Developments in HRSG Technology

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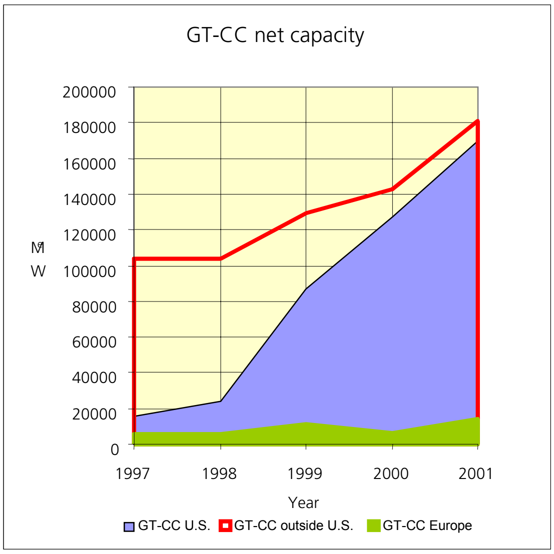
Abstract

The today's requirements and limitations for HRSG design in power generation applications are discussed, considering the case of a Triple Pressure Reheat HRSG for a GT of the largest available size, and a respective outlook for a future development in HRSG Technology is given. Different regional approaches for HRSG plants led to a historical difference in a typical HRSG design: The vertical and the horizontal arrangement of the flue gas duct, surrounding the heating surfaces. The advantages and disadvantages of these two types are presented and, with respect to the latest experiences, discussed.

Introduction

The market for Combined Cycle Power Plants (CCPP) has experienced rapid growth in recent years. This growth has been driven by deregulation in the U.S. and Europe. Due to this e.g. independent power producers (IPP) rose and have induced both a growth in new power production and a shift from coal and solid-fuel-fired conventional steam plants to gas turbine (GT) plants and CCPP leading to economically interesting returns of investment (ROI). In the U.S. alone, while gas turbine and combined cycle plants represent only 10% of the existing base of 860 GW, they currently provide well over 90% of all new capacity [4]. In Europe the markets seem to hesitate, until now deregulation has taken place in some countries, only, e.g. the U.K., but is on the way for the rest of the EU. Expectations in Europe are rather for a consistent growth, than a boost like that in the U.S., which is unlikely, due to the fact that governmental

Picture 1 – Market Developments



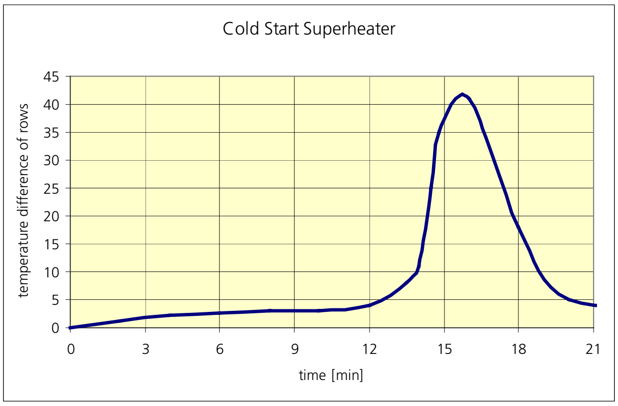
responsibilities for sufficient and reliable power generation in the past led to capacities above the actual needs, although these plants, mostly fossil fired, need replacement in the coming one or two decades. In addition coal fired plants, in several European countries, serve great public economic benefits as a result of large own resources. Same applies to hydro power, e.g. Norway and Austria. Nevertheless growth expected in Europe – selecting F, GER, E, S, UK and FIN – as an average number, is 70 GW for new capacity until 2005 [6]. Considering a 13% gas portion of the fuel mix - which is the status today and which will definitely increase due to environmental regulations, deregulation, etc, most probably not to the portion as the North Americans face it, but significantly – this leads to approximately 10 GW

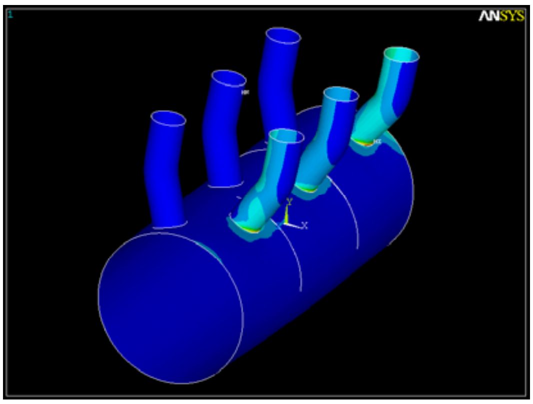
new CCPP's in these 6 countries as a minimum (refer to picture 1).
The deregulation-driven growth is expected to fall off in North America, while at the same time, combined cycle power plants will support continued HRSG growth in the recovering Asia market.
Another key driver is the aggressive technical development of large frame combustion turbines (170 to 250 MW, even 370 MW in a test stage) targeted for the utility power generation market. Over the last decade, large combustion turbines have been developed with higher efficiency and dramatically improved emissions profiles. More efficient water/steam cycles have been developed to take advantage of higher exhaust temperatures from advanced combustion turbines installed in combined cycles. Capital costs of gas fired combined cycle are about 40% of coal fired steam plants [4]. Gas price and availability support a life cycle cost advantage in many regions of North America and Europe. The net efficiency of the combined cycle power plant (up to 60% – expected in the near future, at the time being 58% for high end CCPP's) is much higher than with conventional steam plants (35% to 40%, 45% for high end plants). Combined cycle plants also continue to offer improvements in permitting and installation time thereby reducing the capital cost and risk to plant developers. Combined cycle plants are able to provide lowest levels of NO_x and CO emissions per kWh of electricity produced, especially if low NO_x burners and SCR, CO catalysts are considered.
This all results in a necessary development in HRSG technology, as well as a new understanding of the HRSG supplier delivering a less priced, though key component of a plant gaining more and more shares in power generation and economic success of the owner.

History

To efficiently mate the Rankine steam cycle with high-temperature gas turbines, new HRSGs had to be developed that could operate at substantially higher flue-gas temperatures. New HRSG designs also were required to match each incremental jump in gas-turbine size as combined cycle
units grew larger and larger. Perhaps the most important development in HRSG design was the move from single- to dual-pressure steam production. This change, which enabled lower stack temperatures and thus greater recovery of thermal energy from the gas turbine exhaust, increased thermal efficiency of a combined-cycle plant by nearly four percentage points. Later designs went one step further, from dual- to triple-pressure steam

Picture 2 – Temperature differences vs. Time and resp. Stresses at the header connections

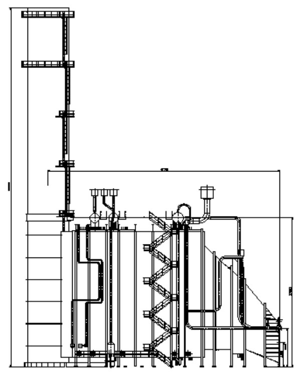
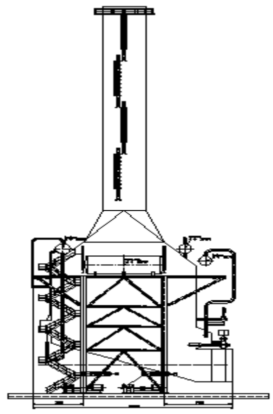




production, and yielded approximately one more percentage point gain for the overall cycle. Today, virtually all HRSG manufacturers offer triple pressure reheat steam systems to maximise efficiency [5].

HRSG manufacturers also offer a choice between a horizontal or vertical flue-gas path. Vertical designs – which have originally been developed in Europe where the major suppliers of this kind still are located

Table 1 – Horizontal vs. Vertical Type HRSG

	Horizontal HRSG	Vertical HRSG
		
Output and Efficiency	Equal	Equal
Surface Area for equal Output	Similar, except the reheater and super heater section which might require slightly more heating surface area mainly due to less advantageous flue gas flow distribution with regard to temperatures and mass flow	Base
Plot Plan Area for equal Output	Up to 30% more, mainly due to the opening angle of the inlet duct and the stack, and if supplementary firing systems, SCR's, CO Catalysts, etc. are required	Base
Emission control	Requires more HRSG length	Requires more HRSG height, cleaning of downstream fouled surfaces has to be carried out carefully, not to poison the catalyst.
Supplementary Firing	Readily installed in the HRSG inlet duct or within the boiler surface area	Readily installed in the HRSG inlet duct, difficult to install within the boiler surface area
HRSG enclosure/Boiler house	Free standing, self supporting enclosure	Attached to and supported by the HRSG structure, light enclosure
Natural Circulation	State of the art	Special design considerations, though state of the art
Modularized/Standard concepts	Typical	Typical
Erection Area, prefabrication on site	Equal, though more crane area is required for pressure part (harps) mounting which typically lasts 5 weeks for large GT CCPP	Equal, though heavy transportation (120 ton) may be required on site, typical time needed for boiler surface mounting: 3 weeks for large GT CCPP.
Cycling	State of the art design experiences severe cycling problems at super heater and reheater stages, design considerations cost effective	Less vulnerable if properly designed
HRSG Cost (ready to run)	Equal	Equal
O&M Cost	Higher number of and larger textile expansion joints, boiler surface replacements not possible, repair by blocking of tubes, cost effective	Replacement and blocking of tubes possible
Regular Inspections	Headers and surfaces not easy to access	Header and surface inspection carried out accessing through manholes without requirement for additional auxiliaries

– offer a smaller footprint and are less vulnerable to thermal cycling problems than the horizontal designs commonly applied and originated in North America. Since the vertical HRSG no longer require forced-circulation pumps, not even for Start Ups, due to design improvements of the evaporator systems both HRSG types offer the same overall efficiency, although the decision may be directed to one type of HRSG: Table 1 – Horizontal vs. Vertical Type HRSG

Today's Requirements

Efficiency, Steam Output

From a technical point of view, several parameters for the HRSG design are state of the art, regarding the application they are asked for. Typically, for large GT CCPP the clients and HRSG manufacturers request for the following:

- Triple Pressure Single Reheat HRSG's – the present existing economic optimum
- High pressure (HP) level – the existing economic optimum is 130 bar, although the thermal optimum lies well above (180 bar [7]) for triple pressure reheat HRSG.
- Steam Temperatures – economic optimum, defined by the steam turbine, is 565°C.
- Steam Output – defined by the economic determination of the Pinch Point (6 to 8 K) at the HP Evaporator and the Approach Point at the Economiser (2 to 4 K), typically 74 kg/s without supplementary firing (SF). 120 kg/s using SF.
- Feed water/Condensate Inlet temperature with respect to the type of fuel used, above 50°C for natural gas, at no sulphur content, and above 110°C for light distillate oil to ensure operation above the acid or the water dew point.
- Stack temperature minimum 80°C
- Steam Purity – entering the Super Heater at 99,9%, especially important if the client requests for solid alkalisation in addition to the all volatile treatment (AVT), being state of the art for HRSG design in Europe.
- HRSG flue gas draft losses – approx. 25 mbar, 35 mbar if catalysts are required.

Load Changes and Cycling

Premature failures of some large heat-recovery steam generators are an early warning that widespread problems are to come - particularly as more units switch from base-load to cycling operation. Users need to ensure that the aggressive start up, loading, and unloading rates promised by gas-turbine makers are not at the expense of the HRSG. Typical for nowadays HRSG is a trend towards daily starts and stops. Design base often considers monthly cold starts, weekly warm starts and daily hot starts, i.e. 300 cold starts, 1300 warm starts and 9000 hot starts. Cold starts usually have to take place within 60 min to full load, 30 min are possible considering thick walled components, although magnetite layers may be damaged and sufficient time of operating the HRSG (at least 2 consecutive weeks) to rebuild this corrosion protection layer should be considered.

Frequency Response and Fast Wind Down operation of the plant are standard requirements for HRSG design.

For economical reasons, e.g. no bypass stacks, HRSG are subject to very rapid and large increases and decreases in the flow and temperature of the GT exhaust gas. The most severe changes occur during cold starts and following trips and subsequent restarts, but generally all starts from any condition may cause some low-cycle fatigue damage due to thermal stresses in parts of the HRSG.

Many HRSG designs were developed to comply with ASME Section I Power Boiler Code, which does not give any reference to low-cycle fatigue damage, but leaves the responsibility with the HRSG manufacturer to define any additional loads to be considered. Fatigue design is mentioned in the British Boiler Code, but is not mandatory and leaves the responsibility with the purchaser to define what fatigue analysis is required. In the German TRD code – as well as in the new European draft standard for water-tube boilers – fatigue caused by thermal and pressure induced

stresses is considered at the inner edge of openings in shells.
The application of these rules leads to allowable start-up and shut-down gradients, i.e. K/min or bar/min, but nevertheless, the approach is only a rough one, and other design-caused critical areas are disregarded. For example, often a standard harp design, i.e. the assembly of tubes between two headers, can be a source of high thermal stresses due to the fact that the individual tube rows operate at different temperatures, especially during "dry" start ups of the super heater and the reheater section, which causes thermal stresses at the weld joints (refer to picture 2). Generally, the best way of handling the transients in the design stage is to apply thermal-mechanical finite element analysis on critical parts to determine the peak temperature gradients and stresses during the most damaging transients and to verify the boundary conditions via practical data and establish design solutions which prevent extraordinary stresses of the respective component.
Each design of HRSG's has unique configurations and header dimensions which may have different fatigue damage rates if subjected to similar transient conditions. But at least the following parts should be assessed with regard to fatigue damage: HP super heaters, reheaters and header connections, HP steam drum and Evaporator circuit, Economisers – low temperature and if partition plates in headers are used.

Steam Temperatures and Control

Temperature Control during operation can be handled in a range of +/-5K if end coolers, by means of spray desuperheaters, are used. This range has to be considered while designing the related pipe work. Inter stage coolers offer an advantage regarding the steam temperature (respective design temperature) at the very end, hot section of the super heater. Especially during Start Up, inter stage coolers alone, might not be sufficient to cool the steam down to the required value by the steam turbine (below 400°C), adding end coolers becomes necessary. Inter stage coolers are more easy to install in horizontal type HRSG due to the boiler surface arrangement using upper and lower headers.

Operation

The above mentioned boundary conditions result in the need for reconsidering the design and base the design philosophy on certain newly made experiences. Two of them are discussed here, comparing the two types of HRSG:

Condensate Forming during different operational modes

During operation modes such as warm, hot starts and purge condensate is forming in the first super heater/reheater stages. The amount of the condensate forming can be easily estimated using state of the art computing tools. Drains, sufficient in size and sometimes even including level switches have to be installed. In case of the vertical type HRSG after a while the build up of a proper steam production pushes the condensate in the flow direction of the steam as well as gravity is pulling it out of the super heater. In case of a horizontal type HRSG gravity and steam flow usually are two forces of opposite direction, thus, and because of the drains limited in number and size, condensate formed in this section is partly remaining in the super heater tubes for a longer time, blocking these tubes, and by that increasing the resulting temperature differences from one single tube to the other, in addition to the temperature differences in flue gas flow direction.

Pre Start Purging

Purging required as a precondition to start the GT through the boiler, is a common requirement of all boiler codes to ensure safety operation of the plant. This rule is historically evolved, since in the beginning of boiler operation severe accidents occurred. Today purging a hot HRSG strains all involved boiler parts to a high extent, special considerations and design features have to be taken into account (see above) to cope with the requirement of daily start ups for a lifetime of 25 years. Comparing the horizontal and the vertical type HRSG, the recent development of steep angles at the horizontal HRSG inlet duct, developed to reduce plot area and cost at the same thermal efficiency of the boiler surface for large HRSG applications, the effect of the purge is questioned. Measurements showed that the purge air does not touch the upper section of the HRSG much, exactly the section where eventually formed explosive gases would gather due to their density being lighter than air [8]. Considering a vertical type HRSG these light gases tend to vanish through the stack at the top or are easily purged by means of the GT converter. Taking the spirit of a CE conformance into account, at least redesign of horizontal HRSG ducting seems to become unavoidable.

Cycling-Corrosion concerns

Potential problem areas as a result of load cycling or on-off cycling include: gas turbine exhaust dew point corrosion, corrosion fatigue, and consequences of not maintaining proper steam cycle chemistry (i.e., on-line, off-line storage and return to service). Corrosion and fatigue damage are cumulative and cannot be reversed. Using HRSG initially designed for base load operation in cycling operation defines the need to carefully evaluate several occurrences with regard to HRSGs. We believe that special attention has to be paid to three of them at least:

Stress Corrosion Fatigue

Since cycling means temperature and pressure gradients from ambient to operational level and air ingress during longer outages, stress corrosion fatigue as a result of these influences will occur. A proper chemistry regime, i.e. maintaining low dissolved oxygen, pH within the required range and proper feed water quality (VGB, O_2 < 0,1 mg/kg), is a must. From the HRSG operating side, the boiler should be kept under pressure as along as possible, e.g. no forced cooling and closing of the stack damper to prevent rapid natural draft cooling.

Flow Accelerated Corrosion

First, the HRSG designer has to consider flow velocities lower than the known limits to erode protective Magnetite layers in water and/or lines carrying two phases, water and steam. Second, the chemistry regime has to be maintained in a way that the oxygen content is not too low to prevent a proper magnetite layer from forming – erosion corrosion is increasing - and on the other hand not too high to accelerate Stress Corrosion Fatigue. In Europe this has been taken into account by the increased maximum O_2 content (VGB, TRD, etc.) for boiler feed water (from 0,02 mg/kg to 0,1 mg/kg for pH > 9). Best choose is not to fall below 0,05 mg/kg (VGB minimum for pH neutral feed water) considering the above.

Gas Side Corrosion

Cold end corrosion is a well known phenomenon, usually faced by increasing the respective water inlet temperature, e.g. condensate recirculation, above the dew point of the flue gases. Cycling leads to a situation at each start up, when the inlet temperature can not be properly increased – deposits on the cold end of the HRSG surfaces are the consequence. This results in decrease in thermal efficiency and increase in draft losses on the long term, fin and tube corrosion if the deposits are moistened – by air humidity or washing. To prevent or limit the effect of cold end corrosion during cycling operation regular inspections and cleaning of the boiler surfaces is recommended. This is usually done by air blasting (little deposits), dry ice blasting (up to 6 layers affected) and washing with large amounts of low pressure water (entire surfaces). The water washing is the most effective, although special considerations have to be made and actions set to prevent corrosion of the casing (horizontal type HRSG) or poisoning a catalyst (vertical type HRSG). Start up after performing water washing is recommended to prevent corrosion of other HRSG parts. The ultimate solution to cold end corrosion is the use of corrosion resistant materials – the only reliable and lasting but expensive solution.

RAMS – Reliability, Availability, Maintainability and Safety

RAMS, clearly a requirement for state of the art HRSG supply, although the termini is usually used to evaluate reliability, availability, maintainability and safety taking certain plant properties into account. We propose not only to consider technical aspects of a product, but proper project handling, manufacturing supervision, transportation risk assessment, erection and commissioning supervision and product development and related R&D as a must.

The very importance of RAMS is due to the fact, that the HRSG is a key component within the power train of the CCPP, though it is only worth approx. 10% of the entire plant and as some press recently stated the less glamorous component. If factors, developed to determines RAMS performance, show that they are not improving or are even below the fixed internal goal for a certain HRSG project, the HRSG supplier will have a set of strategies to come back on track during the design stage or react to non-conformances, e.g. during fabrication processes. All topics discussed in this article contribute in one or the other way to RAMS performance and necessarily lead to a close co-operation of the HRSG-user, the client, the HRSG-supplier and the engineer. A typical example for RAMS performance determination is the pressure part (boiler surfaces) supply procedure from basic engineering to erection on site – any specifics of this process are listed and evaluated with respect to RAMS, thus ensuring a product delivered in time with lasting quality.

The Pressure Equipment Directive (PED)

Since HRSG manufacturers are operating on the international market, different codes and legislative rules have to be considered. For HRSG's to be installed in EU, application of the PED [3] will be obligatory from 29 May 2002. This may change design and manufacturing procedures considerable, e.g. concerning the use of local design codes or the involvement of notified bodies. As part of the "New Approach", the PED contains Essential Safety Requirements, which are defined in terms of general safety objectives. Although the European Committee for Standardisation (CEN) has the mandate to develop "harmonised standards", which, when followed, will give a presumption of conformity with the directive, the HRSG manufacturer is under no compulsion to use them. Since no design code specific to HRSG's exists, now the manufacturer has in principle the opportunity to use different codes or even company-specific rules for a proper design, presuming that the involved notified body certifies that the Essential Safety Requirements are met. This last condition has to be met in almost all cases, since the conformity assessment procedure of most HRSG parts is within category IV of the PED regulations. From this point of view, application of the PED can be a challenge to the manufacturer to use (international) best practise.
If the ASME Boiler & Pressure Vessel Code should be used for HRSG to be installed in the EU, some problems may arise, especially for the use of ASME materials. Since many of them will not be included in the European harmonised material standards, a Particular Material Appraisal will be necessary, which leads – at least – to higher costs. There may be also forces in the EU trying to prevent that the ASME code as a whole gets a recognised standard within the PED, but we'll see what time brings with regard to this subject. For the time being we propose to use ASME code for design if the client is not willing to accept European codes and insists to, but forget about the stamp, gaining the CE conformity using harmonised material standards or Particular Material Appraisals, and ensuring the client and his investors/insurers of the safety standards which are met, then.
Since the in-service inspection rules are not within the scope of the PED, they will be covered by national regulations. If some corresponding details, e.g. inspections periods or inspection range, will depend on the type of code or conformity assessment module used is not clear at the moment. But if this happens, it would be against the "spirit" of the PED.

Today's Limits

Limits are, in this case, meant to be state of the art values of key performance factors of a HRSG application – limits driven by economical and technical considerations for Triple Pressure Reheat Drum Type Boilers, natural circulation:

Table 2 – limiting key factors

Key factor	Unit	Value	Limiting factor
Main steam temperature	°C	567	Steam turbine
Operating steam pressure	bar	170	Start-up time < 60 min
HP evaporator pinch points	K	6	Economics, accuracy of thermal design
HP economiser approach point	K	3 (0)	Horizontal (vertical, due to geodetic height benefit)
HP super heated steam velocities	m/s	70	Sound, economics
HP saturated steam velocities	m/s	20	Errosion corrosion, economics
Two phase velocities	m/s	10	FAC, EC, economics
Water velocities	m/s	2-4	FAC, EC, economics
Sound emission L_w	dBA	90	GT emissions, sound enclosure
Suppl. Firing	%	+50	flow distribution & properties, in case of the vertical type HRSG i.e. flue gas temperature
Cold Starts	-	weekly	Gradients of thick walled components
Fast wind Down	bar/min	5 to 0,5	HP drum gradients
Cycling rate	MW/min	none	GT load changes

Materials

Purchasers demand for higher combined-cycle efficiencies led to a rapid increase in the output and exhaust temperature from GT's with consequent increases in the HRSG physical size, steam flow and especially temperature. Steam temperatures above 600°C are possible, and, therefore, the need for advanced materials with suitable properties at high temperatures at moderate costs is undoubted.

The key components, whose performance is critical, are high-pressure steam piping, headers, and super heater tubing. All these components have to meet creep strength requirements, but thermal fatigue resistance and weldability are important, also. Ferritic/martensitic steels are preferred because of their lower coefficient of thermal expansion and higher thermal conductivity compared to austenitic steels.

Among the 9% Cr steels fully commercialised, the P91 steel has the highest allowable stress and has been extensively used all over the world as a material for headers and steam pipes operating at steam temperatures up to 595°C - nominal, 615°C as a maximum for HRSG applications acc. to the German TRD Code or up to 650°C tube metal temperature acc. to ASME.

The steel P-92, developed by substituting part of the Mo in P-91 by W, has even higher allowable stress values and can be operated up to steam temperatures of 635°C. P-92 is already approved by the ASME boiler code, but no approval according to the German rules is available for the time being. Further developments are E-911, which is already approved in Germany (material number 1.4905) and P-122, which was developed in Japan and has been approved by ASME. The allowable creep strength of these new steels at 600°C is about 25% higher than that of P-91 [2]. As an example for application, a super heater made of E-911 and steam loops made of E-911 and P-92 are operating at steam temperatures of 650°C in the conventional fired power station VEW Westfalen in Germany.

Therefore we have to be aware that the limiting factor for efficiency increasing high steam temperatures is the high end steam turbine, which is commercially available for steam temperatures at a maximum of 565°C, only.

The Ten Commandments of HRSG Design

Combining today's requirements and limits Ten Commandments can be formulated, and if fulfilled to better ensure the purchaser of a HRSG satisfying the client for the entire lifetime of the plant:

1. Determining diameter and wall thickness of thick walled components by calculating allowable temperature and pressure gradients with respect to cycling.

2. Dynamic analysis of cycling conditions and detailed FEA of known localised trouble areas, such as multiple tube rows in one header, piping links and pipe connection between pressure parts and proper design as well as dynamic analysis of cycling with respect to condensate forming, e.g. purging or warm keeping, and proper drain design will prevent low cycle fatigue.

3. FEA of headers with partition plates, if not to be avoided, and proper design will prevent low cycle fatigue.

4. Avoiding of thick walled headers with low fatigue strength and large diameter headers with low creep resistance.

5. Flow model calculation of steam flow within the super heater sections and derived number and diameter of nozzle connections will prevent performance shortages.

6. Flow models of the flue gas flow feeding the supplementary firing and proper design of the ducting will prevent performance shortages.

7. Determination cycling allowances on behalf of the chemistry regime, e.g. magnetite layer resistance, cracking and rebuilt will prevent devastating stand still corrosion

8. 3D modelling and automatic generation of detail drawings and erection guides, will prevent on site modifications

9. RAMS performance evaluation of the supply chain of critical components will ensure delivery in time and lasting quality

10. Transparency, open house philosophy, of the HRSG supplier towards the purchaser will ensure overall project economics

Perspective

We identify three major fields of development in HRSG supplies:
First, based on today's experiences and experiences expected to come, clients and suppliers will come to the conclusion that HRSG contribute quite a part to overall RAMS performance of the CCPP. This will lead to a more close co-operation and fine tuning of each others needs to satisfy the clients needs. Transparency of project management, design control and the entire supply chain is something HRSG suppliers can offer.
Second, HRSG Technology will have to improve with respect to RAMS due to recent developments for CCPP. The next generation of Gas Turbines, the cooling of turbine blades with steam produced in the HRSG, is on the way, linkage of the GT and the HRSG using branched off boiler water to cool the GT cooling air and by that supplying super heated steam back to the HRSG is already realised. This new

technologies will couple HRSG to the GT as never before, since steam will be not just the working fluid for a bottoming cycle but the cooling medium keeping gas-turbine metal from the devastating effects of overheating. For HRSG design engineers, the challenge is not so much one of thermodynamic optimisation, since existing triple-pressure reheat designs represent the high end of present economic and thermodynamic performance. Instead improving RAMS performance again is the goal. Specific goals are especially a reduction in low cycle fatigue, higher modularization to shorten erection time and increase the more reliable work in the workshops, use of flexible ceramic fibre to control hot spots, long term Extended Supply Partnership contracts with suppliers of critical materials and components, e.g. P91 & T91, etc.

Third, HRSG designs differing from the typical bulky triple pressure reheat drum type boiler are innovated by HRSG suppliers. Once trough HRSG have proved to cope with the changing requirements of the market moving from base load to cycling operation, although the confidence of the market is not yet established for large numbers of orders and large GT applications, one reason might be that once through boilers from a technical point of view, especially considering cycling, have to be of the vertical type. Another simple system has been presented some years ago by the author. Combining the proposed Eisenkolb Single Pressure [7] system with large GT's and the now well developed once through technology will definitely increase RAMS performance, while exceeding the 60% efficiency goal.

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