

Supercritical Coal Fired Power Plants

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A Technology Being Successfully Deployed in Developing Countries

Ingo Paul

Supercritical coal fired power plants with efficiencies of 45% have much lower emissions than subcritical plants for a given power output. The paper reviews the major technical and performance aspects of a coal fired plant using this technology. These include the turbine-generator set, the once-through boiler and operational issues such as load change, fuel flexibility and water. Early experience with supercritical plants in the US indicated that they had poor availability i.e. forced outages were greater than with subcritical plants. However experience that takes account of plant performance in Japan and Europe as well as in China and South Africa (where these once through boilers plants are common) shows that these plants are just as reliable as subcritical plants.

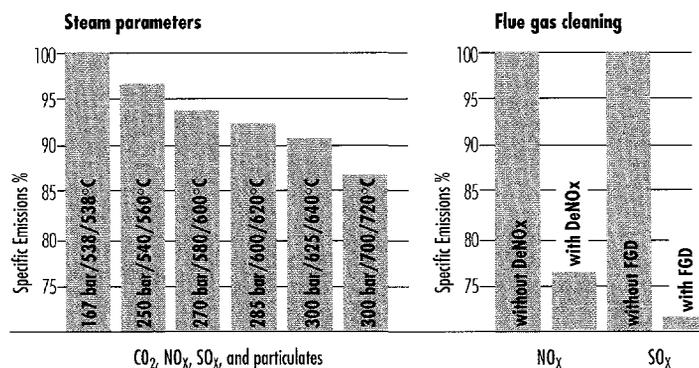
Worldwide, more than 400 supercritical plants are now in operation.

Reviewing the possibilities for the design and manufacture of components for supercritical-fired plants in developing countries, the paper notes that the differences between subcritical and supercritical power plants are limited to a relatively small number of components; primarily the feedwater pumps and the high-pressure feedwater train equipment. All the remaining components that are common to subcritical and supercritical coal-fired power plants can be manufactured in developing countries. The paper concludes with a review of Schwarze Pumpe—the world's largest supercritical lignite fired steam power plant.

Why High Performance Coal Fired Power Plants Matter

Power Markets Today Many regions of the world are experiencing fast growing electricity demand. Permitted emissions from power plants have been reduced so as to meet air quality standards. Power plants are also a source of CO₂, one of the greenhouse gasses that the Kyoto Protocol proposes should be subject to legally binding emissions reductions or lim-

Figure 1 Low Emission Levels
are achieved by High Steam Conditions and Flue Gas Cleaning



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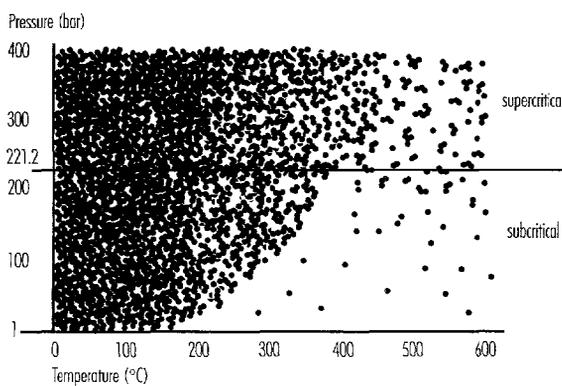
Ingo Paul is Head of Product Management for fossil-fueled steam power plants at Siemens Power Generation (KWU). This paper has been prepared under the aegis of a Siemens/World Bank partnership program (c.f. note on page 8). The paper was reviewed and edited by Masaki Takahashi, Stratos Tavoulareas and Kyran O'Sullivan of the Energy, Mining and Telecommunications Department of the World Bank.



itations. Capital scarcity and competition are maintaining downward pressure on prices of new plant. Meanwhile electricity generated from coal currently accounts for about 40 percent of total worldwide production. Coal is an abundant fuel resource in many of the worlds' developing regions and forecasts show that it is likely to remain a dominant fuel for electricity generation in many countries for some years to come.

It is against this backdrop that power plant suppliers have invested heavily in generation technologies that produce power more efficiently. Enhanced plant reduces emissions of CO₂ and all other pollutants by using less fuel per unit of electricity generated. While the efficiencies of older power plants in developing countries like China and India are still around 30% lower heating value (LHV), modern subcritical cycles have attained efficiencies close to 40% (LHV). Further improvement in efficiency can be achieved by using supercritical steam conditions. Current supercritical coal fired power plants have efficiencies above 45% (LHV). One percent increase in efficiency reduces by two percent, specific emissions such as CO₂, NO_x, SO_x and particulates (Figure 1).

Figure 2 Density Changes (schematic) of Water and Steam



What is Critical about Supercritical?

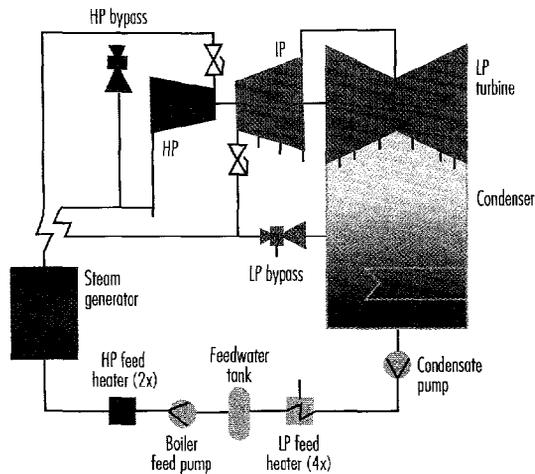
There's nothing "critical" about supercritical. "supercritical" is a thermodynamic expression describing the state of a substance where there is no clear distinction between the liquid and the gaseous phase (i.e. they are a homogenous fluid). Water reaches this state at a pressure above 22,1 megapascals (MPa) (Figure 2).

The "efficiency" of the thermodynamic process of a coal fired power describes how much of the energy fed into the cycle is converted into electrical energy. The greater the output of electrical energy for a given amount of energy input, the higher the efficiency. If the energy input to the cycle is kept constant, the output can be increased by selecting elevated pressures and temperatures for the water-steam cycle.

Up to an operating pressure of around 19 MPa in the evaporator part of the boiler, the cycle is subcritical. This means, that there is a non-homogeneous mixture of water and steam in the evaporator part of the boiler. In this case a drum-type boiler is used because the steam needs to be separated from water in the drum of the boiler before it is superheated and led into the turbine. Above an operating pressure of 22,1 MPa in the evaporator part of the boiler, the cycle is supercritical. The cycle medium is a single phase fluid with homogeneous properties and there is no need to separate steam from water in a drum. Once-through boilers are therefore used in supercritical cycles.

Advanced Steels Currently, for once-through boilers, operating pressures up to 30 MPa represent the state of the art. However, advanced steel types must be used for components such as the boiler and the live steam and hot reheat steam piping that are in direct contact with steam under elevated conditions. Therefore, a techno-economic evaluation is the basis for the selection of the appropriate cycle parameters. Figure 3

Figure 3 Supercritical Steam Conditions are the Key to Economical Operation



Design Features

Super-critical Steam Conditions – 250 MPa/540°C/540°C

Condensate Polishing

Advantages

Higher Thermal Efficiency

Proven Design, Components and Materials

depicts a supercritical cycle arrangement with steam parameters that yield high efficiency while allowing the use of well-proven materials.

Steam Conditions Today's state of the art in supercritical coal fired power plants permits efficiencies that exceed 45%, depending on cooling conditions. Options to increase the efficiency above 50% in ultra-supercritical power plants rely on elevated steam conditions as well as on improved process and component quality.

Steam conditions up to 30 MPa/600°C/620°C are achieved using steels with 12% chromium content. Up

to 31,5 MPa/620°C/620°C is achieved using Austenite, which is a proven, but expensive, material. Nickel-based alloys, e. g. Inconel, would permit 35 MPa/700°C/720°C, yielding efficiencies up to 48%. Manufacturers and operators are cooperating in publically sponsored R&D projects with the aim of constructing a demonstration power plant of this type.

Other improvements in the steam cycle and components can yield a further 3 percentage points rise in efficiency. Most of these technologies, like the double reheat concept where the steam expanding through the steam turbine is fed back to the boiler and reheated for a second time as well as heat extraction from flue gases have already been demonstrated. However, these technologies are not in widespread use due to their cost.

The Turbine Generator Set

There are several turbine designs available for use in supercritical power plants. These designs need not fundamentally differ from designs used in subcritical power plants. However, due to the fact that the steam pressure and temperature are more elevated in supercritical plants, the wall-thickness and the materials selected for the high-pressure turbine section need reconsideration. Furthermore, the design of the turbine generator set must allow flexibility in operation. While subcritical power plants using drum-type boilers are limited in their load change rate due to the boiler drum (a component requiring a very high wall thickness), supercritical power plants using once-through boilers can achieve quick load changes when the turbine is of suitable design.

High Pressure (HP) Turbine In the HP turbine section, the steam is expanded from the live steam pressure to the pressure of the reheat system, which is usually in the order of 4 to 6 Mpa. In order to cater for the higher steam parameters in supercritical cycles, materials with an elevated chromium content giving greater

material strength are selected. The wall thickness of the HP turbine section should be as low as possible and should avoid massive material accumulation (e.g. of oxides) in order to increase the thermal flexibility and accommodate fast load changes.

Intermediate Pressure (IP) Turbine Section The steamflow is further expanded in the IP turbine section. In supercritical cycles there is a trend to increase the temperature of the reheat steam that enters the IP turbine section in order to raise the cycle efficiency. As long as the reheat temperature is kept at a moderate level (approximately 560°C) there is no significant difference between the IP turbine section of a supercritical plant and that of a subcritical plant.

Low Pressure (LP) Turbine Section In the LP turbine section the steam is expanded down to the condenser pressure. The LP turbine sections in supercritical plants are not different from those in subcritical plants.

The Boiler

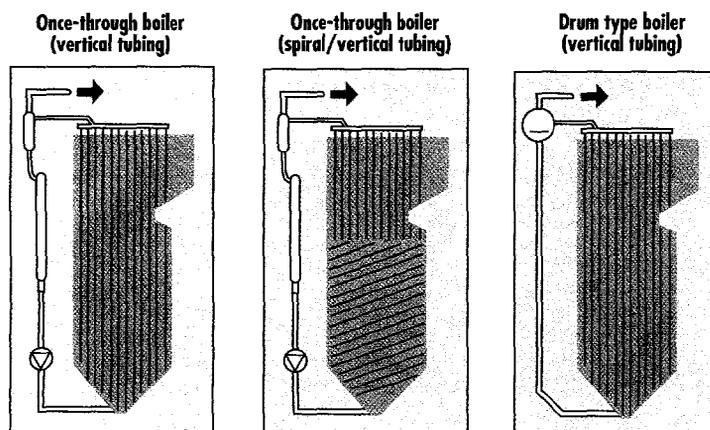
Apart from the turbine generator set, the boiler is a key component in modern, coal fired power plants. Its concept, design and integration into the overall plant considerably influence costs, operating behavior and availability of the power plant.

Once-through boilers have been favored in many countries, for more than 30 years. They can be used up to a pressure of more than 30 MPa without any change in the process engineering. Wall thicknesses of the tubes and headers however need to be designed to match the planned pressure level. At the same time, the drum of the drum-type boiler which is very heavy and located on the top of the boiler can be eliminated. Since once-through boilers can be operated at any steam pressure, variable pressure operation was introduced into power plants at the start of the 1930s to make the operation of plants easier.

Once-through boilers have been designed in both two-pass and tower type design, depending on the fuel requirements and the manufacturers' general practice. For the past 30 years, large once-through boilers have been built with a spiral shaped arrangement of the tubes in the evaporator zone. The latest designs of once-through boilers use a vertical tube arrangement (Figure 4).

Other Cycle Components A comparison of the water-steam cycle equipment in subcritical and supercritical coal fired power plants shows that the differences are limited to a relatively small number of components i.e. to the feedwater pumps and the equipment in the high pressure feedwater train i.e. downstream of the feedwater pumps. These components represent less than 6% of the total value of a coal fired power plant.

Figure 4 Various Boiler Types



Supercritical Plants Have High Efficiency and Reliability

Operational Issues More than 400 supercritical power plants are operating in the US, in Europe, Russia and in Japan. Due to different approaches in their design and operation performance results are not uniform. While the rapid introduction of very large plants in the US in the early 70s created problems in the availability, due to forced outage, of these plants, feedback from other operators is very positive. Availability of supercritical plants are equal or even higher than those of comparable subcritical plants.

A number of power plants operate with once-through boilers and supercritical steam conditions in developing countries today. The South African utility ESKOM has been operating a number of once-through boilers for several years and local industry has participated in the design and manufacture of these plants. The 2 x 600 MW supercritical coal fired power plant Shidongkou in the Shanghai area of China was put into operation in the early 90s.

There are no operational limitations due to once-through boilers compared to drum type boilers. In fact once-through boilers are better suited to frequent load variations than drum type boilers, since the drum is a component with a high wall thickness, requiring controlled heating. This limits the load change rate to 3% per minute, while once-through boilers can step-up the load by 5% per minute. This makes once-through boilers more suitable for fast startup as well as for transient conditions. One of the largest coal fired power plants equipped with a once-through boiler in Germany, the 900 MW Heyden power plant, is even operating in two shift operation as is the 3 x 660 MW power plant in Majuba, South Africa.

Fuel flexibility is not compromised in once-through 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 once-through 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 behaviour 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 supercritical power plants. Problems experienced in the past were largely due to the use of deoxygenated all-volatile (AVT) cycle chemistry. The solution to these problems was the combination of a condensate polishing plant with oxygenated treatment (OT) which is a well proven procedure. No additional installations for supercritical power plants compared to the standard in subcritical power plants are required.

In addition, once-through boilers do not have a boiler blowdown. 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.

Design and Manufacture of Components for Supercritical Coal Fired Plants in Developing Countries

There is a misconception, that the components of supercritical coal fired power plants can only be designed and manufactured in developed countries due to the complexity of the technology. As discussed, the differences in the technology between subcritical and supercritical coal fired power plants are limited to small

number of components. All developing countries using coal in base load (e.g. China and India) have already large manufacturing capacity in the components common to subcritical and supercritical plants and are now building up capacity in those components that are specific to supercritical. For example manufacture of the turbine generator set and boiler for the 2 x 900 MW Waigaoqiao supercritical plant is being done in China.

Life Cycle Costs of Supercritical Coal Fired Power Plants The life cycle costs of supercritical coal fired power plants are lower than those of subcritical plants.

The Schwarze Pumpe Power Plant — A Milestone

The world's largest lignite-fired steam power plant Schwarze Pumpe in Germany (Figure 5) is equipped with two 800 MW steam turbine generators designed for super critical steam conditions of 25 MPa /544 C/562 C. The net efficiency of this plant is about 41%, a very high value for a plant using lignite.

The Schwarze Pumpe concept is based on a study conducted in 1991 for VEAG by an association formed by RWE Energie AG and VEBA Kraftwerke Ruhr AG

The design features:

- A twin unit plant (2 x 800 MW)
- Utilization of flue gas heat for condensate heating
- Dual train flue gas discharge (without bypass around the flue gas desulphurization system) via the cooling tower.

Current designs of supercritical plants have installation costs that are only 2% higher than those of subcritical plants. Fuel costs are considerably lower due to the increased efficiency and operating costs are at the same level as subcritical plants. Specific installation cost i.e. the cost per megawatt (MW) decreases with increased plant size. For countries like India and China, unit ratings from 500 MW up to 900 MW are possible due to their large electrical grids. In countries with smaller grids, unit sizes of 300 MW are more appropriate and the specific installation cost will be higher than that of larger plants.

Boiler feedwater is raised to a pressure of 320 bar by one single pump driven by a steam turbine before being fed through a multi-stage preheating zone and into the boiler at a temperature of about 270°C. In the boiler the feedwater is further heated and then superheated to 547°C. For each of the 800 MW units one boiler feed pump turbine to drive the boiler feed booster and main pumps is used. The boiler feed pump turbine is supplied with steam from an extraction point at the intermediate pressure turbine and a second supply from the cold reheat line

The following requirements were specified for the design of the turbine:

- Super critical steam conditions, single reheat, operation in sliding-pressure mode with main steam conditions at 638 kg/s, 25,3 MPa, 544°C and reheat steam conditions at 5,2 MPa, 562°C.
- Seven-stage regenerative feed heating with a final temperature of 270°C and turbine-driven boiler feed pump

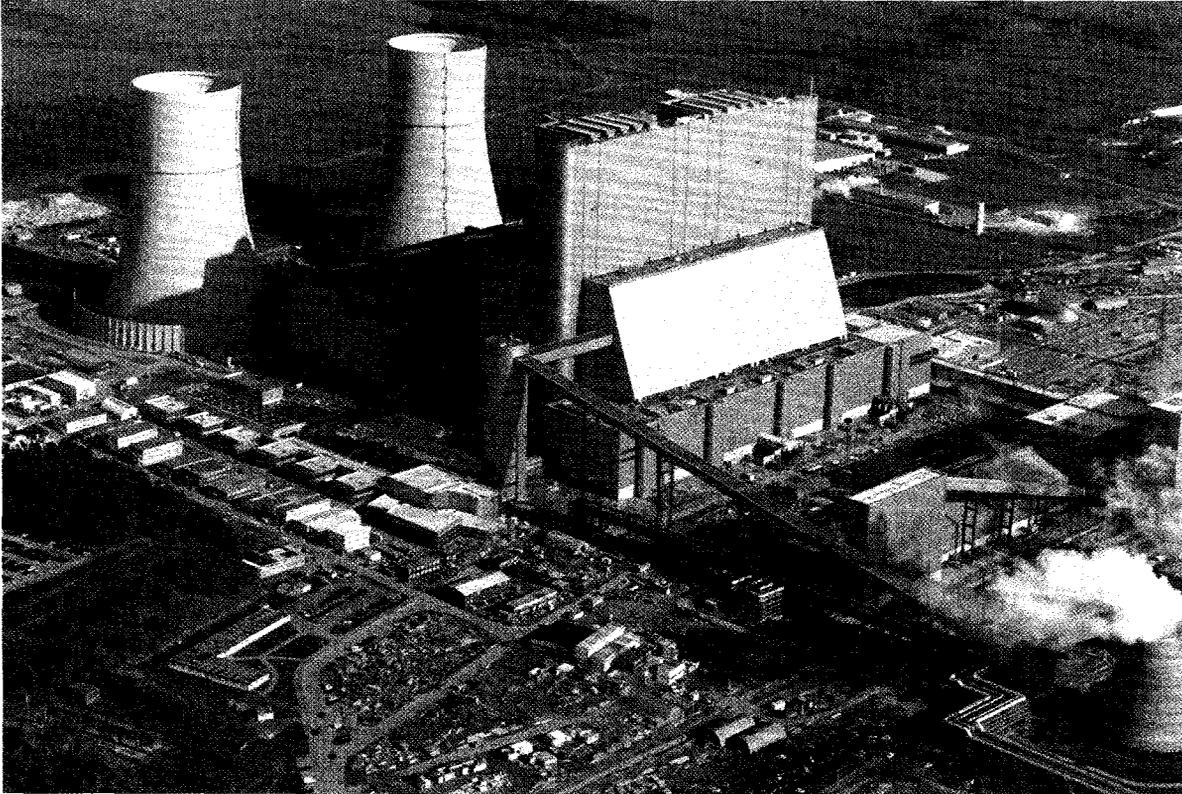


Figure 5
The Schwarze Pumpe
2 x 800 MW Steam
Power Plant.

This paper is one of a series on fossil fuel generation technologies. The others are on modular plant design, open cycle, combined cycle and integrated gasification combined cycle technologies. Issues that are pertinent in developing countries are addressed. The series has been prepared by staff at Siemens KWU in collaboration with the World Bank.

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