomena in the process the location of transducers and the speed of control action of temperature metering system is eminently important. Just for better illustration a simple schematic comparison between both boiler types is shown in following Figure 9.

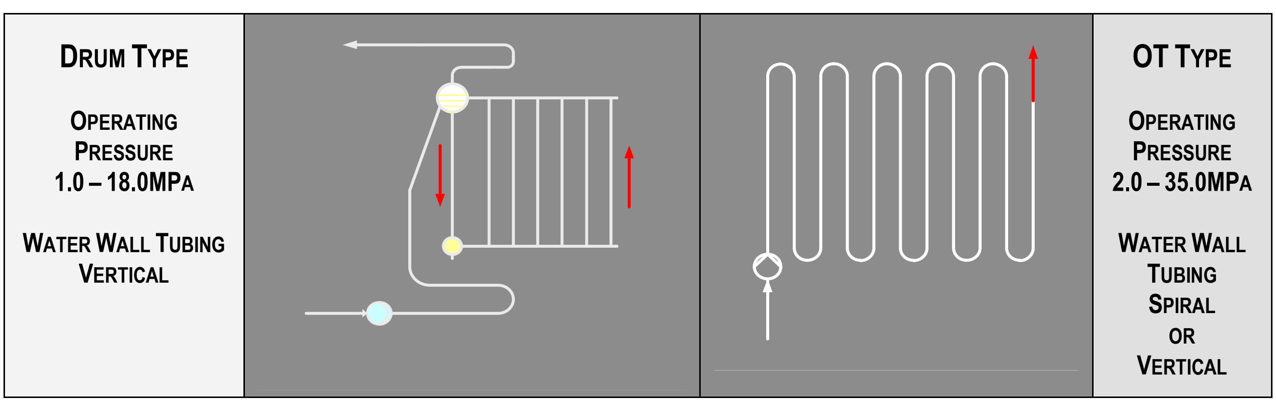


FIGURE 9
SCHEMATIC PRINCIPLE OF DRUM-TYPE VS. OT TYPE BOILER

SC/USC OT boilers operate either with a constant pressure in the furnace tubes or with pressure which vary with the load.

The latter, variable pressure boiler is the current very popular SC/USC boiler design because it is not only more efficient at lower loads, but in combination with a circulation pump, it can also be cycled on- and off- much more rapidly. These features permit the power plant operator to follow the power network system demand more effectively and fast.

The constant pressure design, with vertically oriented tubes, is more popular in United States while the variable pressure design, with spiral tubes wrapped around the furnace, is dominant in Europe.

The spiral tube design utilizes fewer tubes to obtain the desired flow per tube resulting in great benefit of passing all tubes through all heat zones to maintain a nearly even fluid temperature at the outlet of the lower portion of the furnace. However, the fabrication and erection of spiral design are considerably more complicated and costly.

On the other side, because of its relative simplicity and ability to self-support, the vertical tube furnace design is significantly less costly and easier to fabricate and construct than the spiral variable pressure furnace.

The ideal furnace design for an OT boiler would have vertical tubes and capability to operate with variable pressure operation over the load range while exhibiting natural circulation characteristics, thus protecting the tubes from overheating.

These characteristics could be achieved with as low a flow per tube as practical to obtain a low friction resistance to promote natural circulation, minimize furnace pressure loss, and reduce the pump power required. Such design represents a significant advancement for tube protection in OT boiler circulation technology.

Figure 10 shows schematic furnace arrangements for the high mass flow constant pressure vertical tube and spiral variable pressure designs as well as the relatively new advanced low mass flow vertical tube variable pressure design.

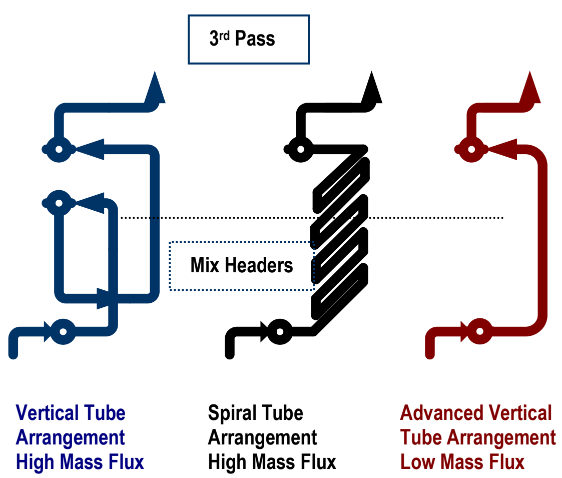


FIGURE 10
OT BOILER FURNACE ARRANGEMENTS

Since the OT boiler does not rely on the density difference between steam and water to provide proper circulation and cooling of the furnace enclosure tubes, it is perfectly designated for operation at SC/USC pressures.

To sum the above up, it can thus be said that:-

- OT boilers are very well suited for operation with frequent load variations managing the load changes of 5% per minute and higher. This makes OT boilers more suitable for fast startup as well as for transient conditions.

  One of the largest coal fired power plants equipped with a OT boiler in Germany, the 900 MW Heyden power plant, is even operating in two shift operation as is the 3x660 MW power plant in Majuba, South Africa.

- Fuel flexibility is not compromised in OT boilers. All the various types of firing systems (front, opposed, tangential, corner, four wall, arch firing with slag tap or dry ash removal, fluidized bed) used to fire a wide variety of fuels have already been implemented for OT boilers.

  All types of coal as well as oil and gas have been used. The pressure in the feed-water system does not have any influence on the slagging behavior as long as steam temperatures are kept at a similar level to that of conventional drum type boilers.

- Water chemistry has been perceived to be more complicated in SC/USC power plants. Problems experienced in the past were largely due to the use of deoxygenated all-volatile cycle chemistry.

  The solution to these problems was the combination of a condensate polishing plant with oxygenated treatment which is a well proven procedure. No additional installations for supercritical power plants compared to the standard in sub-critical power plants are required.

- In addition, OT boilers do not have a boiler blow-down. This has a positive effect on the water balance of the plant with less condensate needing to be fed into the water-steam cycle and less waste water to be disposed of.

The variable evaporation endpoint in OT boilers enables achievement of high main steam temperatures over a large output range independent of operating conditions. This offers higher cycle efficiency over a wide load range.

The fuel/feedwater flow ratio is controlled in the OT boiler in such way that the desired steam temperature is always established at the main steam outlet. This is made possible by the variable evaporation endpoint.

The evaporation and superheating surfaces automatically adjust to operating conditions. In dynamic processes, desuperheaters support maintenance of constant main steam temperature. Minimum output in OT operation at high main steam temperatures is 35% to 40% for furnace walls with smooth tubes and is as low as 20% if rifled tubes are used.

The size and geometry of the furnace of an OT boiler can be optimally matched to the fuel with no restrictions on the water/steam side.

The OT boiler technology enables dimensioning of the furnace based solely on the following combustion engineering aspects:

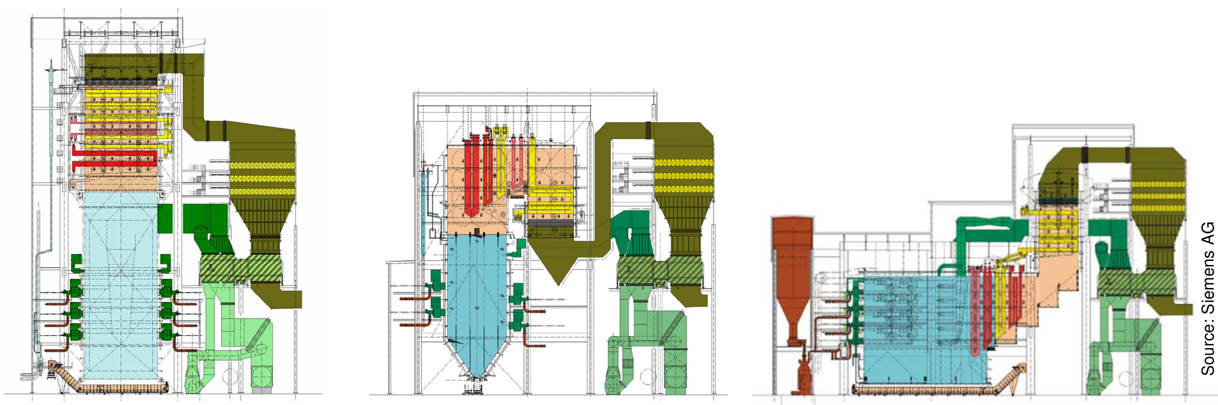
- The transition from evaporation to superheating is not fixed in location and can take place at any point in the upper section of the furnace.

This enables dimensioning of the furnace without restrictions on the water/steam side.

- Forced flow in the evaporator tubes also enables implementation of complex furnace geometries such as for slag tap firing.

Figure 11 shows the most typical OT boiler applications, the single-pass (tower-type), two-pass, and horizontal OT boiler.

The single-pass has the lowest mass of steel and pressure parts; on the other side the horizontal boiler has the advantages of short external piping. However, the economic evaluation of all three alternatives made the single-pass boiler the preferred alternative.



Single-Pass	Double-Pass	Horizontal
Floor space: 2,975 m²	**Floor space:** 4,164 m²	**Floor space:** 4,600 m²
Volume: 166,000 m³	**Volume:** 197,000 m³	**Volume:** 209,000 m³
Efficiency: 95%	**Efficiency:** 95%	**Efficiency:** 95%

Concept study reference power plant North Rhine-Westphalia (RPP NRW), Project 85.65.69 – T-138, VGB PowerTech e.V., 2004

SINGLE-PASS **DOUBLE-PASS** **HORIZONTAL**

FIGURE 11
DIFFERENT OT TYPE BOILERS[11]

Latest design of Benson Type OT boiler created within the EU-sponsored program Thermie 700 is based on horizontal furnace and internally rifled vertical pipes. Internal rifling is a microspiral grooved within the tubes.

It makes the medium inside the pipes to rotate along its trajectory and to throw the cooling medium droplets against the pipe walls via excentrical force (induced swirl). Cooling effect is boosted considerably in this manner.

The outstanding heat transfer characteristics of the optimized rifled tube can be utilized to reduce either tube wall temperatures or mass fluxes in rifled tubes.

From the material point of view the following critical SC/USC boiler components require a very special attention:- high-pressure steam piping and headers, super-heater- and water-wall-tubing.

All these components have to meet creep strength requirements for designed pressure ant temperature working level. In addition, pipes and headers, being heavy section components, are subject to fatigue induced by thermal stresses.

[11] **Courtesy of Siemens**

The overall strategy employed in the material R&D was to use ferritic-martensitic steels to their maximum temperature capability, and then to switch to Ni-based alloys for the final sections of the boiler, so avoiding the need to use austenitic stainless steels and the associated problems of dissimilar metal joints and susceptibility to thermal fatigue that arise from the coefficient of expansion mismatch and low thermal conductivity of these alloys.

Boiler design technology is currently following the trend of ever higher creep rupture stress material. Such are steels P91 to P92, austenitic steels 18-8 to 18-25 like Super 304H, Esshete 1250 as well as the high nickel alloys like Inconel 718 as shown in Table 2.

A majority of the European SC power plants which went in to commercial operation during last 20 years have utilized P91 as main HP steam- and reheat-piping.

SC/USC power plants in Europe and Japan have already proven that P92 steel can handle the very high stresses under SC and USC steam conditions. Also in United States, ASME has approved the use of P92 steel in utility boilers, pressure vessels, and power plant HP piping.

P91 is now the preferred material for heavy sections of SC/USC boilers worldwide. However, the use of P91 will probably be limited to steam conditions of about 593℃ / 25MPa, especially in Europe, where the allowable creep strength is about 10% lower than in Japan and/or the USA.

P92 is being heralded as a superior and lower-cost alternative to P91 steel for new SC/USC units with pressures above 25MPa and temperatures above 595°C to be built in Europe and United States over the next few years.

The switch from P91 to P92 represents the next step in an evolution. According to material test results the P92 steel should allow main steam temperatures up to 620℃ and pressures up to 34 MPa.

Advanced austenitic stainless steels used for super- and re-heater tubing are available for service temperatures up to 650℃ and possibly 700℃. However, none of these steels have been approved by the ASME Boiler Code Group so far.

A very interesting fact is that application of the new steels may actually result in a capital cost reduction. The extra costs of using nickel based alloys can be partly compensated by reduction in the amount of material, because of thinner pipe walls and smaller dimensions of machinery. Also austenitic steel slightly reduces the wall thickness.

The following example illustrates the material savings for HP main steam pipes. The estimation was done for 400MW SC and USC power plant.

Case 1: **25.0 MPa / 560℃ / 560℃**

Tube Material	X20CrMoV121
Inner Pipe Diameter	255 mm
Pipe Wall Thickness	58 mm

Case 2: **29.0 MPa / 580℃ / 580℃ / 580℃**

Tube Material	P91

Inner Pipe Diameter 230 mm
Pipe Wall Thickness 60 mm

Case 3: **37.5 MPa / 700°C / 720°C / 720°C**

Tube Material Super Alloy
Inner Pipe Diameter 175 mm
Pipe Wall Thickness 42 mm

Main steam		When	What	Equivalent to
Pressure MPa (psi)	Temperature °C (°F)			
<20.0 (<2900)	<520 (<968)	Since early 60's	X20	Cr Mo V 11 1
<25.0 (<3626)	<540 (<1004)	Since early 80's	P22	2 ¼ Cr Mo
<30.0 (<4351)	<560 (<1040)	Since late 80's	P91	9Cr – 1Mo
<34.0 (<4786)	<620 (<1148)	Since 1996	P92 (NF 616)	X10CrWMoVNb9-1 EUROPE STBA29-STPA29 JAPAN
<35.0 (<5076)	<700 (<1292)	Start 2010	Super Alloys	CCA 617 - IN 740 – Haynes 230 – Save 12

TABLE 2
COAL FIRED POWER GENERATION-BOILER TEMPERATURE & MATERIAL DEVELOPMENT

This may appear to become the decisive factor for even more intensive expansion of SC/USC technology, because this particular problem of extremely high cost of special steels and alloys was traditionally the main obstacle with even wider application of SC/USC technology.

Long term common goals of THERMIE 700 EUR, COST 522 EUR, EPRI-USA or CRIEPI-Japan initiatives and programs shall produce the capability to construct and operate a boiler to USC conditions of 760°C and 35.0MPa.

STEAM TURBINE

The thermodynamic performance of the ST, more than any other power plant component, determines overall power plant efficiency. Future development of high efficiency advanced ST at advanced USC conditions is largely dependent on the parallel development of advanced materials and super-alloys capable of withstanding the extreme working environments both in terms of corrosion resistance and their creep rupture strength.

Beside of material selection, the appropriate USC ST design and configuration is mainly determinated by unit output rating, LP ST back-pressure, number of reheats and other special requirements (e.g. process steam extraction).

STs for USC duty are extra category among the family of steam turbines. Typical current feature of modern USC ST is the relatively high capacity (between 600MW and 1,300MW) and multi-casing (HP-IP-LP) design.

Cross-section of 600MW_{GROSS}, three-casing UST ST (with single double-flow IP and LP casing) designed by Siemens for RPP project is shown in Figure 12.

In comparison to 50Hz ST (3000rpm) the rotating components of 60Hz ST (3600rpm) are exposed to higher centrifugal forces caused by higher operating speed (factor 1.44).

Due to this increase of centrifugal forces the last stage blade (LSB) of 60Hz application must be scaled-down by factor 1.44 (e.g. from 55” to 38”).

This will, however, reduce the steam exhaust area by factor 2.1. This make the single double-flow LP ST too small. The only compromise for 60Hz alternative is to employ more two double-flows LP sections (e.g. two double-flows LP sections instead of one).

Internal design of SC/USC ST technology has undergone a long evolutionary development. Using CFD (Computational Fluid Dynamics) software, hydrodynamic regime and blade shaping has been processed on the basis of 3-dimensional (3-D) analysis, or advanced three dimensional analyses (3-DS). In this way a complete range of new high-efficiency 3-DS ST blading has been developed.

Adopting the new design philosophy, a new type of blading for HP and IP turbine, the 3-DV blading (blading with variable stage reaction), based on an extension of existing well-proven 3-DS blading, has been developed. 3-DV blading combines the benefits of both, multistage reaction blading and low reaction impulse blading, because it offers greater design freedom.

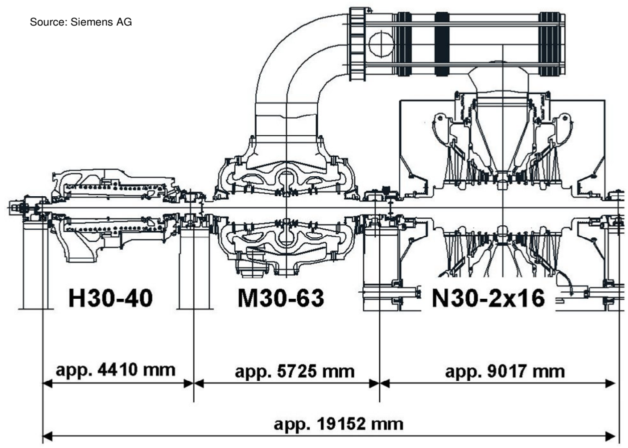


FIGURE 12
600MW$_{GROSS}$, 3-CASING USC ST[12]

With 3DV blading the stage reaction and stage loading for each row can be numerically optimized to gain higher HP and IP efficiency than was possible with previous blading types, resulting in significant improvement in overall plant efficiency.

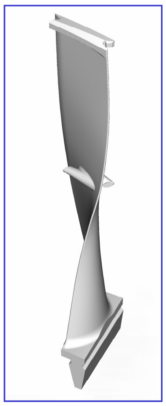
To reduce windage losses, modern USC turbines have the rotor blades fully shrouded by internal shroud blading (ISB). Usually, only the LSB row in the LP ST-section is free-standing, because of the high centrifugal forces acting in that area. The exhaust diffuser provides for pressure recovery of the exhaust steam so that the exit pressure from that blading can be lower than the condenser pressure.

[12] COURTESY OF SIEMENS

MHI apply in their 1050 MW (reportedly the biggest and most efficient 60Hz SC turbine ever built) the longest 46” (1170 mm) LSB (refer to Table 4, Tachibana-Wan 2[13]).

Application of titanium alloys to the long last stage LP ST has been in development for more than 30 years and now it became a commercial reality for many years. Titanium blades are immune to pitting corrosion by the corrosive condensates and are of relatively low weight resulting in lover centrifugal forces.

A disadvantage of titanium alloys is their low vibration damping capacity, which requires an addition of integral shroud and a mid-snubber for improvement of blade dynamic stability by maximizing of mechanical and aerodynamic damping.



Design features 16 m ^{2} - last stage blade

• Rotor diameter	~ 1900 mm
• Blade length	1400 mm (55´´)
• Velocity at blade end	750 m/s (~ Ma = 2.0)
• Mach-number	Supersonic at blade end
• Blade connection	Shroud & snubber
• Exit losses	3D effects

Source: Siemens AG

Concept study reference power plant North Rhine-Westphalia (RPP NRW), Project 85.65.69 – T-138, VGB PowerTech e.V., 2004

Siemens is using 55"/1400mm titanium alloyed LSB’s for their large 50Hz LP STs and 38"/965mm for 60Hz ST. The profile of this blade has a 3-D design and shrouding with supporting snubber in the middle of the profile as shown in the Figure 13.

FIGURE 13 LP ST 16M^2 TITANIUM LSB

Tip clearance losses at the blade tip are reduced by the integral shrouding. Additionally the integral shroud and the mid span snubber give an excellent dynamic stability of the entire stage.

Advanced material application, especially of titanium for the LSB with lower density allows longer blades to be used and thus the exhaust annulus area to be increased. The smaller LP blades are made of high chromium steel and are usually also equipped with integral shrouds to minimize leakage losses.

Advanced materials used for HP SC/USC turbine components are of higher quality grade compare to the conventional steam conditions of 538°C or below.

Many of the latest coal-fired SC/USC power plants are operating (or are designed to operate) with main steam temperatures around 600°C. The use of martensitic-ferritic steels is expected to allow this temperature to be raised to 620°C, which probably represents the inherent limit of capability of these advanced steels.

The optimum design figure for creep resistance after 100,000 hours as a function of temperature for steam turbine components is 100MPa. Within these parameters, the upper temperature limit for chromium steel alloys with between 9% and 11% Cr is 620°C.

[13] CROSS-COMPOUND MACHINE WITH THE HP AND IP CYLINDERS POSITIONED ON THE HIGH-SPEED SHAFT (3600 RPM) AND TWO DOUBLE-EXHAUST LP CYLINDERS ON THE LOW-SPEED SHAFT (1800 RPM).

Research which was currently carried out to extend the application range up to 650℃ has still not been successful (due to current non-availability of suitable materials).

High pressure SC/USC ST materials - comparison of 760℃ - 700℃ - 620℃ class to conventional 560℃ class for 50Hz grid is shown in Table 3.

Main steam temperature	≤560°C	≤620°C	≤700°C	≤760°C
HP Rotor (Forgings)	1Cr Mo V 12Cr Mo V Nb N 26Ni Cr Mo V	9-12Cr W Co 12Cr Mo W V Nb N	IN 625 / IN 740 CCA 617 (NiCrCoMo) Haynes 230	CCA 617 Inconel 740 Alloy 263/625/718
Nozzles / Valves	Cr Mo V 10Cr Mo V Nb	9-10% Cr (W) Cast 12Cr W (Co) 12Cr Mo W V Nb N	CCA 617 IN 625 / IN 714	CCA 617 Inconel 740 Alloy 263/625/718
Inner HP Casing & Shells (Casting)	Cr Mo V 10 Cr Mo V Nb	9-10% Cr (W) Cast 12Cr W (Co) Cr Mo W V Nb N	CF8C (Ni Cr Nb) CCA 617 IN 625 / 718	CCA 617 (NiCrCoMo) Inconel 740 Alloy 263/625
Blading (Vanes & Blades)	10Cr Mo V Nb N Titanium (last LP rotor stage blades)	9-12% Cr W Co Titanium (last LP rotor stage blades)	Wrought Ni-Base Titanium (last LP rotor stage blades)	Wrought Ni-Base Titanium (last LP rotor stage blades)
Bolting	9-12% Cr Mo V NI 80A IN 718	9-12% Cr Mo V IN 718	Nimonic 105/115/718 IN 718 Waspaloy	Nimonic 105/115 Udimet 700/710/720
HP Piping	P 22	P 92	CCA 617	Inconel 740

TABLE 3
COAL FIRED POWER GENERATION- ST TEMPERATURE & MATERIAL DEVELOPMENT[14]

SC/USC ST improved design features include not only improved aerodynamics and application of most advanced materials but also new high-speed control valves, unique shaft and inlet seals, and many other innovations required for power plant safe and highly reliable operation.

Since the different parts of the ST are exposed to different stress-temperature-environment conditions for a given set of steam entry parameters, the distribution of these conditions needs to be defined in order to define the material properties required.

The lack of materials with the necessary required resistance to creep, oxidation, corrosion, and thermal fatigue at the envisaged main steam temperatures and pressures currently limits the adoption of advanced USC steam conditions in pulverized coal-fired power plants.

The steam parameters envisaged for the future USC ST generation (700-760°C and 35.0MPa) are well beyond the envelope of current experience, however the further development of SC/USC technology is ensured due to the continued development of new high temperature resistant materials as required by the joint European project AD700 heading for main steam temperatures of 700 - 760 ℃.

[14] DUE TO THE HIGHER ST OPERATIONAL SPEED IN A 60HZ GRID, THE TEMPERATURE LIMITS FOR THE MATERIALS WILL BE SLIGHTLY DIFFERENT (FOR EXAMPLE ADDING OF BORON & COBALT FOR 9-12%CR STEEL TO INCREASE CREEP RESISTANCE AND REDUCE OXIDATION)

The preliminary outcome AD700 material R&D activities are positive and it is envisaged that the AD700 project could start around 2010 with the construction of a 400 MW demonstration plant in Europe.

Around 5-6 years would be needed for construction, testing, commissioning and around 2 years of operation to pick up operational experiences.

If everything moves well, the AD700 technology should be commercially ready around 2015.

SELECTED SC/USC APPLICATIONS

Comparing to sub-critical pulverized coal-fired power plants, SC/USC technology is one example of a “clean coal” technique that burns coal more efficiently (currently up to 45% compared with an average of around 36% for subcritical units) and with lower emissions.

SC/USC is an emerging technology with limited construction history, although it has been used more extensively in countries such as United States, Russia, Japan, Germany, Italy and Denmark.

The following Table 4 illustrates some selected projects representing state-of-the-art SC/USC technology with reputable parameters that have already been commissioned, or are currently under construction:

Pos	Power Plant Name	Country	Hz	Power Output MW_{NET} (MW_{GROSS})	Thermal Efficiency $\%_{LHV/NET}$ ($\%_{LHV/GROSS}$)	Main Steam MPa /°C /°C	COD
1	Boxberg	Germany	50	915	41.7	26.7 / 555 / 578	2000
2	Niederaussem 1	Germany	50	965	43.2	26.0 / 580 / 600	2003
3	Boa 2 & 3 Neurath	Germany	50	2 x 1100	>43.0	26.0 / 595 / 595	2010
4	Westfalen 1 & 2	Germany	50	2 x 765	46.0	28.5 / 600 / 610	>2010
5	Niederaussem 2&3	Germany	50	2 x 1050	45.2	27.2 / 600 / 605	2010/11
6	Council Bluffs	USA	60	790		25.3 / 566 / 593	2007
7	Weston 4	USA	60	500		26.2 / 580 / 580	2008
8	Comanche 3	USA	60	750		26.2 / 570 / 570	2009
9	Elm Road 1 & 2	USA	60	2 x 600		26.2 / 570 / 570	2009/10
10	Iatan 2	USA	60	850		25.5 / 585 / 585	2010
11	Genesee 3	Canada	60	495		25.0 / 570 / 568	2005
12	Emshaven 1 & 2	Netherlands	50	2 x 780	>46.0	28.5 / 600 / 610	>2010
13	Lagisza	Poland	50	460	43.3	27.5 / 560 / 580	2009
14	Misumi	Japan	60	1000		25.5 / 600 / 605	1998
15	Tsuruga 2	Japan	50	700		25.5 / 597 / 595	2000
16	Tachibana-wan 1	Japan	60	(700)		24.1 / 565 / 593	2000
17	Tachibana-wan 2	Japan	60	1050	43.1	26.4 / 605 / 613	2001
18	Hekinan 4 & 5	Japan	60	(2 x 1000)	42.0	25.0 / 571 / 596	2001/02
19	Isogo 1	Japan	50	600	43.0	25.0 / 600 / 610	2002

Pos	Power Plant Name	Country	Hz	Power Output MW_{NET} (MW_{GROSS})	Thermal Efficiency $\%_{LHV/NET}$ ($\%_{LHV/GROSS}$)	Main Steam MPa /°C /°C	COD
20	Hekinan 4 & 5	Japan	60	2 x 1000		25.0 / 571 / 596	2001/02
21	Tomato-Atsuma	Japan	50	(700)		25.0 / 603 / 602	2002
22	Hitachi-Naka 1	Japan	50	(1000)		25.4 / 604 / 602	2003
23	Kobe 2	Japan	60	700		24.1 / 537 / 565	2005
24	Isogo 2	Japan	50	600		25.0 / 600 / 620	2009
25	Cogan Creek	Australia	50	750		25.0 / 540 / 560	
26	Waigaoqiao I	PR China	50	2 x 900		25.8 / 542 / 568	2004
27	Changshu	PR China	50	3 x 600	42.0	25.9 / 569 / 569	2006
28	Wangqu	PR China	50	2 x 600	43.0	24.7 / 571 / 569	2007
29	Waigaoqiao II	PR China	50	1000		27.0 / 600 / 600	2007
30	Huaneng	PR China	50	4 x 1000		26.5 / 600 / 600	2006/08
31	Yuhuan	PR China	50	4 x 1000	43.0 - 45.0	27.5 / 605 / 600	2006/08
32	Zouxian IV	PR China	50	2 x 1000		27.0 / 600 / 600	2008
33	Yonghung 1 & 2	S. Korea	60	(2 x 800)		25.5 / 569 / 569	2004
34	Tangjin 5 & 6	S. Korea	60	2 x 500		25.5 / 569 / 596	2005
35	Yonghung 3 & 4	S. Korea	60	(2 x 870)		25.5 / 569 / 596	2008/09
36	Poryong 7 & 8	S. Korea	60	2 x 500		25.5 / 569 / 596	2008
37	Taean 7 & 8	S. Korea	60	(2 x 550)			2008
38	Hadong 7 & 8	S. Korea	60	2 x 500		25.5 / 569 / 596	2009
39	Sasan	India	50	(5 x 800)		25.5 / 569 / 569	2008
40	Sipat	India	50	(3 x 660)	39.0	25.0 / 540 / 568	2008
41	Shahapur	India	50	(3 x 800)			2011
42	Mundra	India	50	(5 x 800)			2012

TABLE 4
SELECTED SC/USC POWER PLANTS IN OPERATION OR UNDER CONSTRUCTION

Boxberg 1 USC (Table 4, Pos. 1) and Tachibana-wan 2 SC power plant (Table 4, Pos. 17), achieved the net (LHV) efficiency of 42.7% (Boxberg) and 43.1% (Tachibana-wan) at substantial different steam conditions.

According to MHI, only a steam temperature increase from 538/593ºC to 600/600ºC improves the net efficiency by about 1.1%. On the other side, according to Siemens engineers, raising both, the steam pressure and temperature from 25.0Mpa/540/560ºC to 27.0MPa/585/600ºC increases the net efficiency by about 1.3-1.5%.

So, closeness of the actual efficiency values for the same capacity class turbines with remarkably different steam temperatures, and with regard to similar condenser pressure in the range says that at least one of these STs have noticeable reserves to increase the efficiency.

However, these most impressive efficiencies which have been reached at Boxberg and Tachibana-Wan power plant have been beaten by Niederaussem Power Plant (Table 4, Pos. 6). This plant which is working at more elevated steam conditions, 27.5MPa/580/600ºC, reached a net efficiency of 45.2%.

And even higher net efficiency is targeted for Westfalen's Unit D (Table 4, Pos. 5), with a single capacity of 760MW designed for steam conditions of 29.0Mpa/600/620ºC.

Mitsubishi Power Systems has pushed the limits of steam-turbine design with its 600°C large capacity SC/USC ST units. These large- scale, high-temperature turbines are configured as four case cross- compound units using both an HP and IP turbine on a primary shaft, and two IP turbines on a secondary shaft.

The design and material technology, which includes 12 Cr steel blades was introduced at the Japan's largest coal-burning thermal power plant, the Unit 3 at Hekinan.

The Unit 4 & 5 (supplied by Toshiba) of Hekinan Power Plant (Table 4, Pos. 20) are the first 1,000MW tandem compound type STs in the 60Hz Area of the World.

Also higher efficiencies are expected from latest Japanese coal fired USC power plants with improved steam conditions in the range of 30.0Mpa/630/630ºC by the end of this and early next decade.

Summary

Coal has excellent prospects if efforts to engineer its transformation into a clean energy source with a neutral impact on the climate. Abundant deposits and the favorable global distribution enable a relatively secure energy supply in many countries worldwide, particularly when oil already became scarce and thus expensive and later also natural gas may follow this price escalation trend.

Up to date (July 2008) pulverized coal fired power plants account for more than 40% of electrical power produced in the world.

The transition period in which coal may be the only answer could be limited; this requires fast progress in commercialization of clean and highly efficient coal fired power generation units.

Probably most of the coal fired power plants to be build worldwide during next decades will be of:-

- Pulverized coal fired SC/USC technology; and/or
- IGCC technology

Due to its excellent fuel utilization, the SC/USC is probably one of the best clean coal technologies because it minimizes the amount of coal required for production of relevant MWh energy.

SC/USC power generation technology is superseding conventional sub-critical technology in many countries worldwide.

The further development of this technology is ensured due to the continued development of new high temperature resistant materials as required by the joint European project AD700 heading for main steam temperatures of 700 - 760℃.

Expected reduction in specific investment costs combined with low emissions makes SC/USC technology preferable option for future power generation.

To design & construct an economically optimized pulverized coal-fired power plant, the cycle conditions under which such plant shall operate need to be carefully evaluated taking into account miscellaneous important parameters as the main steam conditions, feed water arrangement as well as the number of reheats employed.

Industrial-scale power plants with SC/USC steam conditions are in operation or are under construction in many countries worldwide. These power plants shall reach net electric efficiencies of over 40%.

To open up further efficiency potentials, the electricity supply industries are developing even more advanced power plant concepts using advanced materials for boiler and ST. This can push the efficiency (heat rate) to 50-52% (7200-6900 kJ/kWh) in 2020 and further development could offer 52-55% (6,900-6,550 kJ/kWh) efficiency (heat rate) in 2050.

The assurance of long-term prospects for coal in the industrialized countries constitutes a decisive precondition necessary to develop the advanced technologies there and also apply them in the developing and threshold countries as required by the envisaged sustainable development.

Pressure on energy resources and demand for zero emission power plant will continue and even grow in future, so there is indeed a need for more effective and sustainable power generation technology. In this respect the overall outlook for pulverized coal-fired SC/USC power plant technology is promising and its further growth lies ahead.

Breakthroughs of backstop technologies such as nuclear fusion need much more time. **Until then more environmentally-friendly use of coal will be of the essence.**

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Major Acronyms & Abbreviations:

ASME	American Society of Mechanical Engineers
CFD	Computational Fluid Dynamics
COD	Commercial Operation Date
COP	Cross-Over Pressure
DCS	Distributed Control System
DOE	Department of Energy
EU	European Union
EPRI	Electric Power Research Institute
FO	Fuel Oil
FWT	Feed Water Temperature
GE	General Electric
HP	High Pressure
IGCC	Integrated Gasification Combined Cycle
IP	Intermediate Pressure
ISB	Internal Shroud Blading
LHV	Low Heating Value
LNG	Liquefied Natural Gas
LP	Low Pressure
LSB	Last Stage Blade

MHI	Mitsubishi Heavy Industries
NG	Natural Gas
OPEC	Organization of the Petroleum Exporting Countries
OT	Once-Through
PLF	Power Load Factor
R&D	Research & Development
RP	Reheat Pressure
RPP	Reference Power Plant
SC	Supercritical
ST	Steam Turbine
Sm^3	Standard Cubic Meter
USC	Ultra-Supercritical