ANSALDO CALDAIE EXPERIENCE IN HRSG DESIGN DEVELOPMENTS

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1. **Introduction**

Several factors require HRSGs to reach high flexibility levels in terms of

- maximum steam production for a wide range of gas turbine loads
- maximum cycling capabilities and plant efficiency.

The first point is typical of combined cycle applications to cogeneration (Combined Heat and Power generation), where electricity and useful heat for several applications (i.e. industry, district heating, desalination) are simultaneously produced. In order to maximise steam production flexibility regardless of gas turbine load, post firing systems (supplementary firing) are provided; for some specific applications the unt can also be equipped with fresh air systems to allow steam production even with gas turbines not in operation. An interesting application has been developed for Ras Laffan B (Qatar) Electricity and Water project where EPC contractor Siemens, in order to fulfil the specified operational requirements, developed a very flexible plant design.The HRSGs are equipped with double post firing to allow very high thermal power input (max 280 MWth) to cope with a wide operational range of GT electrical power and steam production for electricity or desalinated water production. Data collected after some years of operation underline how the tailor-made design developed during project execution allowed the required plant flexibility.

The second requirement is typical of deregulated power markets, where power plants, in order to be competitive with the others, are required not only to operate with the highest possible efficiencies, but also with the maximum operational flexibility in order to dispatch the required power in very short time. This situation is further worsened by other factors like extremely demanding grid requirement in terms of frequency control or variability of different factors like gas price or wind power availability.

In the last ten years Ansaldo Caldaie has developed several applications for heavy cycling combined cycles; one interesting application is the project of once through Benson HRSG for Hamm Uentrop and Herdecke (Germany). Due to the absence of the thickest component (HP drum) on once through boilers, HRSG should not be the limiting component on combined cycle start-up. To cope with this requirement during project execution, a fatigue analysis procedure to evaluate life consumption of HRSG thick components has been set up. Data collected from Hamm Uentrop operations validate the reliability of this procedure to correctly design pressure parts in order to allow the required plant flexibility. On the basis of this experience a step ahead is currently under development to cope with advanced combined cycle application having steam temperatures reaching 600°C.

2. Steam production vs gas turbine load flexibility

2.1 General overview

The power generation sector is generally facing two types of end users: industry and civil consumers. Focusing on the particular case of the Middle East, it is clear that not only power has to be delivered to these consumers, but also drinking water.

When designing a new power plant in these regions the following aspects have to be taken into account:

- water can be produced by means of seawater and heat in desalination plants
- while the industrial sector needs almost constant levels of these goods, civil demand increases greatly during the daytime
- demineralised water can be easily stored while electrical energy cannot
- generally speaking, fossil fuels are widely available

Going through the previous points, and making some rough economic calculations, the following considerations apply:

- both water and electricity can be produced by means of chemical energy derived from combustion
- an integrated system for heat and electricity combined production is advisable
- the integrated system should be capable of high flexibility, especially regarding the electricity production, since power cannot be efficiently stored.

Hence the best technical - economical solution is cogeneration; particularly if the available fossil fuel is oil, a cogenerative utility boiler plus counterpressure - extraction steam turbine solution is almost mandatory, while in the case of natural gas a cogenerative combined cycle can also be considered.

A rough comparison between the two cogeneration technologies shows that cogenerative combined cycle is able to ensure both the best performance and higher flexibility, especially when considering the application of HRSG post firing technology.

2.2 HRSG optimum configuration

In the case that a cogenerative combined cycle has to be designed, many parameters shall be fixed, on the basis of the specific project requirements. Focusing on the HRSG design the following listed below are the most important.

- Steam pressure levels number and value: considering that the general steam cycle foresees a counterpressure steam generation, the use of more than one pressure level is no longer reasonable
- Post firing (PF) use or not: this technology is required as the system flexibility demand increases, which is a common condition for cogeneration application
- Number and location of PF system stages: the simplest solution consists of a unique PF device, generally installed in the inlet duct. Where the project requires a very flexible system, the PF power increases, and the best technical - economic solution shall be carefully evaluated.

At high PF heat input rate three possibilities can be considered to find optimum firing system configuration. Following design and economic considerations are based on Ras Laffan HRSG case, where a double post firing, described in paragraph 2.3, has been selected.

1. One PF installed at the HRSG inlet: the gas temperatures can dramatically rise and HRSG design criteria shall be revised in order to prevent problems due to resistance of fins and non-cooled metal components (membrane water walls can be considered). In Ras Laffan case this would lead to average gas temperatures close to 900°C
2. One PF installed at HRSG intermediate section (generally before HP EVA section): temperature levels are still high, but HRSG design generally does not need to be heavily reviewed. Being post firing placed before evaporator, when great amount of steam is required, a huge superheater section should be considered. This, in the case of Ras Laffan, would increase pressure parts costs by about 30% compared to the double PF solution.

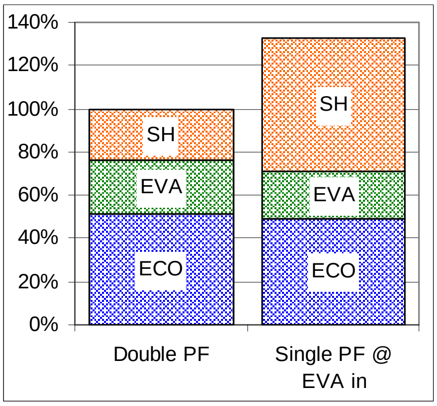

Fig 1 – Cost Comparison

3. Two PF installed one at HRSG inlet (before superheater) and the other at an HRSG intermediate section (before evaporator): this is a good solution in terms of temperature profiles, weight and costs, flexibility and control because of:
   - Optimum gas and steam-water temperature profile that both avoids reaching high gas temperature levels and permits having sufficient ΔT that reduces SH weight
   - PF1 will mainly be used to control steam temperature, while PF2 will be used for steam generation. This will guarantee the required flexibility in all conditions. For example, if only process steam (low temperature, low pressure) were required, PF2 would be controlled on the basis of steam flow requirements and PF1 could be turned

off. On the contrarily, if steam demand were required only for steam turbine operation, PF2 could be turned off and PF1 would be operated in order to maintain steam turbine inlet parameters.

- The possibility to separately control steam production and steam temperatures will permit the boiler to operate with near zero spray attemperation in all conditions.

2.3 Test case: the Ras Laffan project

Fig. 2 – Ras Laffan B HRSGs

For Ras Laffan B Qatar Electricity and Water project, the EPC contractor Siemens developed a very flexible plant design in order to fulfil specified operational requirements in terms of electrical power or desalinated water production. The power island having a total capacity of 1025 MW, is equipped with three V943A gas turbines with bypass stack to allow open cycle operation, three HRSGSs equipped with double post firing and two 200 MW range back-pressure steam turbine; steam from the power island is fed to four desalination units supplied by Doosan for a total water production of 273 million litres desalinated water per day.

The HRSGs are of the horizontal gas flow, top supported, natural circulation type, with one pressure level plus condensate preheater and two staged supplementary firing supplied by Forney.

Ansaldo Caldaie scope of work included engineering, manufacturing, supply, supervision of erection and start-up of the 3 Heat Recovery Steam Generators. The contract was awarded in October 2004 and was completed in June 2006. Ras Laffan B has also been selected as one of the two technical tour during Power Gen Middle East 2010.

2.4 Main design topics

At design condition (100% TG load @ 50 °C ambient temperature) HRSG steam parameters are pressure = 85.4 bar and temperature = 563 °C.

	Nominal	Max
Steam Flow [t/h]	636	703
PF1 power [MWth]	110	145
PF2 power [MWth]	105	170

Several loads, including a severe gas turbine aged condition, has been analysed during design phase in order to verify HRSG capability to withstand with various plant configurations in terms of gas turbine load (related to electrical power demand) and steam production (related to desalinated water demand). On the basis of this analysis post firing design conditions has been selected according to above table. Being post firing system the most critical item, accurate design of overall firing system has been performed. In order to guarantee uniform flow distribution at post firing inlet according to post firing supplier requirement, following flow distribution system has been studied (See Fig. 3)

- devortex device placed at the beginning of HRSG inlet duct to eliminate TG swirl
- grid placed upstream PF1, to uniform flow distribution on post firing burners.

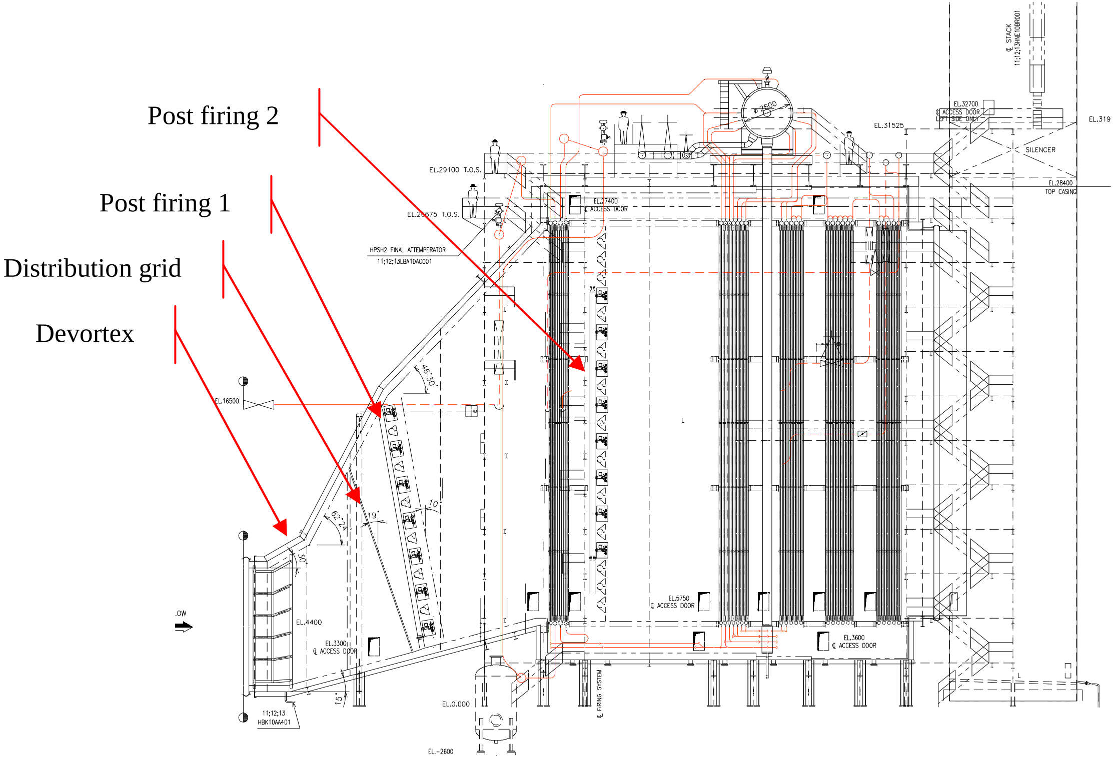

Fig. 3 – Ras Laffan longitudinal section

Fluid-dynamical behaviour of the system for different gas turbine loads has been intensively analysed with the use of Fluent CFD tool (See Fig. 4).

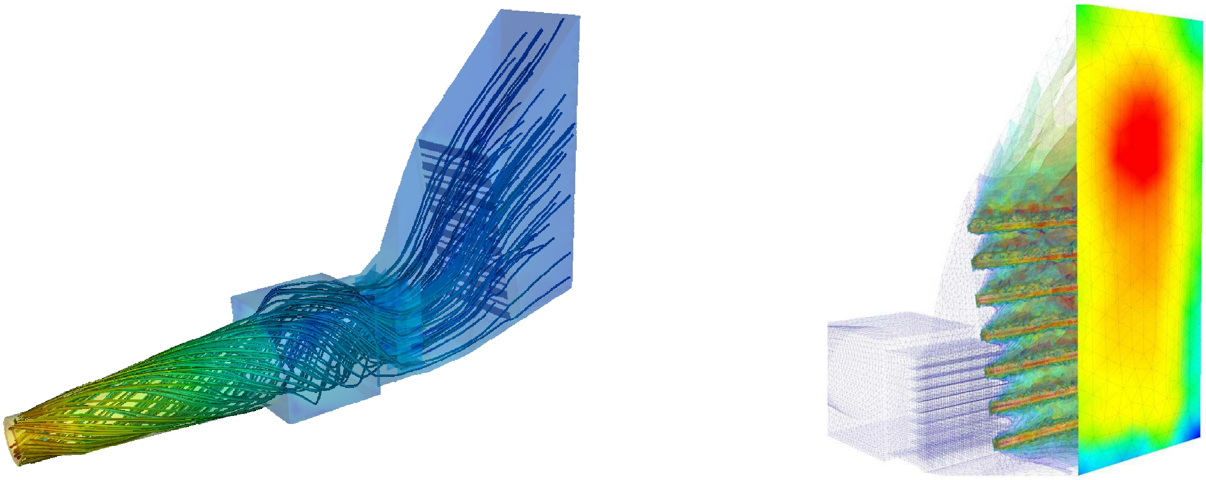

Fig. 4 – Ras Laffan CFD analysis

In order to check possible resonance problems, devortex mechanical frequencies has been calculated with FEM analysis, while natural vibration frequencies has been calculated with CFD dynamical simulation. It has been found that fluid-dynamic frequencies, being one order magnitude less than mechanical ones, are completely decoupled (See Fig. 5).

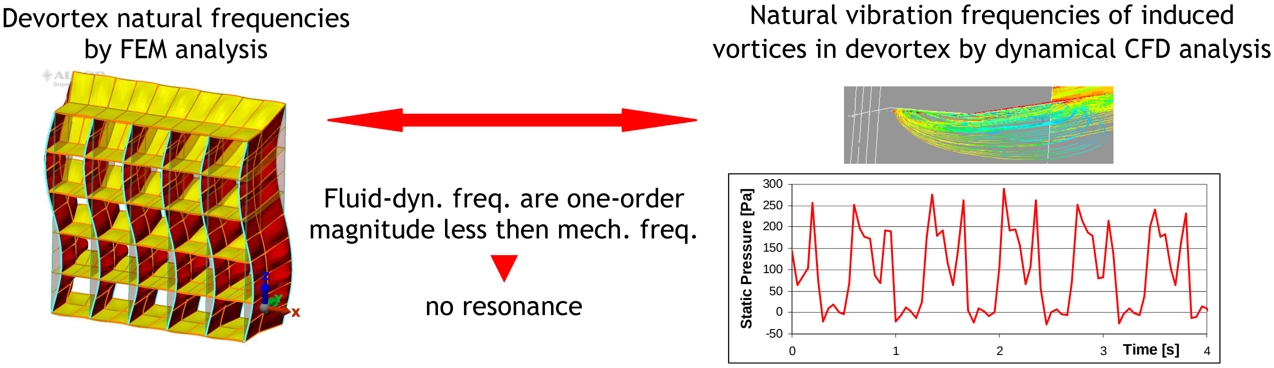

Fig. 5 – Ras Laffan aeroelastic analysis

2.5 Operation vs. design comparison

After more than four years of operation, it is possible to have a general overview of the capability of HRSG to fulfil design requirements in terms of maximum flexibility.

The post firing system commissioning and tuning was carried out without problems, giving the possibility to reach during the commissioning phase the required flexibility in terms of maximum power and post firing modulation between PF1 and PF2 without encountering any boiler limitation, including alarm thermocouples values within the alarm limits.

Figg. 6 and 7 show a comparison between design and operational data; only a selection of the more representative data is shown. Fig. 6 shows steam production as a function of gas turbine load; while the lower curve represents all the operative unfired points, the upper curve corresponds to the maximum steam production of the fired cycle considering both the PF system and gas temperatures limits.

Regarding to the PF system, its physical limit comes from the maximum heat rate that can be supplied by PF1 and PF2 system and corresponds to the maximum heat rate foreseen at operative conditions plus a 10% margin; this boundary condition has to comply with the maximum temperatures forseen for mechanical design.. This is resulting in a non-regular upper limit, depending on the first limit in the high GT load region and the second limit at low GT loads.

It can be seen how the HRSG is able to provide a very wide range of operating conditions, ensuring both a nominal steam output down to less than 60% GT load, and enabling a very wide steam output per each GT working condition. This system flexibility will result in a postfiring operation with high heat input even at low GT loads.

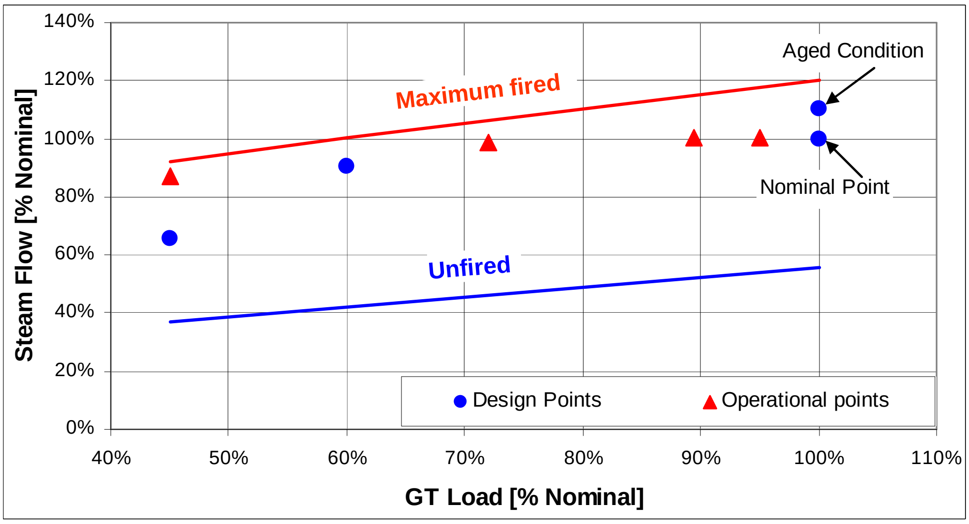

Fig. 6 – Operational point vs design points comparison

Above consideration can be enhanced defining an index of the density of thermal input per unit of gas mass flow:

$PF_{\text{Specific Heat Input}}$ = Total power to PF/ GT Mass Flow

Fig. 7 shows $PF_{\text{Specific Heat Input}}$ as a function of gas turbine load. It can be noted how at low GT loads the firing density increases in order to keep the required desalinated water production unvaried. Even under these severe conditions, the proper post firing design ensures a reliable HRSG operation.

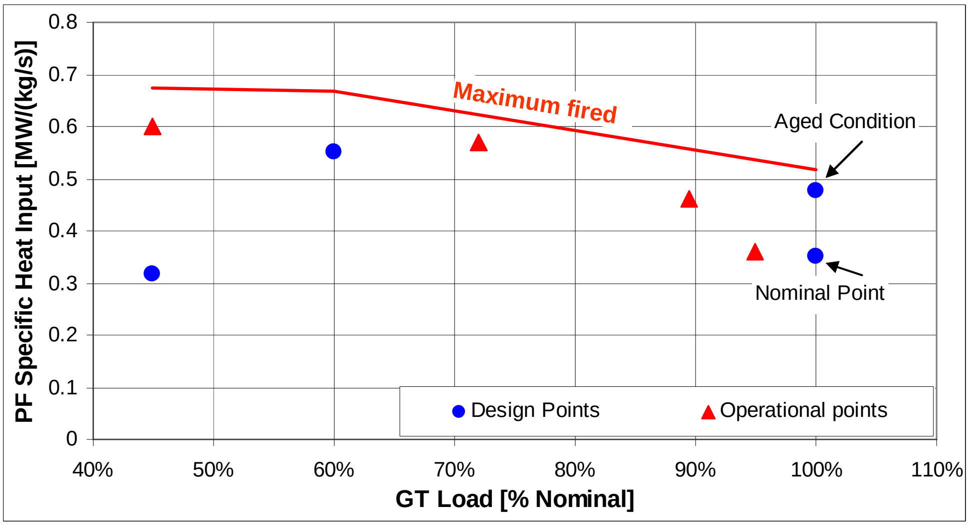

Fig. 7 – Operational point vs design points comparison

3. <u>Cycling flexibility</u>

3.1 General overview

As a result of power markets deregulation, power plants should be competitive the one with the others, and are required not only to operate with the highest possible efficiencies, but also with the maximum operational flexibility in order to dispatch the required power in very short time. This situation is further worsened by other factors like extremely demanding grid requirement in terms of frequency control or variability of different factors like gas price or wind power availability. As a result of aforementioned factors, cycling requirements in terms of fast start-up and number of start-up per year is considerably increased in the last years. Nowadays HRSGs cycling capabilities are mandatory in order to be competitive on a very aggressive market.

3.2 Ansaldo Caldaie specific cycling design features.

In the last ten years Ansaldo Caldaie has developed and successfully applied several design features in order to increase cycling capabilities of different HRSG components in three main fields

1. Basic design

   Basic design should be optimised in order to minimise the impact of frequent fast start-up on boiler behaviour; the major basic design features and design check and evaluations to be considered and implemented are listed below.

   - Small diameter evaporator tubes and consequent smaller evaporator volume limiting drum level fluctuations
   - Automatic drains to ensure effective drainage of condensate and avoid steam/water misdistribution in heated tubes.
   - Final SH and RH spray attemperation to control steam turbine warming with no limitation on gas turbine start-up
   - Evaluation of fatigue life consumption based on EN12952-3 to optimise number of start-ups and start-up time
   - Optimisation of HRSG start-up procedure based on fatigue life consumption analysis to optimise overall combined cycle start-up time
   - Boiler stress evaluator for a creep/fatigue in-line evaluation.

2. Mechanical design

   Mechanical design of the HRSG in general and of pressure parts in particular should be carefully developed in order to reduce stress concentrations due to geometric discontinuities and to facilitate free expansion of the different components; the following mechanical design features are of the utmost importance.

   - Selection of suitable high strength materials (WB36/A302 Gr.B) for the drum shell plates, with enhanced yield stress limiting plate thickness to withstand the thermal fatigue stresses during load transients
   - Full penetration welds to reduce peak stresses on SH/RH tube-to-header connections
   - Cold casing design with the outer structures at a constant ambient temperature and top supported heating elements with free downward expansion to provide the best structural arrangement in order to limit stresses during transients
   - Reduction of number of tubes per header on SH and RH to reduce differential expansions.

3. Heat preservation

   In order to reduce start-up time due to HRSG heat up and pressurisation, HRSG pressure parts should be kept as hot as possible during HRSG shutdown period; to this purpose, the following are the most effective solutions

   - Stack damper and insulated stack to reduce HRSG cooling during shutdown
   - Sparging steam to reduce evaporator heating time and start-up time
   - Motorised valves at superheater outlet to keep drum pressurised.

Several of the above design features are mandatory for a “cycling” HRSG design, like full penetration weld on SH/RH tube-to-header connections, while other items could be selected depending on the project or on client specific requirements.

In general the capability of a particular design feature to fulfil a client's requirements can be proven during commissioning, performance test and reliability run phase or, at least, during the warranty period. The only issue that could lead to serious trouble after several years of operation are those related to component life consumption, i,e, creep and fatigue phenomena. Creep is not an issue for HP drums due to their operational low temperature, generally below 340 °C. Regarding HP superheater and reheaters, a suitable selection of materials can normally result in a design (theoretical) creep time to rupture that will lead to a conventional life consumption of 20%-30% after the standard design time life of 200.000 h. Considering the points made the above, it can be stated that, for state of the art HRSG requirements in terms of temperature and pressure, creep is not an issue if the design temperature and material selection of these components are correctly defined.

As is well known, fatigue is the more severe issue for cycling HRSG lifetime consumption; as a general rule, fatigue life consumption for a given start-up and shutdown cycle is calculated with the following formula

$$L_f = \frac{N}{N_{\max}} \cdot 100$$

N being the number of cycles to be expected during operation and N_{max} the number of load cycles for crack initiation. Total life consumption for the different normal and emergency start-up and shutdown cycles expected during operation is calculated as the sum of L_f ‘s.

It can be seen that overall life consumption depends on the total number of cycles N, selected by end user evaluation of combined cycle operation, and the number of cycles to rupture N_{max} defined by boiler maker on the basis of:

- client requirements (initial and final start-up and shutdown condition, start-up time)
- code requirement for fatigue assessment (TRD 301, EN12952)
- boiler maker internal procedure for fatigue evaluation.

Regarding the last two points, as per the state of the art in boiler engineering, it is expected that HRSGs are designed, manufactured and tested in conformity to Standard Codes and Regulations, and according to the laws of the installation country and/or Client’s Specification.

In particular in Europe the Pressure Equipment Directive (PED) is compulsory Regulation that must be applied to all pressure containing equipment and therefore to HRSGs and relevant auxiliaries, while in many other geographic areas conformity to the well-known American ASME Code may be required.

Following the spirit of the PED, which contains only Essential Safety Requirements, i.e. general safety objectives and prescriptions, the European harmonized Code EN 12952 has been issued and today is commonly used for boilers and HRSGs, giving general standard methods to evaluate mechanical strength of pressurized components, and so to design boiler’s components able to withstand also the main time-dependent damaging phenomena, i.e. creep and fatigue (mechanical and thermal).

In particular, the general criteria and formulas given by the Code for fatigue analysis may be integrated and completed with “tailored” calculation procedures suitable to obtain better simulation of the behaviour of the different components to be designed, in relation to such damage mechanisms.

This approach is fully in accordance with PED requirement and may also be applied as extra code calculation for HRSG designed according to ASME Code Section I (Power Boilers) and so it is always applied by Ansaldo Caldaie in designing HRSG where (almost all cases, today) cycling operation capability is required.

The following paragraphs provide an overview of the possible procedures for fatigue evaluation

3.3 "Extensive" procedure for fatigue assessment

The analysis of thick wall components subject to high temperature and cycling operation is quite complex due to the overlapping of the various different physical phenomena listed below:

1. Transient behaviour of HRSG during:
    - "normal" start-up and shutdown having very different boundary conditions (initial conditions due to the duration of shutdown, gas turbine behaviour due to ambient conditions during the year etc.)
    - emergency conditions (GT trip, GT runback etc)
2. Steam side fluid dynamic behaviour of heat exchanger andrelated thick wall components in conditions far away from nominal (very low steam production, steam condensation in the heating surfaces during GT purging, etc.) and gas side heat exchange, if applicable.
3. Thermal behaviour of thick wall components during transient warm-up or cool-down
4. Mechanical behaviour of the thick wall components

State of the art calculation tools allow above analysis by the use of

1. Dynamic simulation tools to calculate different HRSG sections steam parameters on the basis of transient boundary conditions (i.e. gas turbine mass flow and temperature, steam pressure etc.)
2. CFD simulation tools to calculate headers internal flow and relative heat transfer coefficient
3. FEM tools to calculate thermal transient conditions and relevant stresses, mechanical stresses and stress distribution and concentration due to geometrical discontinuities of the component.

The above analyses are carried out in the company using commercial calculation tools listed below:

1. Protrax for dynamic simulation
2. Fluent for CFD
3. Ansys for FEM calculations

The detailed analysis is time expensive, gives results applicable for given geometries and boundary conditions that cannot be applied to different applications and, due to the non linearity of the physical phenomena that interacts, it is very difficult to consider design margins that must be applied for the design of pressure parts.

3.4 "Quick" procedure for fatigue assessment

As stated in previous paragraph, an extensive procedure cannot be performed during the proposal phase, when optimum design should be defined according to performance requirements (and related guarantees) and economic optimisation.

Sometimes this type of evaluation should be done during "bid-no bid" phase, when unusual cycling requirements should bear on the decision to ask for a clarification before preparing the offer.

In parallel with the extensive analysis, Ansaldo Caldaie has developed an internal procedure that allows a fast evaluation of fatigue life consumption.

This procedure should be not only fast, but also intrinsically safe in order to take into account

- possible unexpected events during plant operation
- variability of local conditions in terms of thermal and mechanical behaviour of heat exchangers and related thick wall components.

With reference to the point discussed in pargraph 3.3, on the basis of well known HRSG behaviour during operation, and of simplified physical models, the following approach has been incorporated in ad hoc calculation tools.

1. Transient behaviour of HRSG.

   On the basis of the behaviour of HRSG's from previous applications plant data, and the integration with specific data from GT and ST start-up, it is possible to build reliable start-up curves. Possible deviation from these start-up curves, due to sudden increment of steam parameters will not reflect on overall fatigue assessment due to the relaxation imposed by thermal conductivity phenomena that leads to thermal diffusion and related mechanical stresses
2. Steam side and gas side behaviour of the component.

On the basis of comparison of CFD analysis of headers internal flow it is possible to settle simplified thermal exchange models to describe convective heat exchange internal to the component and radiative heat exchange external to the component, when placed within the boiler.

3. Thermal behaviour of thick wall components during transient.

   A dedicated numerical model has been developed to calculate transient behaviour in thick wall components via integration of Fourier equation in cylindrical coordinates. From this analysis the maximum temperature difference $\Delta T = T_{innerwall} - T_{meanwall}$ across the thick component is calculated in order to evaluate the maximum thermal stress during the transient.

4. Creep life assessment

   Based on EN 12952, Part 4, the theoretical lifetime L_c for the component subject to creep is calculated on the basis of the operative pressure and metal temperature. The theoretical design life consumption at the design lifetime (usually T_{op}=200.000 hours) is calculated as $L_c = T_{op} / T_{al}$ where T_{al} is the theoretical time to reach rupture for creep.

5. Fatigue life assessment

   For each component the principal stress near the openings or branches as per EN 12952 is found. The circumferential stress is calculated considering the stress caused by pressure and by temperature on the basis of above transient analysis. During the start-up transient, both pressure and temperature of the fluid inside the component grow following each different physical laws. At the internal surface the stress caused by internal pressure is always positive, and grows following pressure increase; on the contrary thermal stress is always negative and grows until a value corresponding to the quasi-stationary conditions is reached (see below Fig. 10). The two effects will result in a reduced (negative) total stress compared to thermal stress only. Since the effective superimposition of the two effects depends strongly to the real start-up curves and initial condition, in order to have additional margins it has been decided to calculate the total stress during start-up as the sum of the minimum value of pressure and thermal stresses. In the same way the maximum value of total stress is calculated during shutdown (as the sum of the maximum value of pressure and thermal stresses) and the cyclic stress range and the number of load cycle for crack initiation N_{max} is calculated.

   The fatigue usage factor is calculates as $L_f = N / N_{max}$ being N the total number of cycles. Total life consumption due to the various normal and emergency start-up and shutdown cycles expected during operation is calculated as the sum of L_f ‘s.

6. Total usage factor

   As per EN12952 the total usage factor is calculated as $L_t=L_f+L_c$ and it should be, for any component, $L_t \leq 1$. This procedure is what the code EN12952-4 suggests to evaluate the effect of both phenomena (creep and fatigue) that occur in a component; besides the code considers that this approach is enough conservative for a normal application due to the conservatives embeddend in this calculation. Of course another approach for consideration of creep and fatige effect combination (see graph “Creep-Fatigue interaction”, ASME case N-47) should be used when life consumption are evaluated by stress (FEM) analysis.

Above points have been integrated in a calculation tool that, starting from start-up and shutdown corves, geometry of thick wall components and related nozzles and material selection calculates, for every start-up and shutdown condition, number of cycles to rupture.

3.5 Test case: Hamm Uentrop project

Hamm Uentrop combined cycle plant located in Germany was developed by Siemens as EPC contractor for Trianel. The plant is composed of two single shaft units based on Siemens V94.3A gas turbine. The HRSGs high pressure level is equipped with once through evaporators based on Siemens Benson low mass flux concept.

The HRSGs are of the horizontal gas flow, top supported type, with three pressure level and reheater.

Fig. 8 – Hamm Uentrop HRSG

The scope of Ansaldo Caldaie scope of works included engineering, manufacturing, supply, erection and start-up of 2 Heat Recovery Steam Generators (Lump Sum Turn Key Contract). The contract was awarded in June 2005 and was completed in November 2007.

Hamm Uentrop HRSGs have been developed in the frame of a multiple purchase agreement with Siemens that included also Herdecke (1 benson type HRSG) and Knapsack (2 drum type HRSGs). Although the specified cycling requirements were different for drum type and Benson type boilers (25 minutes of HRSG strat-up time in cold, warm and hot condition), the same overall design has been maintained for the two configuration, with the exception of the evaporator module.

Hamm Uentrop HRSGs are into operation from more than 3 years and, with Herdecke, are Benson HRSGs into commercial operation from longest time. From a general point of view, overall cycling capability of the HRSG has been proven since the total number of cycles per year, about 230, is in line with the design value (250). At end of year 2009, following a client requirement, the fatigue analysis performed on HP SH outlet header and separator vessel during design phase has been crosschecked on the basis of plant data. This analysis shows a consistency between the assumption done during design phase and the operation data.

Since on Hamm Uentrop unit 20 several additional measurements has been provided in order to tune boiler design, it was possible to check in detail the reliability of the "Quick" procedure discussed in above paragraph 3.4.

Below Figg. 9 and 10 show calculation performed during design phase for HP SH outlet header fatigue assessment. On Fig. 9 hot start-up curves are shown; the blue curve "T Midwall" is referred to the calculated HP SH outlet header midwall temperature. Fig. 10 shows stress calculation for hot start-up as a percentage of the total stress used for fatigue evaluation.

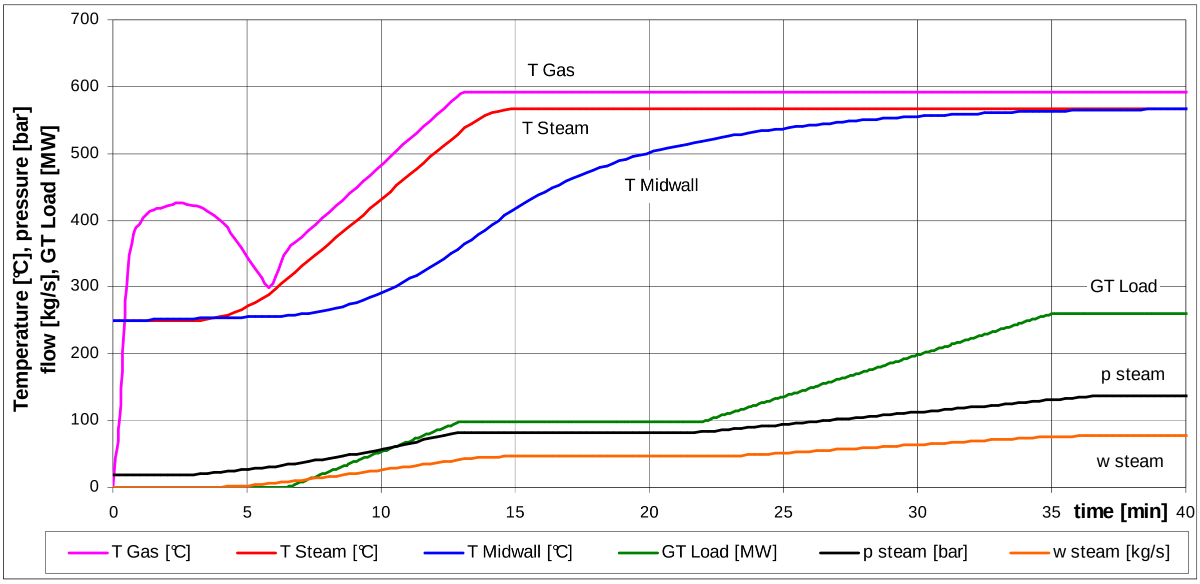

Fig. 9 - HP SH outlet header: design hot start-up curves

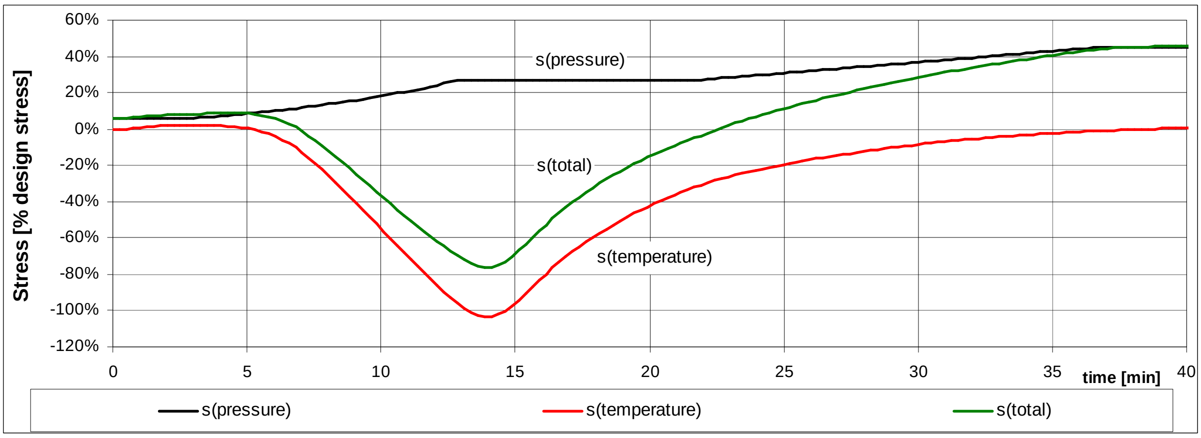

Fig. 10 - HP SH outlet header: Design hot start-up stress curves

Fig. 11 shows hot start-up curves measured. All data are measured excluding “T Midwall calculated” that has been calculated with the “Quick procedure”. The calculation has been performed using design calculation model and plant data as boundary conditions. No tuning on the model has been done to improve measurement versus calculation comparison.

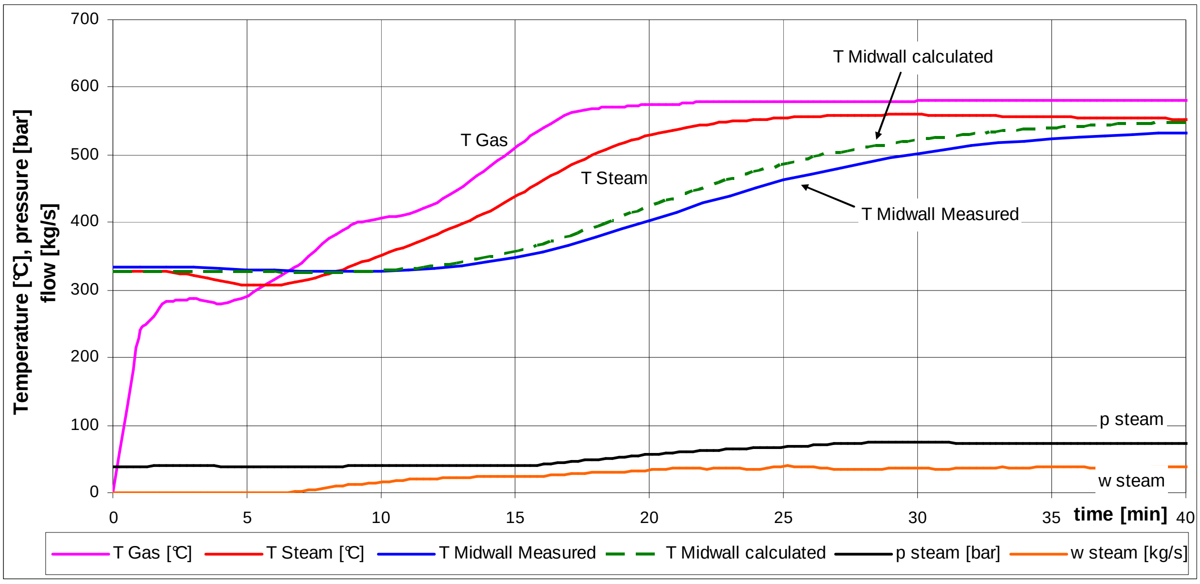

Fig. 11 - HP SH outlet header: Measured hot start-up curves

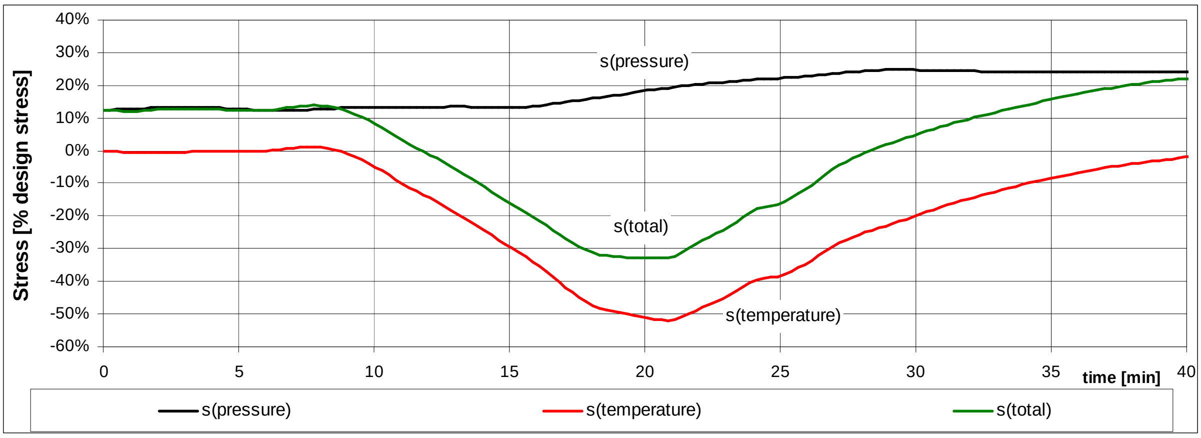

Fig. 12 - HP SH outlet header: Measured hot start-up stress curves

It should be noted that measured start-up time (Fig. 11) is slower than design one (Fig. 9) due to load dispatcher requirement, and not to combined cycle limitation; moreover initial temperature is higher than expected one. Due to above reasons minimum stresses calculated on the basis of measurements (Fig. 12) are significantly lower than design ones (Fig. 10), leading to an overall reduced fatigue life consumption. The most important result is the very good agreement between measured and calculated midwall temperatures shown on Fig. 11 that gives evidence of the “quick” procedure validity.

3.6 Future developments

In step with further developments of Combined Cycle plants and Gas Turbine sizes and power outputs, HRSG’s components are today (and even more so tomorrow) subject to more challenging performance requirements, in terms of steam temperatures and pressures. Considering as well that cycling negatively affects the thickest components, the need for high creep strength materials is “a must”, in order to reduce as much as possible the design thickness. Of course cost issues and physical properties are also considered, suggesting to avoid utilizing, when possible, austenitic stainless steels.

The material actually used as standard for hot components (HP Superheaters and Reheaters) of an high performance HRSG, is the grade 91 ferritic steel, both for tubes and heavy thickness headers and pipes.

Grade 91 steel is adequate for components working with steam temperatures up to 560 – 580 °C, also in case of heavy cycling conditions. Moreover, for medium temperature steam components, the actual design adopts advanced low alloy steels, like grade 23 or grade 24 steels.

The most critical components, i.e. final HP superheater headers and main HP steam pipe and final reheater headers and main RH steam pipe, can be correctly designed with grade 91 steel, in such conditions, assigning no more than 20 – 30 % of design life consumption to creep damage, considering a typical design life of 200.000 hours, and leaving the greater part of the design life available for fatigue life consumption.

In this way also the effect of Creep Fatigue Interaction can be managed.

When higher design conditions and component sizes require an increase in wall thickness, the grade 91 steel becomes inadequate, because in order to limit the creep life consumption it is necessary to increase the thickness, but the increasing of the thickness increases the fatigue life consumption, since normally it is not possible to reduce the required thermal gradients foreseen in cycling operation.

So, better material is required for better performant HRSGs.

In this case the experience gained by the company in USC Utility Boilers can be applied, by adopting advanced alloy steel grade 92, that is suitable and available for heavy thickness components.

Grade 92 steel can be used for components with steam temperatures up to 600 – 620 °C, having allowable stresses (creep strength) suitable to design headers and pipes shell thickness that can satisfy both requirements of creep and fatigue design life (and their combination).

For instance, at 600 °C the allowable stress of grade 92 is about 20 % greater than the allowable stress of grade 91 steel, and so the required thickness is 20 % lower.

Besides the alloy composition class of grade 92 steel is the same of grade 91, and so no particular design modifications are foreseen due to physical and metallurgical behaviour of this steel.

In order to reach a safe and reliable knowledge on behaviour and performance during the lifetime of grade 92 steel, comparing them to the large experience gained on grade 91, the Company started a complete life time analysis study by FEM model of thick wall components.

A significant part of the study is dedicated to the evaluation of published material test data, that up to now are not, of course, so complete and reliable as for grade 91 steel, but are becoming still better.

The target of this study is to compare the results of such complete (“off line”) analysis to similar results of grade 91 cases, and so to have the possibility to tune the Company’s procedure also for this steel, that will be extensively used in the future for such boiler components.

4. Conclusion

HRSGs are known to be very flexible steam generators; two different HRSG configuration has been analysed:

- HRSG with double post firing system to allow a very wide steam production range over entire gas turbine operation range
- HRSG particular design features to allow heavy cycling operation.

Two different applications have been analysed:

- Ras Laffan B (Qatar) for electrical power and desalinated water production cogeneration plant
- Hamm Uentrop (Gemrany) for the fastest HRSG application based on Benson once through design

Even if these two projects are quite different, they share the same design philosophy based on tailor made approach that has been proven by operation data.