

Once Through Benson Boiler – Vertical Tube Furnace

Report No.
COAL R282
DTI/Pub
URN 05/663

March 2005

by

B W Smith

Mitsui Babcock Energy Ltd
11 The Boulevard
Crawley
West Sussex
RH10 1UX

Tel: 0293 612888

Email: BSmith@mitsuibabcock.com

The work described in this report was carried out under contract as part of the DTI Cleaner Coal Research and Development Programme. The programme is managed by Mott MacDonald Ltd. The views and judgements expressed in this report are those of the contractor and do not necessarily reflect those of the DTI or Mott MacDonald Ltd

First published 2005

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SUMMARY

Situated in Henan Province, PRC, Yaomeng Power Plant consists of 4 × 300MWe coal-fired boilers, units 1 and 2 of which, entered service in the mid-1970's. They were of the high mass flux, once through, sub-critical universal pressure (UP) type, designed for base load operation to generate 935te/h main steam at 570°C.

From 1992 onwards, after overheating in some of the pressure parts, which led to a restriction of 545°C on the main steam temperature, the maximum output was reduced to 270MWe. The boiler's intrinsic intolerances to load changes, and operation below 230MWe were also problematic, and the prospect of more onerous emissions legislation was thought likely to impose even further restrictions on plant usage in the future, or even bring about its closure.

Scope of Boiler Refurbishment Contract

In opting for an overhaul of Unit 1, Yaomeng Power Generation Limited (YPGL), favoured the adoption of Mitsui Babcock vertical ribbed tube low water mass flux technology, the main objectives of which were to enable the achievement of full design load, to give the boiler full operational flexibility in following load demand, and to maintain stable operation over the full load range.

The scope of work for Mitsui Babcock was centred on the upgrade of the existing boiler, comprising refurbishment of the furnace pressure parts and improvement of the burners, start-up system and control philosophies.

DTI R&D Project

The DTI-supported collaborative project between Mitsui Babcock and Cranfield University was conceived with the objective of taking advantage of the boiler refurbishment contract to allow a more thorough investigation of the furnace performance than would normally be possible. The DTI-supported project focussed on the design and performance of the innovative features associated with the vertical tube furnace walls, the development of a novel flow meter and an investigation of steam oxidation.

Use was made of the flow metering technology developed at Cranfield and work carried out to assess furnace wall performance pre-and post-refurbishment with a view to using the new vertical ribbed tube low water mass flux technology in future boiler plant, (advanced super-critical).

Project Activities

- (i) Appraisal of Existing Boiler Pre-Refurbishment

The walls of the original furnace were of vertical tube membrane construction. A central, two part, full height division wall connected in series with the outer walls, was used to create a symmetrical twin furnace arrangement, with corner tangential firing. The total furnace width was 17m, the depth 8m and the water mass flux 1800kg/m²s. Flow measuring devices and individual valves were arranged to allow preset in the distribution of flow to each circuit of the furnace panels during the commissioning stage for subsequent plant operation.

For the Mitsui Babcock assessment of the existing plant, thermocouples were attached to selected furnace outlet tubes, and monitored over a range of operating loads. The metal temperature was approximately 360°C, when the unit was operated at high load, well below the design temperature of 400°C. However, when the unit was turned down to 210 MWe (70% load), some tubes started to overheat, the highest tube outlet fluid temperature of the lower furnace increasing to 463°C.

The temperature differential between adjacent tubes was up to 70°C, thereby imposing unacceptably high stresses in the outlet headers and reducing plant life. The highest metal temperatures occurred at the lowest load, and caused failures in both the water walls and outlet mixing headers. On the basis of their analyses of once-through furnace flow dynamics, Mitsui Babcock considered that the high water mass flux design concept was the principal reason for poor operation of the old furnace at low loads.

Tubes located in such furnaces absorb unequal quantities of heat, based upon their location, and changes in the combustion firing pattern due to mill, fuel or combustion air changes, even though the total heat absorption might be constant. For example, corner tubes receive less heat than those at the mid-wall positions.

The high mass flux design, with its negative flow response resulted in a flow reduction with increasing heat absorption, whereas the proposed low mass flux design for Mitsui Babcock's replacement furnace exhibits a positive flow response, which produces a rise in the flow rate with increasing heat absorption. This design ensures that all tubes have sufficient flow to make certain of safe and reliable operation under all steady state and transient conditions.

- (ii) New Low Mass Flux Design

The features which Mitsui Babcock have incorporated into the advanced technology design to achieve intended load and full operating flexibility are:

- new furnace walls with optimised spirally ribbed tube to retain the once through arrangement, whilst using a low water mass flux of 700kg/m²s to ensure full static and dynamic stability,
- an improved start up system that will give a shortened start-up time, and reduced heat and water consumption,
- upgraded burners to improve NO_x emission levels, and extend the safe range of operating loads without fuel oil support, and
- control philosophy upgrades for combustion, feed water, and start-up systems to obtain the optimum loading rates and load flexibility.

To comply with the new requirements for the boiler island, the dimensions of the existing furnace envelope had not to be exceeded. The smaller pipe and tube sizes afforded by the use of the Benson boiler technology ensured that the load limits were such that the original support structure could be retained.

The proposed new furnace arrangement still comprises the external walls, and a dual-panelled division wall, however, the main change in the feed water connections is the creation of a parallel flow regime for the furnace and division walls, the modification having been made possible by the change to a low water mass flux. Thermal performance calculations for the furnace, and an assessment

of the fluid flow distribution through the walls for BMCR and a range of part loads was made using Mitsui Babcock in-house software.

Temperatures were determined for the worst tube in each circuit using the physical characteristics, including ribbed tube geometry, enthalpy conditions on the tube side, fluid mass flow rate, and internal heat flux as inputs. The centre tubes on each furnace wall were examined, and the mean wall temperatures calculated for several locations along the tube length. The results showed that tube mean wall temperatures were within design limits over the entire operating load range.

Static and dynamic stability calculations have been performed for both the division wall and external wall circuits for a number of loads cases, the results being indicative of the stable characteristic of the new boiler design over the entire operating range.

- (iii) Appraisal of Performance Post-Refurbishment

Mitsui Babcock was keen to verify the calculations for the refurbished boiler, and to this end exit temperature thermocouples were fitted to tubes both in the furnace and division walls. As mentioned earlier, heat fluxes are far from uniform in the various areas of the furnace and fluctuations are also quite normal. A section of the furnace in the front half of the left sidewall was instrumented with heat flux meters, non-intrusive flow meters, and both gas- and air-side thermocouples such that these variations could be measured.

The flow meter was developed using a representative section of the ribbed tube mounted in a low pressure / temperature flow rig at Cranfield University, where development trials were undertaken over a range of flow rates. The optimum locations for the flow meters were determined using computational fluid dynamics (CFD) modeling techniques to ensure that they would be in an area of fully developed flow for the single phase water. At site the output was collected by a data acquisition system and forwarded to Cranfield University for subsequent analysis.

A crucial factor in a vertical tube furnace wall with a low water mass flux is that the high heat transfer rates associated with nucleate boiling should be generated in all areas of high heat flux to maintain the metal temperatures within design limits over the whole operating load range. The tube metal temperature is dependent upon the internal rib geometry, and for the purposes of optimising this, the sensitivity of the tube temperature to rib height was studied over the range 0.9mm to 1.2mm.

The tubing selected for Yaomeng features a rib height of 1.1mm and a lead angle of 50 deg., a specification that differs significantly from those used for regular ribbed tubes in more conventional plant. This was also the first time that such tubing had been manufactured on a full production scale. Nevertheless, the close collaboration by Mitsui Babcock with both the UK tube supplier and his toolmaker ensured that the consistently high quality essential for the achievement of the heat transfer performance and pressure loss characteristics would be achieved.

There was good agreement between the results from the flux meters and the design predictions, and although as expected readings on the corner tube were lower than those for the other instrumented tubes, the measured heat fluxes were

up to 30% lower than the design predictions for the upper levels in the furnace, probably due to furnace wall slagging.

Valid data were collected from the flow meters over the load range 230MWe to 300MWe. The measured results indicated that the water mass flux increased broadly in proportion with increasing load, in line with design expectations. Similarly there were indications that, at constant load the mass flux in the tubes towards the corner of the furnace in areas of reduced heat flux was also lower, again in line with design expectations. Thus it was evident that the vertical ribbed tubing was performing well, as also indicated by the significant reduction in the range of exit temperatures, ie the positive flow response characteristic has been demonstrated.

- (iv) Steam Oxidation Studies

For the exploitation of the low mass flux technology for the next generation of advanced super-critical units in particular, and for which the exit temperatures from the furnace walls will be significantly higher than at Yaomeng, an understanding of the oxide growth is an important consideration for the long term performance of the boiler, especially the influence on the continued effectiveness of the optimised ribbed tubing.

An initial investigation was, therefore, undertaken by Cranfield University using short tubular specimens of HCM2S, X20CrMoV12 together with the ribbed tubing used in the Yaomeng furnace, for exposure to a steam oxidation environment in the temperature range 500-575°C over a test period of up to 4000hours.

As expected steam oxidation rates increased with temperature. At each temperature, differences in performance between the materials, including the ribbed tubing, were found to be within the scatter and error bands of the results expected within the limitations of this method of testing. Overall, the results indicated that there was a limited effect of alloy chromium content on steam oxidation rates for the three steels studied.

Success of the Main Contract and DTI Project

The 168-hour full load reliability test was completed successfully during May, 2002. What made the occasion particularly significant for all concerned was that this was the first time Low Water Mass Flux Vertical Ribbed Tube Benson Boiler Technology had been used for commercial power generation anywhere in the world, a very significant achievement by Mitsui Babcock.

The Performance Guarantee Tests (PGT's) were performed by the Thermal Power Research Institute (TPRI) during the end of July / early August 2002, and these results and subsequent operation have confirmed the major improvements in the unit. Peak steam output is 1010.3t/hr and maximum continuous output is 954t/hr, both exceeding the guarantee requirements. Peak power output has increased from 270MWe to 327MWe, and in fact the boiler has now been formally up-rated to 310MWe.

Whereas before the upgrade operation without fuel oil support was difficult at any part load condition, it is now possible down to 40% BMCR. The load following capability has also been much improved. Boiler thermal efficiency has been increased from 90.34% to 91.41%, unburned carbon decreased from 4.72% to

1.65% and the particulates emissions reduced from 1242mg/m³ to 163mg/m³. NOx emissions have also been cut significantly. The new start-up system has decreased boiler start-up and shut-down times appreciably, with up to 60 minutes having been trimmed from the time for a cold start.

Apart from a short outage for maintenance prior to the PGT's and an enforced shutdown caused by a failure in another item of plant, the boiler unit has operated almost continuously, mainly at full design load or above for the twelve month period from June, 2002 to the planned outage at the end of May, during which the average operational availability was 95%. The corresponding figure prior to the upgrade was substantially lower. The total electricity generated over the period, 2053 Gigawatt-hours, was 77% of the total possible for the unit based on an up-rated output of 310MWe. Only ten outages of any significance were recorded during the period, none of which were attributable to pressure parts failures.

YPGL have expressed their complete satisfaction with the outcome of the boiler upgrade, which was also ratified by the Chinese State Power Company and its boiler experts as a resounding success. The Chinese Power Industry Authorities have confirmed their full acceptance of the Mitsui Babcock technology, and this endorsement has established a favourable platform for future UP boiler refurbishment and super-critical once through projects in China

Benefits of DTI Support

The successful completion of this refurbishment is a major milestone in both the development of the technology of once through low mass flow vertical tube boilers and Mitsui Babcock's presence in the refurbishment market in the PRC. Wherever sub-critical once through boilers are suffering load restrictions, intolerances to load changes or high metal temperatures, this technology now offers a proven solution, which also extends to super-critical pressure conditions.

Within the UK, operators are already considering the use of this technology, which along with changes to the HP piping and turbine will allow the move from a sub-critical to a super-critical steam cycle at state-of-the-art steam conditions. Mitsui Babcock believes that this technology will become a standard for fossil fired boilers of the future, and are pleased to have enjoyed the support of DTI to enable them to be in the forefront of the development of the technology and application of it.

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1. INTRODUCTION

Yaomeng Power Plant is situated at the edge of Pingdingshan City in the central southern area of Henan Province, PRC, and consists of 4 × 300MWe coal-fired boilers. Units 1 and 2 entered service in the mid 1970's, and were the first domestically designed, coal-fired boilers of this size to operate within the PRC. Units 3 and 4 followed during the mid-1980's. The original boilers were of the universal pressure (UP) type, once through sub-critical with re-heater, designed for base load operation to generate 935te/h main steam at 570°C.

The boilers featured a twin fireball, indirect firing arrangement, with a division wall forming the first water-phase pass after the economiser, and the furnace membrane walls forming the second. At approximately 1800kg/m²s, the water mass flux was classified as 'high', in line with many other boilers of this type in the PRC. A view of the original boiler unit is shown in Figure 1.

From 1992 onwards, following steam turbine limitations and overheating problems in some of the pressure parts, the maximum output was reduced to 270MWe, due to the need to limit the main steam temperature to 545°C. Towards the end of the 1990's, it was recognized that high exit temperatures, uneven fuel distribution and poor fuel fineness were impairing the boiler efficiency. The boiler's intrinsic intolerances to load changes and operation below 230MWe were also problematic due to the resultant high furnace metal temperatures, together with the attendant pressure parts failures, around 250 of which were reported during the 1990's. In addition, the prospect of more onerous emissions legislation was thought likely to impose even further restrictions on the use of the plant in the future, or else bring about the possibility of plant closure.

In fact rather than condemn the plant the operator, Yaomeng Power Generation Limited (YPGL), opted for an overhaul of Unit 1, and though there was no previous full scale example of the application, YPGL and the boiler experts who were called in to advise them, decided that the extensive test work and analysis performed by Mitsui Babcock and Siemens Power Generation favoured the adoption of their vertical ribbed tube low water mass flux technology for the refurbishment, of the plant, particularly in the light of the space restrictions at the site.

The main objectives of the upgrade were:-

- to enable full design load to be achieved once again,
- to give the boiler full operational flexibility to follow load demand, and
- to maintain stable operation over the full load range.

Within the main Yaomeng refurbishment project, the scope of work for Mitsui Babcock was, therefore, centred on the upgrade of the existing boiler, and consisted of an overhaul of the furnace pressure parts and improvement of the burners, start-up system and control philosophies. The enhancements to the steam turbine, control systems, pulverised fuel systems and draft systems, together with the provision of a new electrostatic precipitator were all managed by others.

The DTI-supported collaborative project between Mitsui Babcock and Cranfield University was conceived with the objective of taking advantage of the boiler refurbishment contract to allow a more thorough investigation of the furnace performance than would normally be possible. This project focussed on the design and performance of the innovative features associated with the vertical tube furnace walls, the development of a novel flow meter and an investigation of steam oxidation.

Use was made of the flow metering technology developed at Cranfield and work carried out to assess furnace wall performance both pre-and post-refurbishment with a view to using the new vertical ribbed tube low water mass flux technology in future boiler plant, (advanced super-critical).

2. ORIGINAL FURNACE DESIGN AND PERFORMANCE

2.1 Boiler Performance Status

The original boiler design parameters compared with the actual capability prior to refurbishment were as follows:-

	Design	Actual
Main steam pressure	16.37MPa	16.37MPa
Main steam temperature	570°C	545°C
Main steam flow	935te/h	890te/h
Reheat steam inlet /outlet pressure	3.33/3.14MPa	3.33/3.14MPa
Reheat steam inlet /outlet temperature	337/570°C	337/545°C
Feed water temperature	260°C	260°C

2.2 Description of the Original Furnace

A sectional view of the original furnace is shown in Figure 2. The furnace walls were of vertical tube membrane construction. A central, two part, full height water-cooled division wall of tangent tube construction was used to create a symmetrical twin furnace arrangement, with corner tangential firing. The overall furnace width was 17m, with a depth of 8m.

To maintain the high mass flux, the flow of sub-cooled water through the division wall and furnace wall tubes was arranged in series, such that it first passed through the division wall before entering the furnace outer wall. The HP feed-water heaters fed the economiser bank and this in turn fed the furnace front and rear division walls in parallel. At the top of the furnace, the outlets from the division walls were returned to the bottom of the furnace via external down-comers to supply the furnace wall circuits. The lower furnace flow passed through the various levels of mixing headers before supplying water / steam to the upper furnace.

Flow measurement devices and individual flow distribution valves were arranged in each supply pipe of the 24 circuits to allow adjustment of flow distribution to the furnace panels. During the commissioning stages the water flow for each circuit was set up via the valve at 73% load, to be consistent with the expected mean heat flux to each circuit. Thereafter the flows were fixed at these levels for subsequent plant operation.

2.3 Test Instrumentation

To permit evaluation of the possible reasons for the poor performance, test work was undertaken in conjunction with the Thermal Power Research Institute of Xi'an, (TPRI) a Design Institute well-respected in the field of boiler performance testing in PRC. Thermocouples were attached to selected lower and upper furnace outlet tubes at the elevations shown in Figure 2. The thermocouples were then monitored for periods of up to one hour, over a range of operating loads. The temperatures recorded should have indicated the saturation temperature unless the fluid in a particular tube had reached dry-out conditions, in which case the higher steam temperature should have been detected readily by the thermocouples.

2.4 Test Results

The furnace tube metal temperature was approximately 360°C when the unit was operated at high load, which was well below the design temperature of 400°C. However, when the unit was turned down to 210 MWe (70% load), some tubes started to overheat. The highest tube outlet fluid temperature of the lower furnace increased by over 100°C to 463°C. The fluid temperature differential between some adjacent tubes increased to 70°C, imposing unacceptable thermal stresses in the outlet headers and reducing plant life. Operation at low load resulted in water wall failures due to overheating, and the thermal stresses caused by excessive fluid and metal temperature differentials between tubes also resulted in failure of the outlet mixing headers.

The series of illustrations in Figure 3 shows the tube metal temperature measured at the lower furnace outlet of a typical tube for a series of loads increasing from 207 MWe to 283 MWe. The highest metal temperature occurred at the lowest load, but by the time the load had increased to 250 MWe, the tube was clearly at saturation temperature, indicating that the inner wall surface was wetted.

On the basis of their detailed analyses of once-through furnace flow dynamics, Mitsui Babcock deduced that the high water mass flux concept was the principal reason for poor operation of the Yaomeng furnace at low loads, the main symptoms being:-

- The worsened heat transfer in the plain tubes at low load,
- The negative flow characteristics caused by the high water mass flux, as explained later in this report
- The need to balance the flow to groups of tubes artificially by use of manually operated valves, and
- The exacerbation of the problem by unstable and unreliable operation of the combustion system at low loads, and the inability to reconcile successfully the feed-water flow with the heat input.

2.5 Mitsui Babcock Observations

Tubes located in such boilers absorb unequal quantities of heat, based upon their location in the furnace and changes in the combustion firing pattern due

to mill, fuel or combustion air changes, even though the total heat absorption might be constant. For example, corner tubes receive less heat than the tubes at the mid-wall locations.

The original high mass flux design, with its negative flow response resulted in a flow reduction with increasing heat absorption. In contrast, the proposed low water mass flux design for Mitsui Babcock's replacement boiler exhibits a positive flow response, which produces a rise in flow with increasing heat absorption.

This design, aided by the optimised internally ribbed tubing, ensures that all tubes will have sufficient cooling flow to make certain of safe and reliable operation under all steady state and transient conditions. A comparison between the capability of the spirally ribbed tubing in the prolongation of good heat transfer local to the dry-out region, and the limitations of smooth bore in a similar environment is given in Figure 4. Good ribbed tubing ensures that this is achieved, for if it is not, the tubes will overheat, possibly leading to failure.

Figure 5 illustrates the pressure loss versus heat absorption characteristic for a 300 MWe furnace tube of high mass velocity operation similar to Yaomeng. Increasing heat absorption results in an increase in dynamic pressure loss and a reduction in static pressure loss. The large increase in dynamic loss would result in an overall increase in tube pressure loss, however, as furnace tubes are connected between common inlet and outlet headers, the tube pressure loss is determined by the mean conditions for the set of tubes, and will not change for an individual tube or small group of tubes which might absorb more or less than average heat. Therefore, the tube flow changes automatically to maintain the constant pressure drop.

Tubes absorbing greater than average heat see a flow reduction and those absorbing less than average see a flow increase. Thus the high mass velocity design demonstrates a negative flow response. In simple terms, this means that the hottest tubes, which need the most cooling flow, in fact receive the least amount of fluid. This results in high metal temperatures and thermal expansion stresses. Conversely, tubes, which are cooler and need the least amount of cooling flow, receive the most.

Figure 6 illustrates the pressure loss versus heat absorption characteristic for a 300MWe furnace tube of low mass velocity design. Increasing heat absorption results in an increase in dynamic pressure loss and a reduction in static pressure loss. The small increase in dynamic loss compared with the high static loss results in an overall reduction in tube pressure loss.

For the same reasons as the high mass velocity design, the tube flow changes. However, now tubes absorbing greater than average heat see a flow increase, and those absorbing less than average see a flow reduction. Thus the low mass velocity design demonstrates a positive flow response. This is often known as a natural circulation or self-compensating characteristic, where the tubes needing the greatest flow receive it. This behaviour limits excessive metal temperatures and thermal expansion stresses.

2.6 Mitsui Babcock Refurbished Design

The Mitsui Babcock retrofit of the existing furnace uses the optimised internally ribbed tube, the benefits of which in maintaining the operating metal temperature through a higher heat transfer coefficient at the low water mass fluxes and steam qualities that will be present, having already been shown in Figure 4.

Figure 7 shows the calculated furnace tube wall metal temperatures for the existing high mass velocity design, and the Mitsui Babcock proposed low mass velocity when 30% additional heat input is applied over the whole tube length. The metal temperatures are calculated for a heat absorption upset of 30% above average to allow for tube position and local surface cleanliness effects. An upset of this extent is probably excessive, but a conservative approach for a new design.

The steady state metal temperature calculations clearly show the benefits of the low mass velocity design, particularly under low load operation. The tube metal temperatures are virtually uniform up the height of the tube and are lower at lower loads. Metal temperatures for all load conditions are reasonably uniform, reaching a maximum at around the 20m level just above the burners. No temperature excursions occur.

This demonstrates the positive flow response of the system and its ability to limit metal temperatures to acceptable values. The ribbed tubes of the new furnace are of a superior grade material intended for a higher metal temperature than the existing design. A substantial margin between the operating temperature and the design temperature of 450°C is maintained at all times.

3.0 DESIGN OF THE REFURBISHED VERTICAL RIBBED TUBE FURNACE

3.1 Description of the Refurbished Furnace

The specific features which Mitsui Babcock have incorporated into the advanced technology design to permit the achievement of design load and impart full operating flexibility to the boiler are:-

- New furnace walls featuring optimized internally ribbed tube to retain the once through arrangement, yet offering fully flexible operation and the required load changing rates, with the advantage to the unit heat rate and auxiliary power consumption of sliding pressure and low boiler pressure loss.
- Full static and dynamic stability established through verification by detailed hydraulic modelling.
- An improved start up system with separator vessel and circulating pump that will give a shortened start-up time, and reduced heat and water consumption.
- Upgraded burners to provide controlled fuel and air admission, thus improving NO_x emission levels, and extending the safe range of operating loads without fuel oil support.

- Control philosophy upgrades for combustion, feed water, and start-up systems to assist in obtaining the optimum loading rates and load flexibility.

To comply with the new requirements for the boiler island, the original dimensions of the existing furnace envelope had to be observed rigorously. Also, reinforced concrete had been used for the majority of the main support structure on the original boiler unit, and in order to minimize the refurbishment costs and outage time, there were very strong incentives to retain this for the upgraded boiler. The reduction in the pipe and tube sizes afforded by the use of the Benson boiler technology ensured that the load limits from the pressure parts on to the structure could be met, and this was decisive in enabling the original foundations and support structure to be re-used.

The proposed new furnace arrangement is shown in Figure 8. It comprises the outer enclosure walls, and a dual-panelled division wall consisting of identical front and rear sections located on the centre line of the furnace. This effectively results in a twin furnace arrangement with four groups of burners situated in each furnace chamber.

Two burner assemblies are positioned in the front wall of each furnace chamber and two in the rear wall. In each chamber the burners are arranged to fire tangentially into the furnace chamber. Each burner assembly includes four pulverised fuel nozzles arranged vertically with secondary air nozzles situated between them.

Feed water from the economiser outlet header is directed through two economiser downcomers terminating locally at the supplies to the furnace enclosure and division wall inlet headers. Supply piping then transfers the feed water to the respective furnace inlet headers:

The function of the furnace walls (including the division wall) is to generate the desired quantities of saturated or superheated steam (above the Benson load) from the water fed through the economiser and down-comers. At loads below 40% BMCR (during start-up & shut-down), the furnace walls form part of a circulation system together with the separator start-up system, to provide saturated steam. At loads above 40% BMCR, the furnace walls provide superheated steam which passes through the separator to the furnace roof and the several stages of superheat.

Steam generation in the furnace wall is achieved principally by radiant heat absorption from the combustion process. The furnace outer walls, comprised mainly of vertical ribbed tubes, are of membrane wall construction, and site fabricated from shop-assembled panels. Openings for burners, instrument tappings, maintenance and observation doors, and after-air ports are incorporated into the panels at appropriate locations.

The division wall tubes go directly from the bottom inlet headers to the top outlet headers above the roof. A set of 36 risers takes the water / steam from the furnace wall outlet headers to 12 mixers to achieve further blending. The water / steam is then carried by individual pipes from the mixers to the two separator vessels. The division walls are of tangent tube construction. Groups of 5 tubes are linked together using wrap-arounds and small bars in between, allowing the centre tube to carry the weight of all 5 tubes.

Ribbed-bore tubing with an optimised profile is used over the whole of the furnace including the front vestibule floor and the screen. The rear wall sling tubes are larger diameter plain tubes. The furnace and division walls utilise a number of tube sizes to achieve the desired static and dynamic stability. The transitions from the lower to the middle sections, and from the middle to the upper sections are made by the inclusion of individual tube transition (swage) pieces.

3.2 Design Performance

Mitsui Babcock have developed a detailed model for the furnace and performed extensive analysis to confirm that the proposed vertical ribbed tube once-through furnace circuits will achieve the optimum operational performance. To summarise, the proposed new design achieves the objective of overcoming the limitations of the old furnace by:

- Lowering the furnace mass flux rate to $\sim 700 \text{ kg/m}^2/\text{s}$ to give a positive flow characteristic by using a low flow velocity in vertical tubes,
- Enabling a 100% BMCR steam output capability (264 kg/s at 545°C, 168 Barg),
- Minimising temperature divergences between adjacent tubes, thus preventing undue differential thermal stresses,
- Providing full operational flexibility for load range and load changing,
- Providing sliding pressure operation and lower heat rate,
- Eliminating the auxiliary support systems required by spiral tube designs, thereby lowering the weight,
- Maintaining the existing furnace heat rating by retaining the furnace division wall,
- Improving the boiler efficiency to 91.25% (LHV),
- Reducing NOx emissions, and
- Facilitating simple tube layout and installation.

3.3 Furnace Performance Analysis

3.3.1 Furnace Heat Flux Distribution

A thermal performance calculation for the furnace was made using Mitsui Babcock in-house software. This program is used to determine the gas-side furnace thermal performance from heat input, water / steam conditions and the furnace geometry, and calculates the furnace heat absorption and furnace exit gas temperature.

Heat absorption to the various sections of all the walls were then determined by establishing heat flux profiles, both horizontally and vertically within the furnace chamber.

3.3.2 Furnace Flow Distribution

Fluid flow distribution through the various walls was predicted by use of Mitsui Babcock in-house software, which is capable of modelling the flow and pressure loss distribution through a network of parallel steam / water circuits. The model requires user-specified input data for physical geometry, and heat absorptions for all sections within the network. There are six parallel circuits in the Yaomeng furnace:-

- Furnace front wall
- Furnace left hand side wall
- Furnace right hand side wall
- Furnace rear wall
- Furnace front division wall
- Furnace rear division wall

Each of these circuits was sub-divided into discrete sections in the model so that a more detailed analysis could be performed, and such that the flow distribution in each circuit could be predicted readily for BMCR and a range of part loads.

3.3.3 Static Stability

Static stability analyses have been performed for both the division wall and external wall circuits for a number of loads cases, the results of which are shown in Figures 9 and 10. The curve of pressure loss against tube mass flow always shows a positive gradient, such that there are no plateaux or points of inflection which would indicate the potential for instability, as would be the case with a high mass flux system for which dynamic pressure losses are dominant.

As expected the pressure losses are lower at boiler outputs below 950te/h. The influence of operation without feed heaters has also been checked and also shows the desired rising characteristic. These calculations show without doubt the inherently stable characteristics of the new boiler design over the entire operating range, (and well beyond), and that adverse flow pulsations will not occur in the furnace or division wall circuits.

3.3.4 Dynamic Stability

The dynamic stability of the furnace circuits was assessed using Siemens licensed software (Dynastab).

An average tube in each circuit was modelled and the relevant input data established. These data included physical geometry, fluid flow rate and heat input up the tube height. The dynamic response was reviewed for a heat input increase of 1.2 x the average in a time step of one second.

Results were obtained for the following tubes at both BMCR and 40% BMCR:

- Furnace front wall
- Furnace side wall
- Furnace rear wall

- Division wall main tube
- Division wall edge tube

Figures 11 and 12 give the results of the dynamic stability assessment for those two load conditions. They show that all tubes exhibit dynamic stability over the full load range. There being no long-term pulsation, the perturbation to the system is quickly damped.

3.3.5 Tube Metal Temperatures

The thermal performance of the furnace has been calculated and found to be in agreement with the data taken from the plant and reported by TPRI. Vertical and horizontal heat flux distributions on the division wall and outside walls have been determined. Metal temperatures under upset conditions have been calculated and found to be totally acceptable.

Departure from Nucleate Boiling, (DNB) does not take place, and the metal temperatures are well within acceptable limits for the tube material and thicknesses selected.

Tube temperatures were determined using licensed Siemens software (Wathun). The worst tube in each circuit was modelled using the physical geometry, including ribbed tube geometry, enthalpy conditions on the tube side, fluid mass flow rate, and internal heat flux as inputs. The centre tubes on the furnace front wall, sidewalls and rear walls were examined, and the tube mean wall temperature calculated for several locations up the height of the tube.

The results of these calculations are shown in terms of the tube metal temperatures for the external walls at 100% BMCR load for the mid-wall position and for the face of the tube exposed to furnace heat fluxes in Figure 13. The bulk fluid temperature is also shown for reference, thus identifying the sub-cooled length and point at which dry-out is complete. Figure 14 shows the tube metal temperatures at 50% load, and a comparison with the existing high mass flux furnace is given in Figure 15.

3.3.6 Furnace Instrumentation

To assess the actual performance of the new furnace against the corresponding design predictions, it was instrumented to measure the following parameters:

- Heat flux profiles
- Metal temperatures
- Water mass flux
- Inlet water temperature
- Boiling regime transfer point locations
- Steam temperature profile at outlets

A section of the furnace in the front half of the left sidewall between the corner and the mid wall locations, was selected to be instrumented fully. Four wall tubes across the width of this section, which during operation are exposed to different heat flux profiles from the combustion process due to their location, were each fitted with:

- A non-intrusive novel water flow meter located at a level just above the inlet to the wall tube in the single phase water section. This was developed by Cranfield University under the DTI-supported collaborative project, and reported in more detail in section 3.3.7.
- Five heat flux meters incorporating gas side metal temperature measurement at various levels up the tube, and,
- Six non-gas side thermocouples also at various levels up the tube.

The optimum locations for the Cranfield flow meters have been determined by computational fluid dynamics (CFD) flow modelling techniques to ensure that they are located in a fully developed flow regime in a section of single phase fluid. A total of 196 conventional metal temperature thermocouples were attached to selected tubes within the full extent of the furnace water wall boundaries, including the division wall, generally at both lower and upper furnace locations to enable the profiles of the tube metal temperatures to be established, particularly those for the tube outlet metal temperatures. Details of the locations of the additional instrumentation are given in Figure 16.

3.3.7 Novel Flow Meters

As has been mentioned already, heat fluxes are far from uniform in the various areas of the furnace and indeed also fluctuate regularly at any particular locations. The advantage exhibited by the low water mass flux vertical tube once through boiler in this respect is the ability of the system to respond automatically to such fluctuations by altering the flow rate through the tubes to compensate for the variable heat fluxes.

Mitsui Babcock was keen to verify the calculations for the refurbished boiler, and to this end flow rates in representative tubes required to be measured to permit comparisons with design expectations. The flow meters needed to be non-intrusive relative to the waterside so as not to interfere with the flow distribution patterns, and were novel in that this was the first time that ultrasonic techniques had been used for such a purpose on such small bore, thick walled ribbed tubing combined with such high temperatures and relatively low flow rates. Indeed the application was out-with the capability of commercially available equipment and as a result a prototype instrument was specially developed by Cranfield University.

The flow meters are located in the lower water wall region of the boiler in which the fluid would be single-phase water. Each flow meter consists of two sets of ultrasonic sensors, one in each pair being the transmitter, and the other the receiver. The principle of operation relies upon the measurements and interpretation of the resultant fluctuations of the ultrasonic beams caused by the attenuation within the waterside flow.

The electronic signal processing consists of a signal generator which drives the transmitting sensor at a resonant frequency of the system and not the ultrasonic sensor. A resonant cavity is thus set up in the system consisting of the pipework and the fluid. Thermal fluctuations in this cavity give rise to an amplitude modulation of the received signal. The drive signal is of the order of 10V peak to peak at 100kHz, and the received signal is typically 0.3V peak to peak and the same frequency.

The sensors are mounted on the outer end of the threaded stalks, which provides them with thermal protection. They are bonded to the end of the stalks with a tungsten-loaded epoxy. The contact between the inner end of the stalks and the outer surface of the ribbed tube is established by use of silver foil, which can accommodate any minor surface irregularities, and thus ensures that there is good ultrasonic coupling at this interface.

The instrument was developed using a flow meter clamped to a length of representative section of the tube similar to that used for the furnace lower water wall, mounted in a low pressure flow rig at Cranfield University, using a fluid temperature of approximately 50°C. The instrument set-up is shown in Figure 17, in which the two pairs of ultrasonic sensors may be seen mounted on to the support bracket attached to the membrane wall on either side of the instrumented tube.

Development trials were undertaken over a range of flow rates compatible with those which would be encountered in the water walls during boiler operation load range over the service life. The modulated signal from each of the transmitters was collected by the corresponding receiver and passed to a signal-conditioning box. The output was captured on a spectrum analyser, and fingerprinted over a range of flows. At site the output data from the flow meters were transmitted to a data acquisition system the contents of which were forwarded to Cranfield University in the form of numerical data for subsequent analysis / conversion to mass flow rates.

Upon successful demonstration of a robust ultrasonic instrument, four such production flow meters were manufactured by Cranfield University and each was first attached to a small membrane panel insert manufactured under contract conditions at the Mitsui Babcock factory, such that mounting and calibration could be performed under laboratory conditions, after which the assemblies were shipped to Yaomeng site for installation into the furnace side-wall pressure parts.

3.3.8 Improved Start-up System

A minimum flow of 365te/h is needed by the furnace tubes. During the initial stages of pressure raising, this flow is provided solely by a circulating pump. Water is separated from the furnace outlet flow and collected in a vessel that provides the pump suction. A discharge valve regulates the water level, and as the level falls, feed water makes up the flow to 365te/h. An overflow valve deals with the expansion and expulsion of water by steam. Once the feed supply alone is enough for the furnace, the circulating pump is switched off.

To suit the layout of the boiler at Yaomeng, the flows from the furnace walls are gathered in a series of collector pots. The connections to the pots ensure good mixing before discharge into one of two separator vessels. Connections deliver steam to the super-heater via the furnace roof, and water is discharged to a single water level vessel. The pump is suspended by a vertical large bore suction pipe from this vessel. The outlet pipe delivers the re-circulating flow to the feed manifold at the rear. The water separators are slung one on each side of the boiler, and the water discharge pipe-work runs into the lower half of the water level vessel slung at the front of the boiler.

3 3.9 Ribbed Tube Selection and Manufacture

A crucial aspect of heat transfer in a furnace wall with vertical tubes is that the high heat transfer rates associated with nucleate boiling should be maintained in all regions of high heat flux to restrict the metal temperatures within acceptable limits over the whole operating load range, even with the low water mass flux.

The tube metal temperature is dependent upon the tube internal rib geometry. Rib height is primarily dependent on the tube drawing process and the sensitivity of the tube temperature to this parameter was studied across the range from 0.9 to 1.2mm. The results of the rib height effects on tube metal temperature showed that this was only slightly sensitive at sub-critical pressures and has set the tolerance on the tube manufacturing process. As the critical point was approached, there was a rapid rise in tube wall temperature with decreasing rib height. The internal spirally ribbed tubing selected for the Yaomeng furnace lower front, side and rear walls was as follows:-

Parameter	Unit	Design
Tube O/D	mm	26.9
Lead angle	Deg	50
Rib height	mm	1.1

The carefully optimised lead angle and rib profile differ significantly from those featured in the more commonly-used regular ribbed tubes, in that they are steeper and higher respectively. A comparison between this specially optimised ribbed tubing and regular ribbed tubing used in more conventional plant is shown in Figure 18.

This was the first time that such tubing has required to be manufactured on a full production scale. Nevertheless, as a result of very close collaboration by Mitsui Babcock with both the UK tube supplier and his toolmaker, during which many trials were undertaken on each size and type of tube, the consistently high quality and dimensional tolerances essential for the achievement of the heat transfer performance and pressure loss characteristics was assured.

4. BOILER PERFORMANCE

4.1 168 Hours Reliability Run

The full load 168-hour reliability test was completed successfully during May, 2002. What made the occasion particularly significant for all concerned was that the Yaomeng refurbishment featured the conversion of the furnace to Low Water Mass Flux Vertical Ribbed Tube Benson Boiler Technology, this being the first time that it has been accomplished on a commercial power generation scale anywhere in the world, a very significant achievement by Mitsui Babcock.

4.2 Performance Guarantee Tests (PGT's)

After a brief outage of the boiler unit for maintenance, the PGT's themselves were performed by representatives from TPRI during the end of July / early August 2002. The results from the PGT's and subsequent operation of the refurbished plant have revealed major improvements in the performance of the unit.

Peak short term steam output is 1010.3t/hr and maximum continuous output is 954t/hr, both having exceeded the guarantee requirements. Peak power output capability has increased from 270MWe to 327MWe, and indeed the boiler has now been formally up-rated to 310MWe. Whereas operation at any part load condition without fuel oil support was difficult before the upgrade, it is now possible down to 40% BMCR. The load following capability has also been much improved.

Boiler thermal efficiency has increased from 90.34% to 91.41%, unburned carbon has decreased from 4.72% to 1.65% and the particulates issued from the chimney have been reduced from 1242mg/m³ to 163mg/m³. NOx emissions have also been reduced significantly. The new start-up system has decreased boiler start-up and shutdown times appreciably, with up to 60 minutes being cut from a cold start period, and 30 minutes from a hot start.

4.3 Furnace Wall Temperatures

The graphs in Figures 19 & 20 give plots of tube exit temperatures for the front and side water walls for a series of ten load conditions over a range between 203MWe and 309MWe taken during the weeks leading up to the PGTs. The actual operating load corresponding to the readings in each of the ten series is shown in Table 1. These results are generally representative of the exit temperatures for all of the furnace outer and division walls. Taken as a whole the performance of the boiler and the overall heat absorption of the furnace have both proved to be in accordance with the design expectations.

4.4 Flux Meter Outputs

There was good agreement between the measurements from the flux meters at the lower elevations and the design predictions, and the heat fluxes measured on the corner tube were lower than those associated with the other instrumented tubes towards the mid wall location, also in line with design expectations. However, the measured heat fluxes were up to 30% lower than the design predictions for the upper levels in the furnace, probably due to furnace wall slagging.

4.5 Novel Flow Meter Results

Valid data were collected from the flow meters over the load range 230MWe to 300MWe. A comparison of the actual measurements with the design predictions is given in Figure 21 and Table 2. From the measured results it was apparent that the water mass flux increased broadly in proportion with increasing load, in line with design expectations. Similarly there were indications from the site data that, at constant load the mass flux in the tube towards the corner of the furnace in areas of reduced heat flux, were also lower, again in line with design expectations. These were, however, not as

pronounced as had been predicted, although this was also true of the profile of the measured heat fluxes across that section of the furnace side wall.

Nevertheless, it was evident that the vertical ribbed tubing was performing well, as indicated by the significant reduction in the range of exit temperatures, ie the positive flow response characteristic has been demonstrated in so far as to show that adequate heat transfer was occurring automatically with variation in the heat flux applied to the tube walls.

4.6 Steam Oxidation Studies

For the exploitation of the low mass flux technology, and for the next generation of advanced super-critical units in particular, for which the exit temperatures from the furnace walls will be significantly higher than at Yaomeng, an understanding of the oxide growth is an important consideration for the long term performance of the boiler, especially the influence on the continued effectiveness of the optimised ribbed tubing.

An initial steam oxidation investigation was, therefore, undertaken to examine the behaviour of a range of materials suitable for furnace walls, HCM2S (T23) and X20CrMoV12, as well as the 15Mo3 ribbed tubing being used in the sub-critical Yaomeng furnace.

The work was performed by Cranfield University, and for these studies a series of laboratory tests was carried out using short tubular test specimens mounted in a muffle furnace and exposed to low-pressure steam produced from de-ionised water. Tests were performed at four temperatures in the range 500-575°C for periods from 300 to 4000 hours, with intermediate exposures of 700, 1000 and 2000 hours.

It is worthy of note that the 300, 700 and 2000 hours specimens were subject to a single heating / cool-down cycle, whilst the 1000 and 4000 hours specimens experienced two, and in view of the tendency for the oxide to spall under thermal cycling conditions, care was taken in the selection of the measuring techniques and the positions at which the measurements were taken during the assessment of oxide growth / metal loss to ensure that the results were not influenced unduly by the method of testing.

As expected steam oxidation rates increased with temperature. At each temperature, differences in performance between the materials, including the ribbed tubing, were found to be within the scatter and error bands of the results expected within the limitations of this method of testing. Overall, the results indicated that for the three steels studied, there was a limited effect of alloy chromium content on steam oxidation rates in the range 500-575°C.

The samples of ribbed tubing exhibited similar degrees of oxidation both inside and out, indicating that the ribbing process had apparently not affected the oxidation behaviour. Under prolonged exposure to such temperatures the ribs would grow in width and, with the possibility that spalling would probably be more likely on the smaller diameter, the rib height would reduce and the sharp edges at the top of the flanks would become rounded with the metal loss. The consequences of this would almost certainly be a compromising of the performance of the optimised ribbed tube in terms of its ability to maintain the high levels of heat transfer required.

That said it must be clearly recognised that the exposure temperatures experienced during this series of tests were significantly higher than would have been seen in service at Yaomeng, and as such the 15Mo3 would not oxidise significantly at the actual Yaomeng service temperatures. Its performance would therefore be assured over the full service life, however, it does serve to demonstrate the importance of correct material selection for the particular application.

Below approximately 70 – 75 % full load, a super-critical plant would actually operate sub-critically and hence for a vertical tube low water mass flux design, assistance would still be required from the ribbed bore to maintain heat transfer in the dry-out region. Again care would be required in the choice of material for the ribbed tube to recognise the elevated operating temperature at higher loads under super-critical operating conditions

5. OPERATIONAL FEEDBACK SINCE THE PERFORMANCE GUARANTEE TESTS

5.1 General Operating History

Since the beginning of June, 2002, apart from a short period for maintenance prior to the PGT's, and an enforced temporary outage towards the end of December caused by a fault not related to the boiler island, YPGL has continued generating almost continuously at design load or above to meet the grid generation requirements, including peak output of up to 327MWe, for virtually twelve months up to the planned shutdown at the end of May, 2003.

5.2 Boiler Operational Availability

Figure 22 shows the availability of the refurbished boiler unit by month from June to December during 2002. The hours over which the unit was generating electricity are shown as a percentage of the elapsed time for each month. For this period as a whole, the average operational availability was 92.1%, and from September to November inclusive it was as high as 99.7%.

For the twelve-month period up to the end of May, 2003 the overall figure was 95%. The corresponding availability prior to the upgrade was substantially lower.

5.3 Electricity Generated over the 7 Month Period

Figure 23 shows the total electricity generated during the same post-upgrade period prior to the enforced outage. The total electricity generated during each month is shown as a percentage of the total capacity of the upgraded unit, based on the enhanced rated output of 310MWe. The total electricity generated, 1198 Gigawatt-hours, is 75% of the total of 1592 Gigawatt-hours possible for the period on that basis.

The corresponding figures for the twelve-month period to the end of May, 2003 are 2053 Gigawatt-hours generated, 77% of the 2663 Gigawatt-hours possible, again based on a rated output of 310MWe.

5.4 Boiler Outages

Over the same period, only ten unscheduled boiler outages of any significance were recorded, none of which were directly attributable to a malfunction or failure of the pressure parts.

5.5 Customer Satisfaction

In October, 2002 the Chinese State Power Company convened a meeting in Beijing to assess the outcome of the Yaomeng Refurbishment Project. It was attended by officials of various power companies in China and several boiler experts from Design Institutes and Universities. YPGL expressed their complete satisfaction with the outcome of plant refurbishment, which was also confirmed by the State Power Company and its boiler experts as a resounding success.

The Chinese Power Industry Authorities have confirmed their full acceptance of the Mitsui Babcock technology, and this endorsement has positioned the expertise favourably for any future UP boiler refurbishment and super-critical once through projects in China. Figure 24 shows the refurbished boiler as it is now, the marked reduction in particulate emissions being in evidence when compared with Figure 1.

6. FUTURE APPLICATIONS

The successful completion of the refurbishment of No 1 boiler at Yaomeng is a major milestone in both the development of the technology of once through low mass flow vertical tube boilers and Mitsui Babcock's presence in the refurbishment market in the PRC.

Wherever once through boilers are suffering load restrictions, showing an inability to change load or exhibiting high metal temperatures, this technology offers a proven solution on a major utility boiler, and the technology is a key step forward for the future development of the large super-critical once through, low mass flow, vertical tube Benson boilers as well as for the refurbishment of sub-critical boilers. Both will benefit from the low mass flux vertical tube design by virtue of the low feed pump power requirements, ease of construction and reduced variation in tube metal temperatures.

Within the UK operators are now considering the use of this technology, which along with changes to the HP piping and turbine will allow them to move from a sub-critical to a super-critical steam cycle at state-of-the-art steam conditions. Extensive testing has by Mitsui Babcock and Siemens Power generation has demonstrated that the low mass flux vertical tube once through system also exhibits positive flow characteristics at super-critical pressures, and the fact that super-critical units still run at sub-critical conditions during part load operation means that an optimised ribbed bore is still required to promote the enhanced heat transfer required for safe dry-out.

Mitsui Babcock believes that this technology will become a standard for fossil fired boilers of the future, and are pleased to have enjoyed the support of DTI to enable them to be in the forefront of the development and application of it. As has been demonstrated the full scale heat transfer and pressure loss test data, on which the Yaomeng design was based, extends to super-critical

pressure conditions. Thus the technology for super-critical plant is available within Mitsui Babcock now and there is every reason to believe that the move to such higher pressures will be equally if not even more successful.

7. CONCLUSIONS

1. Boiler steam output has met both the guaranteed continuous and peak levels.
2. Boiler thermal efficiency guarantees have been met.
3. Peak NOx levels have shown a significant improvement over the original unit.
4. The refurbished unit has shown stable load operation at all levels above 40% MCR without fuel oil support, and exhibited better load following characteristics compared with the original unit.
5. Unburned carbon has decreased from 4.72% to 1.65%
6. The particulates issued from the chimney has been reduced from 1242mg/m³ to 163mg/m³
7. The new start-up system has worked well, with up to one hour having been cut from the start-up time.
8. From June, 2002 to May, 2003 the average operational availability for the unit was 95%.
9. The total electricity generated over the same twelve-month period, 2053 Gigawatt-hours, was 77% of the total of 2663 Gigawatt-hours possible for the unit, based on a rated output of 310MWe.
10. The Benson boiler low mass flux vertical ribbed tube technology has been introduced successfully at Yaomeng, and the technology accepted by the Chinese Power Industry Authorities.
11. The flow meters confirmed design expectations in that they indicated a flow rate which increased proportionately with boiler load, with the lowest flow rate at the corners in the lowest heat flux zones.
12. Furnace and division wall outlet temperatures have been reduced to acceptable levels for predicted safe operation of even the most critical items of plant over the 150,000 hours design life extension.
13. The overall performance of the boiler has proved to be in accordance with the design and the overall heat absorption of the furnace is correct.
14. The Customer, YPGL, has expressed total satisfaction over the results of the upgrade, which has been seen in China as a resounding success.

FIGURES and TABLES