Coal Fired Plants:
Horizontal Boilers Make 700°C Steam Economic

Author:
David Smith

Reprint from
ModernPowerSystems
In a world of rapidly advancing deregulation, it has become increasingly difficult for coal fired power generation to compete. Now the pendulum may be beginning to swing back.

It is not just the forecast of a doubling in natural gas prices in the next three years that is driving this trend. Under the influence of stringent political regulatory regimes, unstable gas prices, the prospect of heavy emissions trading costs, carbon taxes and the response to Kyoto, interest in advanced coal fired generation technology is enjoying a resurgence.

Often dismissed by many senior pundits as having little prospect of economic viability in the foreseeable future, ultra supercritical coal fired utility boilers to generate steam at over 700°C and 350 bar is beginning to be more vigorously pursued, particularly in Europe, and in Germany and Denmark in particular.

The main hurdle in the past has been the horrendously high cost of the high nickel alloys needed to withstand these temperatures and pressures. However, new designs of boiler using a horizontal furnace configuration have now been developed by Benson licensor Siemens that greatly reduce the impact of the cost of high nickel alloys (see Figure 1). The concept has been developed in the context of a study of future advanced coal fired plants with ultracritical steam conditions.

Development work has been underway on horizontal furnace boiler technology for some years. In the medium term, a demonstration plant incorporating the new boiler, working at current state of the art conditions, could prove the viability of the design. A fully developed ultra supercritical version could start operation in 2010.

Horizontal vertical tube boilers

There is nothing new about vertical tube Benson boilers - from as early as 1930 up to the mid 1960s the use of vertical tubes with refractory linings was the popular design approach. Since then the furnace tubing has generally been configured in a spiral configuration with the tubes welded together to form membrane walls.

Various concepts for using vertical tubes in the form of membrane walls were developed in the USA in the late 1950s. The main problem with this arrangement was achieving adequate cooling of all of the tubes under a wide range of load conditions. The use of high mass flow densities was the generally adopted solution.

A novel design of Benson boiler with horizontal furnace and internally rifled vertical tubes has been developed by Siemens. In association with the EU-funded Thermie advanced 700°C PF power plant programme it has been designed for steam conditions of 350 bar/700°C/720°C. The reduced height of the boiler minimises the amount of expensive high nickel alloys required for the steam lines to a point where the economics are competitive. Mounting the steam turbine at the level of the boiler steam outlet headers results in further cost reductions.

David Smith

In the 1980s Sulzer developed a concept that used internally ribbed tubing which has been used in the 2 x 700 MWe gas fired power plant at the Kawagoe site and the Matsuura 700 MWe coal fired plant in Japan.

Full load mass flow density in the tubes for this design of boiler is in the range 1600–2000 kg/m²s.

To accommodate temperature variations that would occur at the evaporator outlet due to differences in heat input conditions, tubes expected to be subject to insufficient heat input are fitted with flow restrictors. But rather than assume complete evaporation in the furnace, a convection evaporator section is added for completion of the evaporation process.

Siemens has been conducting experimental research into heat transfer and flow conditions in such tubes for some years in a high pressure test loop in Erlangen, and many reports have been published by Joachim Franke, Rudolf Kral and his colleagues over the last decade. They have produced an extensive database which shows that the heat transfer is highly sensitive to changes in internal rifling rib geometry.

Heat transfer in a rifled (also called ribbed) tube (Figure 2) is exceptionally good, especially during evaporation. This is because centrifugal force transports the water fraction of the wet steam to the tube wall. The resulting
Wall wetting causes excellent heat transfer from the wall to the fluid. This has the following advantages over smooth tubes:

- No deterioration of heat transfer even in the range of high steam quality.
- Very good heat transfer even at low mass flux.
- Only slight increase in wall temperature in case of film boiling near critical pressure (interval from about 200 bar to critical pressure).
- Potential for increased heat transfer by optimisation of rifling geometry.

The low mass flux design not only enables downward extension of the output limits for vertical tubes to 300 or 200 MW and use of large-diameter tubes, but in particular it also changes the flow characteristic of a once-through system: with increased heating of an individual tube, the throughput of that tube increases instead of decreasing.

In a rifled tube, the boiling crisis does not take place until steam quality is less than 0.9 shortly before the end of evaporation due to the swirl flow generated by the spiral ribs inside the tubes. Differences in centrifugal force separate the water from the steam fraction and force the water towards the tube wall. This maintains wetting up to high steam quality levels, resulting in high flow velocities even at the boiling crisis location.

The main advantages of vertical internally rifled tubes in a Benson boiler can be summarised as:

- Reduced mass flow, from 2000 to 1000 kg/s, with flow characteristics as in drum boilers, ie increased heat input to an individual tube increases throughput in that tube (as shown in Figure 3).
- Cost effective fabrication and assembly.
- Minimum Benson output can be as low as 20 per cent.
- Simple start up system for 20 per cent evaporator throughput.
- Reduced slagging on combustion chamber walls.

Siemens, Babcock Lentjes Kraftwerkstechnik and Steinmüller carried out large scale testing in a rig installed in PreussenElektra’s supercritical 320 MWe Farge coal fired power plant in 1993 which served to verify the experimental results and yield input to design codes for a new vertical tube Benson boiler concept.

The theoretical conclusions for this concept regarding pressure drop and thus for flow distribution with non-uniform heating were tested in practice in the Farge plant. It was important to achieve the physical height which is significant for a natural circulation characteristic but which cannot be attained in laboratory operation. A furnace heat exchange surface with the low mass flux design was in trouble-free operation at the Farge plant for more than 10 000 hours. This confirmed the calculation fundamentals and at the end of trial operation the tubes were still practically as good as new, the rib profile not smoothed by deposits.

Heat transfer measurements were not performed in Farge, as important factors such as heating and the thickness of the insulating ash layer on the tubes vary constantly, preventing reliable, reproducible measurement results. But the low mass flux design with its optimised internally rifled tubes has even greater benefits when applied to the low profile horizontal furnace boiler configuration.

The thermohydraulic principles of low mass flux design have already been proven in commercial operation in the horizontal Benson heat recovery steam generator used in Siemens’ most advanced V94.3A gas turbine combined cycle field development plant, at Cottam, UK (see MPS, September 1999, pp 40-43), shown in Figure 4.

The parallel tubes of the evaporator for the HP and IP stages arranged sequentially in the exhaust flow path are characterised by extremely different heat uptakes. In the selected concept, mass flows automatically adjust to the heat input ie all parallel tubes of the HP evaporator show saturation temperature at first pass outlet and low temperature differences between the rows of the second pass (Figure 5). The thermoelastic construction of the Benson boiler significantly increases flexibility of the combined-cycle power plant over that of a drum boiler, especially during start-up.

One third of the height

Figures 1 and 6 show the schematic layout of the horizontal coal fired boiler for which very considerable cost reductions are claimed, particular-
Siemens’ new four-stage turbine have this configuration.

The main advantages of the low-profile boiler configuration are obvious:

- Reduced structural steelwork costs.
- Simplified installation.
- Installation time is reduced as the furnace, lateral pass and vertical pass can be installed in parallel, which also reduces interest during construction.
- The steam lines between the boiler and turbine are shorter and more direct.
- All of the burners are mounted on one side of the combustion chamber.

The modular design of the boiler lends itself to variations in output rating – a 700 MWe version can be put together with dual furnace sections to make a 700 MWe unit with twice the width but the same height as a 350 MWe unit (see Figure 7).

Whereas with more conventional steam conditions the superheated steam lines account for some 5 per cent of the power plant costs (see Figure 8), this number increases to about 15 per cent in plants with steam temperatures of 700 °C (using Ni base alloys and state of the art power block design). But with the compact horizontal furnace boiler the figure decreases once again to around 3 per cent. This is because with the horizontal furnace boiler the length of pipes is reduced to 20 per cent of that in the conventional design.

Also, in the horizontal furnace boiler, the convection section with the horizontal and vertical passes is located downstream of the horizontal furnace, and is largely identical with proven two-pass boilers (see Figures 1 and 6).

**Materials**

Increasingly purposeful negotiations have recently been held between nickel alloy suppliers Inco and the 40 strong members of the Thermie 700 project, which include all of the boiler makers in Europe, many utilities and manufacturers concern. Significantly, other German utilities and the power plant operators association VGB are expecting to join the group before long.

It seems that the projected cost of the high nickel alloys needed to handle the 700 °C steam is now down to around 10 x the cost of present P91 and P92 materials instead of the 40 x figure recently mooted.

The new boiler layout clearly reduces the amount of High Nickel Alloy 617 in the superheated steam pipes, but thick castings in this material are still needed for the high pressure turbine casings. Table 1 indicates the progression of high temperature steam system alloy applications to date.

**Four-stage turbine**

As already mentioned, the turbine envisaged for use with the horizontal furnace boiler has four stages: HP1, HP2, IP and LP (see Figure 9). The design takes into account the high costs of nickel-based alloys and the need to restrict component weights. Accordingly, the HP cylinder is split into separate HP1 and HP2 cylinders. The HP1 cylinder includes parts made of nickel-based alloys and is designed to be very compact. The HP1 exhaust steam flows directly into the HP2 cylinder, which can be designed for moderate steam conditions and thus manufactured from conventional materials, eg cost effective 9 ... 12 per cent chromium steels. Reheat steam enters the IP cylinder, in which the hot areas will be manufactured from nickel-based materials, while conventional materials will be used for the colder areas (Figure 10).

**Reference**

J. Franke and R. Kral, Advanced boiler design for high efficiency power plants, to be presented at Parsons 2000, Cambridge, 5-7 July 2000. These authors acknowledge participants in the advanced 700 °C PF power plant project carried out under the EU funded Thermie programme and the financial contributions from the European Commission and the Swiss government.

May 2000 Modern Power Systems 41