HIGH-EFFICIENCY COAL-FIRED POWER PLANTS DEVELOPMENT AND PERSPECTIVES

Jørgen Bugge[*]* and Sven Kjær
Elsam Engineering A/S
7000 Fredericia
Denmark

Rudolph Blum
Elsam A/S
7000 Fredericia
Denmark

ABSTRACT

The Danish power stations have a long-standing tradition of building plants with high efficiency. Elsam's two most recent power plants commissioned in 1997 and 1998 represented a turning point in Europe for high-efficiency conventional power plants with double reheat and steam temperatures of 580°C. The operational experiences have been good and the plants are just as flexible in operation as more traditional plants. With a background in the two plants and as coordinator of the EU financed AD700 project, Elsam has been on the forefront of the development of a future coal-fired power plant with 700°C steam temperature. The project comprises about 40 companies representing all actors in the European power industry and is now in its second phase. The presentation will briefly show the historical development and present status and perspectives for the AD700 technology.

Keywords: AD700, supercritical, coal-firing, superalloys, steam plant, Nickel.

---

[*] Corresponding author: Phone: +45 7923 3200, Fax: +45 7556 4477, E-mail: jb@techwise.dk

NOMENCLATURE

PFBC = Pressurized fluid bed combustion

IGCC = Integrated gasification combined cycle

USC = Ultra Super Critical

SCR = Selective Catalytic Reaction

PC = Pulverised coal

NG = Natural gas

CC = Combined cycle

INTRODUCTION

The Danish power stations have a long-standing tradition of building plants with high efficiency. This is a consequence of among other things that all fuel from the beginning had to be imported.

Apart from a period from the sixties and up to the first oil crisis coal has always been the preferred fuel due to its low price.

In the early nineties when the trend was that the further development in coal-firing should be PFBC or IGCC, Elsam decided to build two 400 MW units with advanced steam parameters and double reheat. Steam temperatures from the boiler were 3 × 582°C and live steam pressure was 290 bar. This decision was taken after a thorough study of the 3 technologies dealing with efficiency, cost and risk.

The USC concept would give the highest efficiency at the lowest cost and risk as Elsam's metallurgists had confidence in the new developed steel P91.

NORDJYLLAND AND SKÆRBÆK

The units were planned for pulverised coal-firing, but the Danish energy authorities demanded that one of them should be fired by gas, which was to be Skærbæk unit 3. So only Nordjylland 3 is actually coal-fired.

The boilers for the two units are identical except that the Skærbæk boiler is not fitted with coal-firing equipment. The turbines are also identical except for minor differences in relation to the district heating systems.

The boilers were built by a consortium of Burmeister and Wain Energy (BWE), Aalborg Industries and Vølund as tower boilers and the turbines were supplied by Alstom. The turbines have 9 cylinders arranged in 5 casings: Very High Pressure, High Pressure and Intermediate Pressure 0, Intermediate Pressure 1 and 2 and two Low Pressure casings.

The coal-fired plant is fitted with flue gas cleaning consisting of high dust SCR NO_x removal, electrostatic precipitator and wet scrubbing SO_2 removal making the plant a real clean coal plant.

THE 600°C PLANTS

Japan was the first to raise the steam parameters but that was on gas-fired units. Elsam's decision to build Nordjylland and Skærbæk represented a turning point in Europe where a number of coal-fired plants with advanced steam parameters has been built since then.

The experiences from the newest USC power plants have already demonstrated satisfactory performance with respect to reliability, flexibility, emission control and economy, table 1. The plants are based on major use of newly developed boiler and turbine component designs, and wide use of the newly developed high performance materials, but the availability has been as good as less advanced power plants. The additional investment costs have been marginal, and are fully returned by the efficiency increase. Therefore, the overall production costs have shown the expected figures.

On this background, it can be concluded that the “600°C generation” of USC power plant will end up as a true success.

THE AD700 PROJECT

It was natural to follow the idea further, but it was clear that for ferritic materials there was a limit just above 600°C. The new developed Ni-based materials gave hope that they could be used to increase the temperature to 700°C.

In January 1998 the Advanced 700°C Pulverised Coal-fired Power Plant Project was started. It is financed by 40% by EU and the Swiss and UK governments. It comprised about 40 companies ranging from utilities and manufacturers to research organisations and laboratories. The first phase runs from 1998 to 2003. The second phase, which comprises 35 companies, runs from 2002 to 2005 and is by 50% financed by EU and the Swiss governments. The project is now called AD700.

The overall technical objective of the complete project is a phased development and demonstration of an economically viable, pulverised coal-fired power plant technology with a net efficiency of more than 50%, the potential for which has already been established during the first phase of the project.

An advanced super critical water/steam cycle will boost maximum steam temperatures from the standard 540-560°C range to the 700-720°C range and main steam pressure from the present 250 bar range to the 350-375 bar range.

The phase 1 results indicate net efficiencies in the range of 50-51% for a power plant with a single reheat cycle cooled by a wet cooling tower and 53-54% for a double reheat cycle cooled by sea water. Plant sizes studied are 400 MW and 900 MW. Figure 2 shows the water/steam cycle for an inland location.

The AD700 technology opens for long-term improvements of the net efficiency of more than 15%-point from the current 35% average in European coal-fired capacity to more than 50%. Even a comparison with today’s state of the art super critical plant with steam parameters of 250 bar and 540/560°C and a net efficiency of 44% shows that the AD700 technology efficiency is more than 6%-point better.

A programme for development of materials for the AD700 technology and demonstration of their properties is listed below:

- New Nickel-based superalloys for long-term operation at steam temperatures in the range of 700-720°C. Superalloys will be developed for thin-walled super and reheater tubes, thick-walled outlet headers and steam piping and castings and forgings for the turbine.
- Fabrication methods of components in super-alloys.

- New austenites for boiler tubes operating in the temperature range 600-700°C to minimise the use of expensive superalloys.
- Methods for welding of similar materials and for welding of dissimilar materials.
- Investigation of the corrosion resistance of new alloys operating at 700-750°C in an existing boiler fired by coal only or co-fired with biomass.

Currently, European boiler and turbine manufacturers are in the forefront worldwide and the AD700 technology targets a major step forward to improve the competitiveness of European power technology after a successful demonstration somewhere in Europe shortly after 2010. Therefore, design studies are included in the project to investigate the potential of reductions in the use of expensive super-alloys to make the concept even more economically attractive:

- Steam turbines will be redesigned and revised or new joining methods will be developed to save superalloys.
- New boiler structures will be developed, which will allow steam lines between boiler and turbine to be shortened substantially thereby reducing investment cost.
- Major components outside the boiler and turbine areas like bypasses and safety valves will be redesigned to comply with advanced steam parameters.

Design studies from phase 1 indicate that this will all be accomplished without jeopardising the simplicity, plant economy and high reliability characteristics of the components in a more traditional power station. The AD700 technology will be mature shortly after 2010 and long-term targets after 2020 are net efficiencies above 55% based on maximum steam temperatures in the range of 800°C.

Coal-fired plants offer the possibility to co-fire biomass as the coal ash has a benign effect on the corrosive elements in the biomass. Therefore, utility-based efforts to reduce CO2 emissions through the use of biomass will have their economy substantially improved by co-firing biomass and coal in a power plant with a very high net efficiency of more than 50%.

The potential of CO_2 reductions through improved generating efficiency is clearly illustrated by figure 3, which also shows that 20% biomass being co-fired with coal will bring CO_2 emission levels close to those of natural gas burned in gas-fired CC installations. If the leakage of natural gas from the transmission and distribution lines is being considered this will make the emission levels from the AD700 technology comparable to those from gas-fired CCs.

MATERIALS FOR AD 700

In order to realise a 700°C USC power plant, extensive materials development is necessary including the use of Ni-based superalloys in the most severely exposed components. These developments can be categorised into four groups reflecting the key components of such a power plant i.e.:

- Furnace panels
- Superheaters
- Thick section boiler components and steam lines
- Turbine rotors, casings, valves and bolts

For furnace panels, steam temperatures above 500°C must be foreseen. An interesting candidate material for such conditions might be the 12Cr steel HCM12. This material has well proven mechanical properties as well as sufficient corrosion and oxidation resistance. The main criterion for proving its applicability in furnace panels is to demonstrate good weldability with no need for post weld heat treatment. Demonstration tests comprising large test panels and one full boiler construction of HCM12 have shown excellent service performance, but they indicate that some work is still needed to develop a welding procedure, which guarantees unproblematic production of gas tight furnace panels.

An alternative to HCM12 could be IN617, but this would lead to a very expensive construction.

For superheater tubing the aim is to develop an improved austenitic tube material with sufficient strength and flue gas corrosion resistance to operate at steam temperatures around 650°C, and to develop a Ni-based superalloy to fill the gap up to 700°C steam temperature. Intensive development work is ongoing in the AD700 project to demonstrate a suitable austenitic tube material with 100,000 hour rupture strength of about 100 MPa at 700°C and a Ni-based tube material with 100,000 hour rupture strength of 100 MPa at 750°C. Corrosion and oxidation resistance of both materials have been tested in a laboratory and will later be validated in in-plant test rigs. Results so far have been encouraging, and commercial scale production of both materials is foreseen in the second half of 2002.

For thick section boiler components and steam lines there are two goals for the development. An improved ferritic/martensitic 9-12%Cr steel is needed to expand the present temperature range for ferritic steels up to approx. 650°C. A Ni-based superalloy with a 100,000 hour rupture strength of 150 MPa at 700°C is needed to allow construction of outlet headers and main steam lines with acceptable wall thicknesses, figure 4.

The task to improve the 9-12%Cr steels on top of the impressive developments in the last two decades has proven to be very difficult. In the recent five years worldwide research has resulted in a large number of new alloys being announced, and from short-term tests they seemed very promising. However, in long-term tests the strength fall off and so far, no ferritic alloy has demonstrated long-term creep strength better than steel P92. In order to be able to improve the strength, a fine-tuning of the composition is needed based on a thorough understanding of recent developments. Recent advances in microstructure characterisation techniques and thermodynamically based microstructure models may prove to be the only way to go further in the development of improved ferritic steels.

Alloy 263 or an improved version of IN617 may meet the demands for outlet headers and steam lines at 700°C steam temperature. Long-term creep data and demonstration of fabricability – pipe production, hot bending and welding – is needed before a 700°C power plant can be realised. Alloy 263 is under investigation in the “Advanced ("700°C") PF Power Plant” project and the improved version of IN617 is investigated by the German national project MARCKO DE2. In the second half of 2002 commercial scale production of Alloy 263 and IN617 pipe is foreseen. The products will be used for qualification of the materials.

Recent results of the developments of 9Cr boron alloyed steels in Europe support the expectations that ferritic turbines can operate up to app. 625°C steam temperature. But similar to the ferritic steels for thick section boiler components a substantial understanding of the microstructures is needed to fine-tune the chemical composition for optimum strength performance.

For turbine constructions above 625°C steam temperature, a suitable Ni-based superalloy is sought amongst existing gas turbine disc materials. Long-term creep data are under development and the fabricability of full-scale turbine components will be demonstrated during the next phases in the “Advanced ("700°C") PF Power Plant”

The start of similar projects in the USA and Japan are important indications of how the AD700 technology is considered to have a great potential and attraction across the globe. In Japan, R&D work on the use of super-alloys in the 700°C range has started headed by the Electric Power

Development Company (EPDC) and strongly supported through the Ministry of International Trade and Industry (MITI). In the USA the Department of Energy (DOE) have announced plans in their Vision 21 Strategy to work towards temperatures > 700°C.

THE NEXT STEPS

Where phase 1 has been screening, selection and testing of materials together with design and feasibility studies, phase 2 is design and testing of various components and preparation for the final implementation.

Next step, phase 3, will be testing of the critical high temperature part of the cycle preferably in full scale or close to that for a 400 MW plant. That can be done in connection with a “600°C plant” where the existing high pressure turbine is replaced with a new 700°C high pressure turbine, and steam from the existing boiler is further superheated up to 700°C in a new boiler (superheater). The exhaust steam from the new turbine goes back to the existing boiler and the rest of the cycle is unchanged for the existing plant, Figure 5.

The design pressure for the AD700 concept will not be reached but the important thing is that full temperature is reached and that load cycling takes place. Heavy load cycling (from full temperature) will in fact represent an “accelerated test of the concept” The full load steady state performance is easier to test in a laboratory.

If funds can be found for the test facility operation, a commercial plant can be envisaged in 2014.

THE NEED FOR HIGH EFFICIENCY COAL-FIRED PLANTS

To assure the electricity supply in the future there is a strong need for coal-fired power plants. In case of the European Union, the Commission published a Green Paper named “Towards a European Strategy for the Security of Energy Supply” in November 2001. The paper shows the severity of the situation by stating that: “if no measures are taken, in the next 20-30 years, 70% of the Union’s energy requirements, as opposed to the current 50%, will be covered by imported products.”

In the long term, as the North Sea resources are being exhausted, natural gas will mainly come from Russia and North Africa and oil from the Middle East, which stresses the importance of coal for European security of supply. Therefore, it is being concluded: “The characteristics of the world coal market (geographical and geopolitical spread of supply and absence of price tensions) are reassuring in view of growing external dependence. In this respect one can speak of a stable economical and physical supply”. The situation is the same in many other places around the world.

CONCLUSIONS

Five years of operation experiences with USC power plants have already demonstrated that the “600°C generation” power plants will end up as a true success.

The development of a 700°C steam power plant to operate on coal in combination with biomass will enable a reduction of CO_2 emission of around 40% compared with the most advanced USC power plants operating today. This will bring the emissions from a combined coal-biomass fired 700°C power plant close to the figures of gas fired combined cycle plants.

The 700°C steam power plant offers a flexible technology with minimised CO_2-emission based on coal - the most reliable energy source in the world. Further, it gives the demanded production flexibility in order to stabilise a grid with a high amount of unpredictable renewable energy input.

The technical realisation of a 700°C steam power plant depends on a successful development and qualification of advanced ferritic, austenitic and Ni- based alloys. With respect to austenitic and Ni-based alloys promising results have been achieved.

The economic criterion for the realisation of a 700°C steam power plant is a realistic budget price. The consumption of large quantities of expensive Ni -based alloys has significant influence in this respect, and a successful development of an improved ferritic steel to be used at temperatures up to 650°C would improve the situation.

REFERENCES

[1] http//www.ad700.dk

[2] *Research and Development on the Ultra Super Critical Pulverised Fuel (USC-PF) Plant Concept* (large number of references), Elsam October 1994.

[3] Sven Kjær et al. *The Advanced Supercritical 700°C Pulverized Coal-fired Power Plant*, Powergen 2001.

Figure captions:

Figure 1: Efficiency in the Elsam System

Table 1: Recent “600°C” Power Plants

Figure 2: The AD700 cycle

Figure 3: CO_2 emissions from coal and gas-fired plants

Figure 4: Future prospects for thick walled components

Figure 5: Set-up for a full scale test facility

Figure 1:

Efficiency in the Elsam system

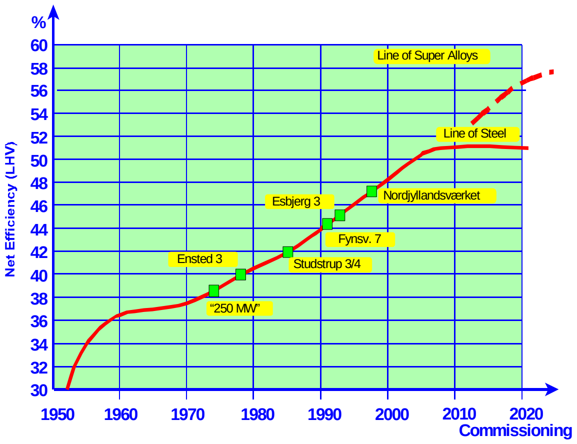

Table 1:

Recent ”600 °C” Power Plants

Power station	Cap. MW	Steam parameters	Fuel	Year of Comm.	Eff. %
Matsuura 2	1000	255bar/598°C/596°C	PC	1997	
Skærbæk 3	400	290bar/580°C/580°C/580°C	NG	1997	49
Haramachi 2	1000	259bar/604°C/602°C	PC	1998	
Nordjylland 3	400	290bar/580°C/580°C/580°C	PC	1998	47
Nanaoota 2	700	255bar/597°C/595°C	PC	1998	
Misumi 1	1000	259bar/604°C/602°C	PC	1998	
Lippendorf	934	267bar/554°C/583°C	Lignite	1999	42.3
Boxberg	915	267bar/555°C/578°C	Lignite	2000	41.7
Tsuruga 2	700	255bar/597°C/595°C	PC	2000	
Tachibanawan 2	1050	264bar/605°C/613°C	PC	2001	
Avedøre 2	400	300bar/580°C/600°C	NG	2001	49.7
Niederaussen	975	265bar/565°C/600°C	Lignite	2002	>43
Isogo 1	600	280bar/605°C/613°C	PC	2002	

Figure 2:

The AD 700 cycle

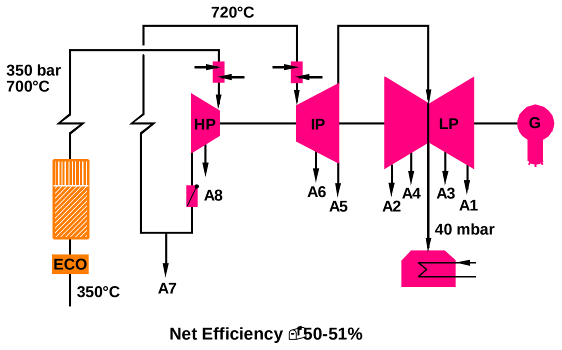

Figure 3:

CO_2 emissions from coal and gas-fired plants

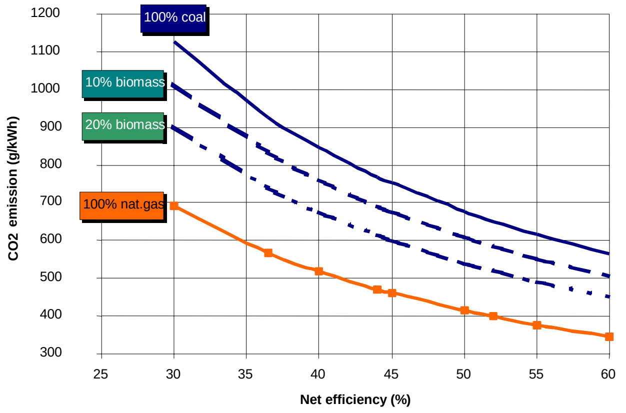

Figure 4:

Future prospects for thick walled components

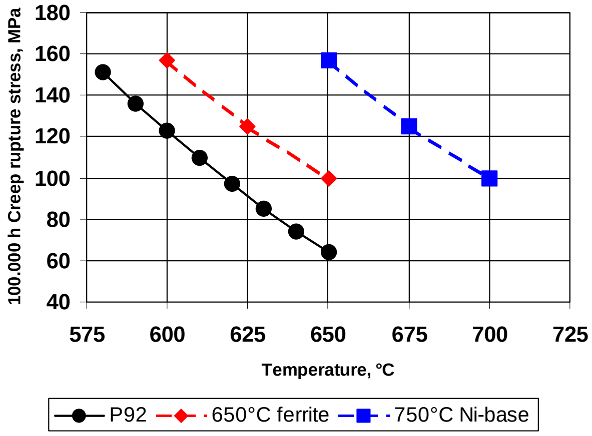

Figure 5:

Set-up for a full scale test facility