HEAT RECOVERY STEAM GENERATORS FOR POWER GENERATION AND OTHER INDUSTRIAL APPLICATIONS

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by

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Executive Summary

A ‘Technology Status Review of Heat Recovery Steam Generators for Power Generation and Other Industrial Applications’ has been completed for the Future Energy Solutions (FES), on behalf of the UK Department of Trade and Industry (DTI). The aims of the review were to:-

- Assess objectively the current state of development and application of heat recovery steam generator (HRSG) technologies world-wide, identify trends in future developments and assess the market potential for exploiting these technologies.
- Critically assess the strengths and shortcomings of existing technologies in relation to commercial or near-commercial needs and provide information on manufacturers, suppliers, developers, consultants and major users, quantifying the potential future demand for such technologies in the world on a regional basis.
- Review current activities and capabilities of companies/organisations working in the HRSG field, with particular emphasis on the UK.
- Identify priority areas in which UK research, development and demonstration (RD&D) activities could/should be focused to enhance the market opportunities for UK manufacturers, developers and consultants, including any small- and medium-sized enterprises (SMEs) who are active but perhaps lack the resources needed to succeed.

The review has been led by Power Technology (part of Powergen UK plc) in partnership with Mitsui Babcock Energy Limited and ME Engineering Limited.

The main conclusions of the review are:-

- Current Status
    - Current state of the art utility scale HRSGs operate at high pressure (HP) steam conditions of up to 124 bar/565°C allowing the associated combined cycle gas turbine (CCGT) plant to deliver electrical power at a claimed net efficiency of up to 60%. The CCGT is built at a cost of around £425/kW, with the HRSG accounting for 10-15% of this total, and delivers energy at around 2.2p/kWh.
    - Operational experience with HRSGs shows that the inclusion of specific design features and attention to detail during fabrication are

essential to reliability. Key areas for improvement include build quality, access for in-service inspection, control & instrumentation and capability for flexible operation. Overall cycle chemistry philosophy also needs to be more thoroughly considered at the design stage.

  - The current challenge for operational HRSGs, particularly in the UK, is the need to cycle plant that has been designed for and/or previously operated at base load. Many users are currently carrying out investigations/trials and plant modifications.

- New & Developing Technologies
  - Future increases in HRSG operating conditions will largely be dictated by increases in gas turbine (GT) exhaust temperature. Areas of significant interest are once through design, with it’s advantages for flexible operation and the use of HRSG steam for GT blade cooling, which presents significant challenges to HRSG design. In addition, the use of HRSGs within integrated gasification combined cycle (IGCC) plant is now approaching the status of commercial operation, although the costs still remain relatively high. Other development areas include modular design to reduce build costs, improving reliability and improving access.
  - Industrial scale HRSG technology is relatively mature, but tends to benefit from the ‘trickling down’ of technology from utility scale HRSGs.
- World Wide Activities
  - Over the ten years, 1992-2001, the biggest sales of utility scale HRSGs have been in the USA (with 48% of the market), the United Kingdom and Japan (4% each). Key manufacturers were Alstom Power (14.2%), Nooter/Eriksen (12.6%), Deltak (9.5%), NEM (7.7%) and Aalborg Industries (7.5%).
  - Sales of industrial scale HRSGs were biased more towards Europe (33% of sales in each of the USA and Europe), with the other leading market being Asia and Australasia (excluding China) with 19%.
- Market Potential
  - Whilst the utility scale HRSG market has been healthy in recent years, there is a predicted sharp downturn in the HRSG market in the short-medium term due to plant over capacity. The situation is not expected to pick up again until around 2007-2011. Key future HRSG markets are seen as the USA and China (via IGCC).
  - For industrial scale HRSGs, the European market is depressed due to falling electricity prices and rising gas prices. However potential markets include Russia, Central and Eastern European countries, Turkey and the Middle East. In the USA, despite problems on the utility scale, there are still opportunities for development of combined heat and power (CHP) schemes on industrial sites.

  - The current surplus of generating capacity in the UK and fluctuations in the price of natural gas have led to a low requirement to build large scale power generation plant within the UK, although plant performance upgrade opportunities are present.
  - The combination of the New Electricity Trading Arrangements (NETA) and a high natural gas price has dramatically reduced the market for new HRSGs / CHP schemes. Enhanced government support for CHP is required if its target of $10GW_e$ by 2010 is to be met.

- UK Activities
  - There are a number of utility-scale HRSG turnkey contractors operating within the UK (e.g. Alstom Power, Mitsui Babcock, Foster Wheeler Energy Ltd, Mott MacDonald, Nooter/Eriksen-CCT Ltd and Siemens KWU). Whilst Mitsui Babcock has its headquarters and manufacturing facilities in the UK, the remainder have their headquarters and manufacturing facilities overseas or subcontract the manufacture. Thermal Engineering International Ltd - Greens (TEI Greens) is the largest independent manufacturer of utility-scale HRSG's in the UK and has manufactured utility-scale HRSGs for most of the world's leading boiler designers/makers on both domestic and export projects.
  - Wellman Robey, BIB Cochran, ME Engineering and TEI Greens are UK companies of UK origin with the capability to design and supply industrial HRSGs. Wellman Robey and BIB Cochran manufacture shell type boilers and have UK manufacturing facilities. ME Engineering supply water tube or shell boilers manufactured outside the UK. TEI Greens design and manufacture industrial HRSGs of water tube or smoke tube design in the UK. The UK arm of Nooter/Eriksen also supplies industrial HRSGs although its design capability is based in the US.
  - In such a competitive HRSG market, licensing agreements and collaborative partnerships have been necessary in order for companies to maintain the ability to compete. Under such conditions the requirement to be continually developing new technologies is vital. Areas of current research include once through technology, cyclic operation, new forms of gasification and novel low emission power cycles.

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1 INTRODUCTION

1.1 Scope of Report

Towards the end of 2001, FES, on behalf of the UK Department of Trade and Industry (DTI), invited proposals for the completion of a 'Technology Status Review of Heat Recovery Steam Generators for Power Generation and Other Industrial Applications'. The aims of this review were to:-

- Assess objectively the current state of development and application of HRSG technologies world-wide, identify trends in future developments and assess the market potential for exploiting these technologies.
- Critically assess the strengths and shortcomings of existing technologies in relation to commercial or near-commercial needs and provide information on manufacturers, suppliers, developers, consultants and major users, quantifying the potential future demand for such technologies in the world on a regional basis.
- Review current activities and capabilities of companies/organisations working in the HRSG field, with particular emphasis on the UK.
- Identify priority areas in which UK research, development and demonstration (RD&D) activities could/should be focused to enhance the market opportunities for UK manufacturers, developers and consultants, including any small- and medium-sized enterprises (SMEs) who are active but perhaps lack the resources needed to succeed.

The review aimed to address various types of HRSG technologies - from large-scale units suitable for use in combined cycle gas turbine (CCGT) and integrated gasification combined cycle (IGCC) power plant to medium / small size units generating steam for small-scale power / combined heat and power and other industrial process applications. However for the purposes of this review, heat exchangers for producing hot water were not included.

The report is broken in to the following sections:-

- HRSG technologies: brief introduction to the development of HRSGs and their applications; outline of the main designs and their features.
- Current status of HRSG technologies: review of current commercial applications and operating regimes; operational experience of current HRSG designs.
- New and developing technologies: discussion of emerging HRSG designs and applications
- World-wide activities: review of companies active in the HRSG market world-wide and their capabilities.
- Market potential: assessment of world-wide trends in the HRSG market; measures required to stimulate the market and enhance opportunities for UK companies.
- UK activities: review of the capabilities of UK companies active in the market

1.2 The Technology Status Review Partners

This review has been led by Power Technology (part of Powergen UK plc) in partnership with Mitsui Babcock Energy Limited (MBEL) and ME Engineering Limited. Given the respective activities of each company in HRSG technology and markets, it was believed that a co-operative effort would produce a better value report than could be offered by any of the individual participants. The rationale in using this partnership was that MBEL and ME would be able to offer their experience as suppliers of utility scale and industrial scale HRSGs respectively, whilst Powergen would be able to offer it's experience as a user.

Power Technology is the focus of engineering and scientific consultancy within Powergen, and employs approximately 230 specialist scientists and engineers. It provides technical support to a large number of CCGT projects and smaller CHP projects including the HRSGs, both within Powergen and for external customers. Powergen alone currently has 4 CCGT sites (two of which are joint ventures) and 14 CHP sites featuring HRSGs (with one fluidised bed combustion plant under construction). However, Power Technology also supports many external sites, and has experience of many leading manufacturers.

Mitsui Babcock is a major energy engineering company incorporated in the UK, and since 1995, a wholly owned subsidiary of Mitsui Engineering & Shipbuilding of Japan. The company is a technology leader in large fossil fuel steam generating plant, and specialises in the design, engineering, manufacture, construction and commissioning and after sales servicing of high efficiency, high availability coal, oil and gas fired boilers for the power stations of electricity generating companies world-wide. The company is also a major manufacturer and supplier of heat recovery steam generating plant, industrial, fluidised bed and other clean burn coal fired boilers, coal milling plant, flue gas desulphurisation plant and low NO_x burners.

ME Engineering's UK business in 'steam generation' has been established for in excess of 50 years. As a part of Thermax group, ME have extended experience in the design manufacture and supply of wide range of industrial steam generating plants based on coal, liquid fuel, biomass and waste heat. Principal product and project activities comprise industrial boilers, heaters, co-generation, water and waste management, and absorption cooling.

2 HRSG TECHNOLOGIES

2.1 Introduction

Many industrial processes and power generation systems produce a high temperature exhaust gas. Gas turbine exhaust temperatures are typically in the range 425 - 600°C, while the exhaust from a sponge iron plant for example may be at 1000 - 1200°C. If this hot exhaust is released straight to atmosphere it clearly represents a large loss of energy. For a typical gas turbine the exhaust heat loss might be greater than 60% of the fuel lower heating value (LHV). In other industrial processes, the process requirements themselves may dictate that a gas stream may need cooling. If some of this heat loss can be recovered and converted to useful energy, the process efficiency will be increased with both economic and environmental benefits.

The design of HRSGs in Europe has evolved from conventional boiler designs. The earliest boilers were of fire-tube (also termed ‘smoke tube’) design. In these designs, the hot flue gas is passed through a set of parallel small diameter tubes. The tubes are enclosed in a water filled shell – hence the alternative name of ‘shell boiler’. The heat transfer across the tubes from the hot gas to the water boils the water to raise steam, which is piped off from the top of the shell. As higher steam pressures and flows were demanded, the shells had to become increasingly thick and a practical limit was reached. Boiler explosions occurred with increasing regularity in the 19th Century emphasising the need for safer alternatives. The alternative is the water tube boiler in which the water / steam is contained in the small diameter tubes with the hot gas flowing around them. This allows the use of much higher pressures with greater safety. The first patent for a water tube design was taken out by William Blakey in 1766, but James Rumsey came up with the forerunners of modern designs with water and steam spaces linked by tubes running through the firebox [1].

2.2 Utility vs. Industrial HRSGs

Nowadays HRSGs are employed in a number of applications. The largest units are used in large combined cycle power plants recovering heat from gas turbines (GTs). These are referred to as utility scale HRSGs. HRSGs are also used behind other engines and in various industrial processes and these are referred to as industrial HRSGs. HRSGs used behind small GTs in combined heat and power applications are also often termed industrial. In this case the distinction between utility and industrial scale is somewhat artificial – units serving GTs with output above around 50MW_e are usually considered as utility scale.

2.3 Background to the Development and Use of HRSG Technology

Whilst the evolution of the gas turbine owes much to the development of the jet engine, its use for power generation in fact precedes its use in aircraft propulsion, with the first commercial gas turbine, a 2 MW_e Brown-Boveri machine originally installed in Switzerland in 1939 [2].

The use of gas turbine HRSGs evolved from the requirement to provide a significant improvement in the overall efficiency of a gas turbine generating plant by utilising the heat available in the exhaust flow of the gas turbine. With the thermal efficiency of the gas turbine inherently low due to the high exit gas temperatures (425 - 600°C) and high excess air levels (220 – 300%) in the combustion products, the thermal energy remaining in the exhaust gas was targeted for recovery via a heat exchanger system which circulated water and generated steam, thus "*combining*" additional electricity from a steam turbine generator. A schematic of a simple combined cycle system consisting of a single gas turbine generator, a HRSG, a single steam turbine generator, a condenser and the associated auxiliary systems is shown in Figure 1.

Considering the HRSG alone, a variety of different physical configurations are available alongside differences in the method of circulation employed, the number of steam side pressure levels achieved, and the specific mode of firing selected. A description and discussion of the impact of these factors is presented in the following sections.

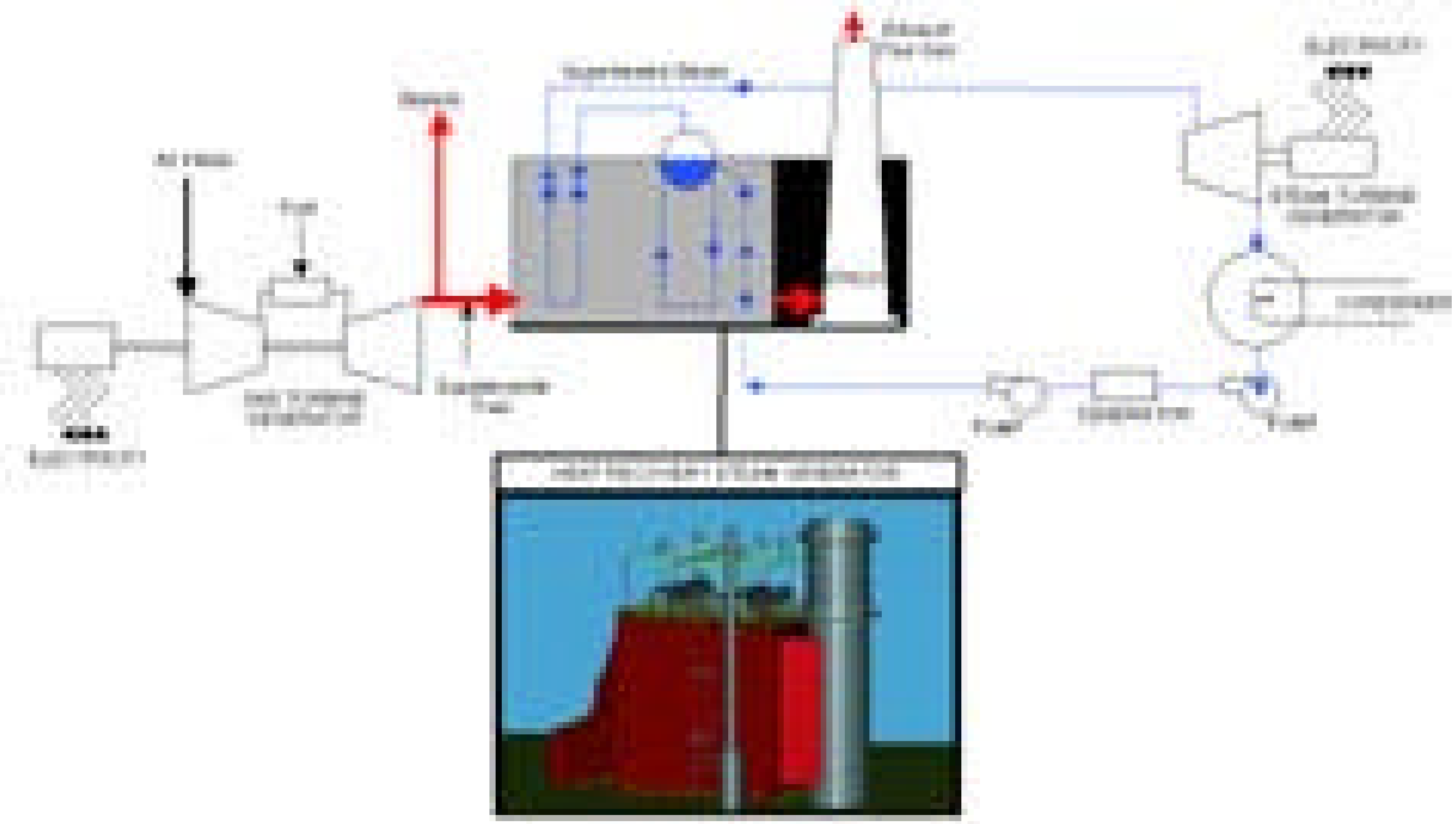


Figure 1: Schematic of a CCGT plant (Courtesy of Mitsui Babcock Energy Ltd).

2.4 Utility Scale HRSG Technology

2.4.1 Justification for Using Gas Turbine HRSGs

Today, the employment of a HRSG results in an electrical output from the combined gas turbine and steam turbine in the general region of ~ 30 to 50% greater than the output available from the gas turbine alone [3]. Significantly, this extra electrical output is obtained with no necessity for any additional fuel input.

Combined cycle systems make use of a Brayton cycle gas turbine firing natural gas or distillate oil and a Rankine cycle steam system to achieve efficient, reliable power generation. The Brayton cycle has high source temperature and rejects heat at a temperature that can be conveniently used as the energy source for the Rankine cycle. Table 1 shows the energy utilisation for a typical combined cycle plant.

COMBINED CYCLE PERFORMANCE				
	% OF FUEL INPUT			
Fuel Input LHV	**100**			
Gas Turbine Power	36			
Gas Turbine Losses	1			
Gas Turbine Exhaust heat	**63**			
Stack Loss		22		
Input to Steam		**41**		
Steam Turbine Power			19	
Steam Turbine Losses			1	
Heat to Condenser			21	
Gross Electric Power				**55**
Auxiliaries Power				2
Total Net Power and Efficiency				**53**

Table 1: Typical modern day combined cycle performance.

The gas turbine may typically convert 36% of the fuel energy into power leaving 63% as heat passing to the HRSG from the exhaust of the gas turbine (typical mechanical electrical and heat losses in the GT accounting for 1%). The HRSG captures approximately two thirds of the gas turbine exhaust heat with the remaining third being lost in the exit stack. Finally 19% of the fuel input is converted into power via the steam turbine with 1% lost in the turbine and 21% of the fuel energy lost in the spent steam which is sent to the condenser. The combined gross power of gas and steam turbines equates to 55% (LHV) of the fuel energy. Plant auxiliaries account for ~2% of the fuel input finally leaving 53% as net output combined cycle efficiency. Therefore the main justification for utilising HRSGs within utility power plants lies in the clear benefit from superposition of the gas turbine Brayton cycle over the steam turbine Rankine cycle (Figure 2) which results in an enhanced overall thermal efficiency.

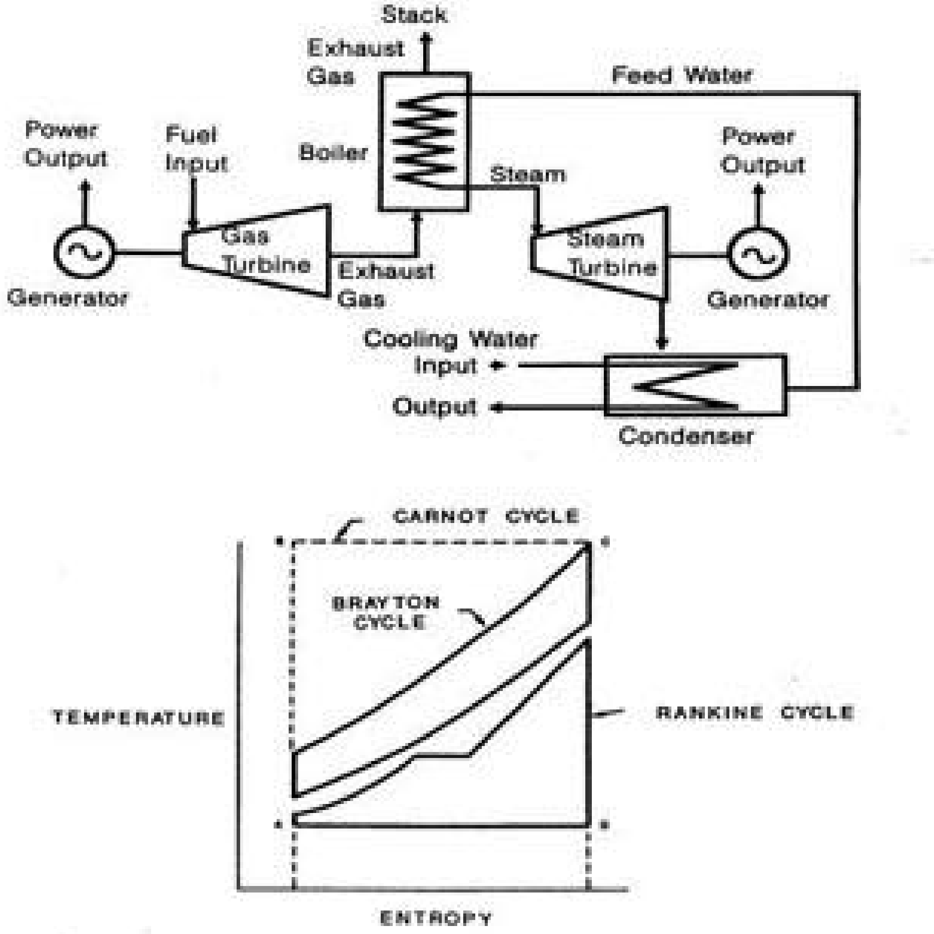


Figure 2: Gas turbine combined cycle (Courtesy of Innogy plc).

In terms of emissions to atmosphere, CCGT plant is significantly better than conventional coal-fired plant. Table 2 shows average emissions data for both plant types from the Powergen UK fleet during 2000, including part-load operation and starts [4]. It should be noted that emissions vary considerably between units depending on fuel composition, plant design, emission abatement technology and, to a lesser extent, running regime.

Emission	Typical operating CCGT	Typical operating coal-fired plant
CO_2, kg/kWh	0.43	0.92
SO_2, g/kWh (highly fuel dependent)	0.00	7.17
NO_x, g/kWh	0.28	2.31
Particulates, g/kWh	0.00	0.18

Table 2: Comparison of emissions from operating CCGT and coal-fired plant.

Further general benefits associated with the gas turbine combined cycle include increased plant flexibility and a relatively low capital outlay. Gas turbines can be used independently to provide a rapid start-up, peaking service with the HRSG boiler system usually brought from a cold start to full load steam generation in approximately 60 minutes. In terms of capital, gas turbine HRSG systems are relatively low due to the standardised components, modular construction, rapid erection and minimum support system costs.

2.4.2 Technical Considerations for Utility HRSG Design and their Economic Implications

The gas turbine HRSG is essentially a counterflow heat exchanger consisting of a series of superheater, boiler (or evaporator), and economiser sections arranged from the gas inlet to the gas outlet in order to maximise heat recovery and supply the rated steam flow at the required temperature and pressure to a steam turbine.

The critical temperature differences that influence the amount of heat transfer surface are the pinch point and both the economiser and superheater approach temperatures. The pinch point and approach temperatures are illustrated in Figure 3 for a single pressure HRSG and are defined as: -

- **Pinch point:** The difference between the gas temperature leaving an evaporating section and the temperature at which the boiling is occurring (i.e. the saturated water temperature).
- **Economiser approach point:** The difference between the saturated water temperature in an evaporating section and the incoming feedwater temperature.
- **Superheater approach temperature:** The difference between the inlet exhaust gas temperature from the gas turbine and the exiting superheated steam temperature.

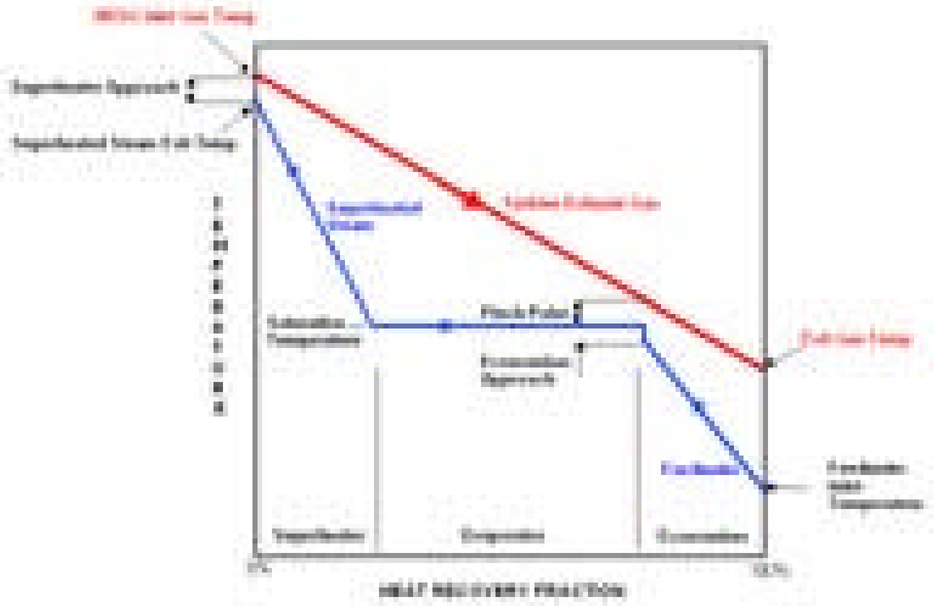


Figure 3: Temperature profile of a single pressure HRSG (Courtesy of Mitsui Babcock Energy Ltd).

Considerable efforts are made by HRSG designers to obtain maximum levels of heat recovery from the turbine exhaust gas. The principles applied for designing HRSG equipment are in many ways similar to those used for conventional utility boiler design.

In general the technical design of any gas turbine HRSG is centred on the following five features [5] and their respective economic implications:

- **Allowable back-pressure:** The HRSG cross sectional area significantly influences the gas turbine back-pressure. Smaller, more compact HRSGs require higher gas turbine back-pressures to drive through the flue gas, however, whilst the size reduction may reduce HRSG cost, the requirement to provide a higher pressure at the turbine exit has a detrimental effect on gas turbine efficiency. (Typical values of gas turbine back-pressures are 2.5 to 3.7 kPa in most units).
- **Steam pressure and temperature:** The steam pressure and temperature are selected to provide an economical design. Higher steam pressures lead to increased system efficiency but can limit total heat recovery from the flue gas in single pressure HRSGs due to the higher saturation temperature. Multiple pressure HRSGs as discussed in Section 2.4.5 are used to overcome this constraint.
- **Pinch point and superheater approach temperatures:** Small pinch point and superheater approach temperatures correspond to a lower temperature difference between flue gas and the steam within the exchanger pipework. As a result of these smaller temperature differences the surface area required is much greater in order to produce the same heat transfer. The direct consequence is that more material is used and hence capital cost is seen to rise (typical values of pinch point and superheater approach point are between 11 to 28 K and 22 to 33 K respectively).

- **Economiser approach temperatures:** The economiser approach temperature is typically set to avoid the economiser steaming at the design point. (Typical values of economiser approach point are 6 to 17 K). Furthermore the economiser inlet water temperature must be fixed at a level above that of the acid dew point of the combustion gases so that corrosion from sulphuric acid condensation is avoided (a typical value of economiser feedwater temperature is ~120°C when sulphur is present in the fuel; see Section 3.3.1.3).
- **Stack outlet temperatures:** As for the feedwater temperature in the economiser, the minimum flue gas exit temperature (stack temperature) has to be controlled to avoid the financial penalties associated with designing against acid corrosion.

2.4.3 Requirement for Finned Tube

Consideration is also required on the actual tubing utilised to form the gas to water/steam heat exchanger. The heat transfer rate between the tube and the high density water on the inside of the tube is far greater than the transfer rate between the tube and the low density flue gas passing on the outside. The outside heat transfer rate is said to be "controlling" and therefore responsible for the overall heat transfer rate. In the case of a HRSG this overall rate of heat transfer is lower in comparison with a fired utility boiler, due to the lower flue gas temperatures and the reduced effect of radiation. Therefore, in order to increase the rate of heat exchange in the HRSG tubes, the surface area on the outside of the tubes is extended by finning.

There are many variations of fin design available. A commonly employed finning process is where the fin is fabricated from an L shaped strip of metal. The longer leg of the strip is slit and the strip is wound and welded in a spiral around the tube. This results in the slits of the protruding long leg spreading out as the L is wrapped around the parent tube as illustrated in Figures 4 and 5. Alternatively a plain strip can be high frequency welded on to the tube to give 'I' finned tube as shown in Figure 6. The differences between 'I' and 'L' section finning are discussed in Section 3.2.6. With either method, the resulting fin area can be several times the area of the bare tube.

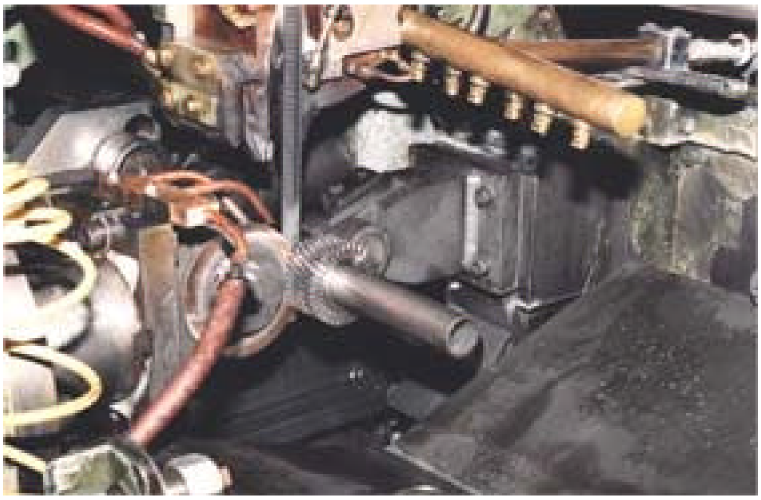


Figure 4: Finned tube manufacture (Courtesy of Mitsui Babcock Energy Ltd).

Figure 5: Finned tube bundle (Courtesy of Mitsui Babcock Energy Ltd).

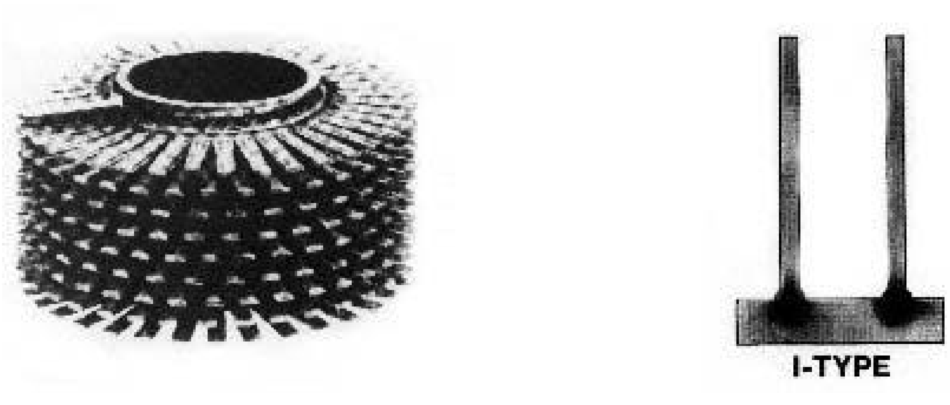


Figure 6: High frequency welded segmented fin (Courtesy of Mitsui Babcock Energy Ltd).

The actual gas side temperature limit for finned tubes will be influenced by fin material considerations. In general, if the inlet gas temperature to the HRSG is below about 750 to 800°C finned tubes may be used exclusively. However if the HRSG is to be fired in a supplementary mode with the use of duct burners (as described in Section 2.5) and gas temperatures in excess of approximately 750 to 800°C are encountered, the rows of tubes in the hotter zones may well require to be bare or have a reduced level of finning (see Section 3.4.4 for discussion of operational experience).

2.4.4 HRSG Circulation and Configuration

A HRSG may have a gas pass which is either horizontal or vertical in orientation. In the first case (Figure 7), the gas turbine exhaust is ducted horizontally through the casing of the HRSG and then passes over top-supported tubes before being turned vertically to a stack. For this horizontal gas flow case, the evaporator tubes are vertical thus allowing water circulation in the evaporator by natural convection without the need for a circulation pump. Whilst the evaporator tubes are vertical, the superheater and economiser tubes for the horizontal gas flow can be either vertical or horizontal and are usually chosen on the basis of providing the best drainage.

When the gas flow is vertical, the evaporator tubes are horizontal (Figure 8) and in order to ensure a more consistent flow of water, circulation is generally achieved by a pumped or forced circulation means. There are however some exceptions and HRSGs have been built with vertical gas flows and horizontal heating surfaces which by utilising elevated drums ensure adequate circulation via a natural circulation mechanism.

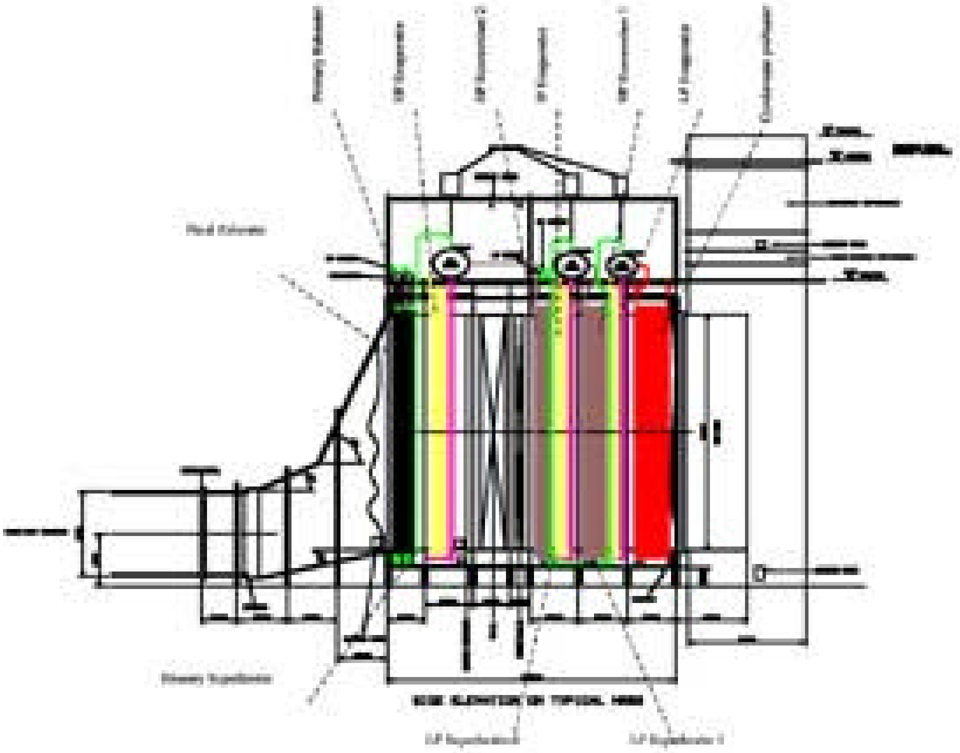


Figure 7: Typical modern horizontal gas-flow, natural circulation HRSG (Courtesy of Mitsui Babcock Energy Ltd).

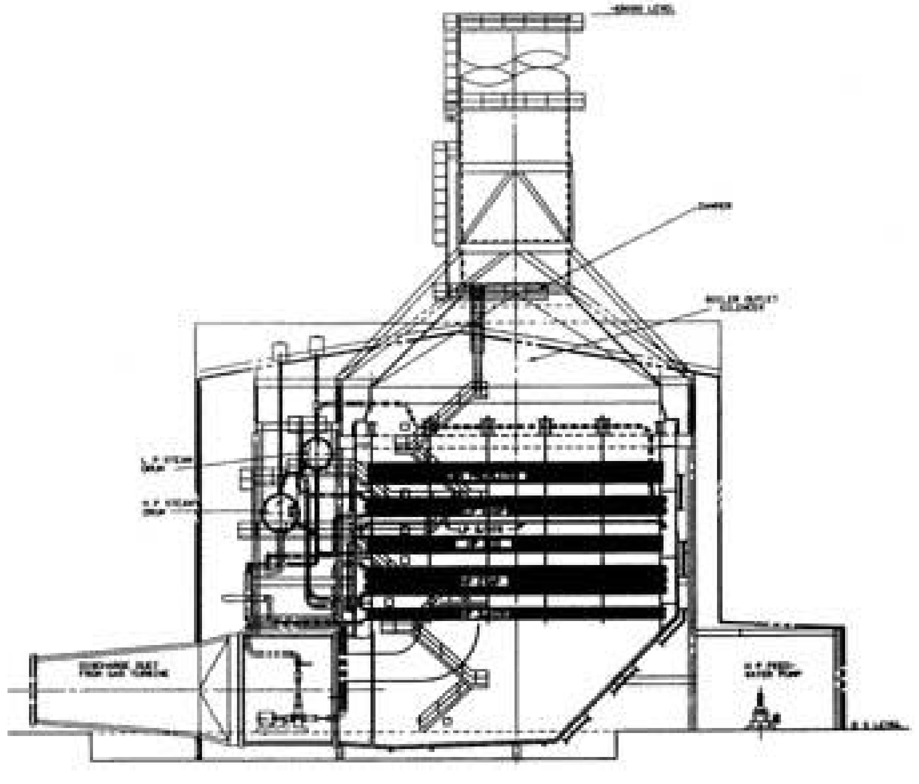


Figure 8: Typical modern vertical gas-flow, assisted circulation HRSG (Courtesy of Mitsui Babcock Energy Ltd).

Both HRSG orientations have essentially the same components included in the scope of supply. These typically consist of:

- An expansion joint at the gas turbine exhaust interface
- An exhaust by-pass damper
- A by-pass stack and silencer
- An inlet transition duct with flow correctors
- Duct burner (required for supplementary and auxiliary firing units)
- Heat recovery steam generator modules
- Steam drums
- Access ladders and platforms
- Exhaust stack

Each circulation method has its own advantages and disadvantages as outlined in Table 3 (assuming that vertical HRSGs are pumped circulation).

<table>
<tr><th colspan="2">Natural circulation (horizontal gas pass) HRSGs</th></tr>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>· Reduced power requirements due to absence of boiler circulating pumps
· No maintenance of circulating pumps, motors, motor and pump controls etc required
· Vertical or inclined tube boilers can be more effectively drained
· Overall height of the boiler plant can be more easily restricted.
· Tube “spacers” instead of tube “supports” can be employed. This minimises problems with fretting.
· Easy to provide a water-cooled combustion zone or furnace
· More forgiving of flow and temperature maldistribution, especially for fired units.
· Easier to incorporate supplementary firing and a split superheater design.</td><td>· Flow disruption is not flow compensated as in forced circulation system
· May have slightly increased plot area under certain circumstances
· Greater care to maintain cleanliness required, particularly with “dirty” gases
· Can be difficult to withdraw single tube elements</td></tr>
<tr><th colspan="2">Pumped Circulation (vertical gas pass) HRSGs</th></tr>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>· May allow slightly reduced plot area under certain circumstances
· On very restricted sites boiler can be mounted directly over GT with vertical exhaust straight into boiler
· Stack being supported off the already elevated boiler structure, height and costs are reduced
· Generally lower water content than natural circulation unit of equivalent output
· Horizontal tubes with vertical fins provides a self cleaning surface
· Easy to arrange fully drainable superheaters irrespective of the size of the bank
· Ease of individual tube element withdrawal without disturbance of other tubes</td><td>· Increased power consumption due to circulating pumps
· Additional maintenance items:- Circulating pumps, motors, motor and pump controls etc.
· Effectiveness of the draining is not as efficient
· Restrictions on boiler height difficult to achieve
· Water-cooled tube supports required with gas temperatures above 760°C
· Not as easy to provide a water-cooled combustion zone.
· Difficult to add SCR and CO catalyst support systems.
· Designing for high earthquake considerations is considerably more difficult.
· Difficult to incorporate a split superheater with supplementary firing.</td></tr>
</table>

Table 3: Characteristics of natural and forced circulation HRSGs.

Both types of technology can be instrumented and controlled to the same level of automation, both incorporate with equal ease an emission control catalyst for NO_x and SO_x, both hold similar records for plant life and reliability and both take up a similar plot area.

In order to maintain a position within the marketplace, equipment which essentially performs the same function must be similarly priced. Thus no significant price difference between the natural and pumped circulation technologies is apparent, although the market currently demands a 90-95% preference for horizontal gas-flow designs.

An area where the technologies do differ is supplementary firing (see Section 2.5) as this is easier to incorporate into a natural circulation, horizontal gas-pass design. A major superheated steam temperature control tool, the split superheater design, is difficult to incorporate into a pumped circulation design.

2.4.5 Significance of HRSG Pressure Levels and Reheat in Increasing Cycle Efficiency

As mentioned previously in Section 2.4.2, a HRSG may be designed for operation with multiple, separate pressure water/steam circuits in order to maximise heat recovery. Over the years, the pressure levels available have increased from the early single level installations, through the dual pressure systems of plants built in the early 1990's to the more recent triple pressure HRSGs. The number of pressure levels incorporated within an HRSG and the use of reheat has a direct effect on steam cycle efficiency. Therefore the use of a 'triple pressure with reheat' circuit can, for example, contribute directly to the combined cycle efficiency of the plant.

Consider, as the turbine exhaust gas passes through the HRSG, heat is transferred to the circulating water and steam via the heating surface. Having passed through the HRSG, if the temperature of the flue gas leaving the stack is lower then the greater the amount of transferred heat to the steam and therefore the greater the level of heat recovered.

In the case of a single pressure cycle, water from the condenser enters the HRSG at the cold end and is then heated until near saturation by the exhaust gases. Following this the water then enters the evaporator circuit via the steam drum where the flow is circulated and heat is transferred at constant temperature. Finally the steam is superheated by the hottest flue gas before passing to the steam turbine. However, whilst the high steam pressure is required at the steam turbine in order to achieve a high steam cycle efficiency, the choice of a high pressure level simultaneously limits the amount of heat transferred to the steam. Therefore in order to generate high pressure "useful" steam for the steam turbine and maximise the amount of heat transferred from the flue gas, other pressure levels are required.

With a dual pressure cycle the high pressure circuit ensures high steam pressure delivery whilst the low pressure circuit ensures that maximum heat is extracted from the gas turbine exhaust gas. Thus the problem of balancing maximum enthalpy capture with an efficient steam cycle is addressed. Due to the nature of latent heat, the evaporation of steam by a gas will always be such that a large temperature difference will develop between the streams. This resulting loss in performance can however be minimised by the adoption of further steam evaporation levels such as the triple pressure cycle.

In addition to introducing various pressure levels to the steam circuit the possibility of re-heating steam which has initially passed through the high pressure section of the steam turbine is also considered by HRSG designers. Reheat aims to optimise the lower pressure end of the steam turbine performance. When re-heat is utilised, the steam turbine performance is superior to non-re-heat cycles, due to the increased temperatures specifically, of the lower pressure steam supply. There are however consequences in enhancing this temperature. For example the additional heat required in the HRSG re-heater section results in lower HP steam production. Furthermore, whilst the steam turbine performance is improved, the gas turbine output degrades slightly due to the need to overcome the pressure drop associated with the additional HRSG re-heat surface. In general re-heat adds control complexity and potentially higher capital costs due to higher costs of piping, controls and a suitable steam turbine. Some consideration is therefore required prior to selection to ensure the most effective configuration is achieved.

In general, the overall cycle efficiency can vary in the range of around three percentage points depending on whether a single pressure or triple pressure with re-heat cycle exists [6]. The obvious disadvantage, however, in increasing the number of HRSG pressure levels is the associated increase in capital costs with each new pressure level.

The following trends have been previously highlighted [6]:

- The single pressure non-reheat cycle has a low installed plant cost and is envisaged as a sound investment when fuel is inexpensive, ash bearing and with a high sulphur content (e.g. oil firing).
- The dual pressure non-reheat cycle has a higher installed plant cost than the single pressure non-reheat cycle and has proven in the past to be the most economical choice when fuel is more expensive and clean burning with little sulphur content (e.g. natural gas).
- The upper range of pressure levels i.e. the dual pressure level with reheat and triple pressure level with reheat are usually matched to gas turbines with high exhaust temperatures. In this case, there is sufficiently high temperature energy to the HRSG to make the reheat steam cycle practical. Therefore, the non-reheat dual pressure cycle is common for older and smaller gas turbines, with the modern generation of larger gas turbines such as the GE 9FA lending themselves to steam cycles with an additional pressure level and reheat capability.

Typically, the largest step achievable in enhancing cycle efficiency by means of incorporating various pressure levels is 1.7% points (single pressure to a dual pressure non-reheat system). A triple pressure with reheat cycle provides a further 1.3% points improvement over the dual pressure non-reheat case and, of this 1.3% points increase, 0.5% points is directly attributable to the reheat line itself.

An obvious approach to enhancing cycle efficiency is to continue adding further pressure levels to the HRSG system thus further increasing heat recovery of the exhaust gas and lowering stack temperature. However, in practice there is a limit to the incorporation of pressure levels due to the fact that the low pressure steam produced has an insignificant contribution to the steam turbines power output. Furthermore the stack temperatures themselves must be maintained above acid dew point thresholds in order to prevent the expense of designing against possible corrosion.

2.5 Alternative Modes of Operating HRSGs

Due to the fact that gas turbines operate with a high air throughput (~ three and a half times stochiometric) a gas turbine exhaust contains sufficient oxygen to support further combustion (approximately 15 % w/w is present in the exit stream of the gas turbine compared to some 23 % w/w in air). As described previously, HRSGs can be unfired in which case they only utilise the sensible heat of the gas as supplied. However, they may be fitted with additional firing equipment (grid burners) positioned in the exhaust gas stream across the inlet transition duct. These burners are commonly fired with gas, although oil burners can be utilised but tend to be avoided due to complications with the atomisation of the fuel.

When duct burners are present, two additional HRSG modes of operation are possible, these are known as:

- Supplementary firing mode
- Auxiliary firing mode

2.5.1 Supplementary Firing Mode

Supplementary-fired HRSGs involve further combustion of additional fuel in the gas turbine exhaust gas by utilising duct burners. The result of this additional firing being that the flue gas temperature is substantially increased which in turn improves steam production and raises superheated steam temperature.

Normally large gas turbines provide an exhaust gas at a maximum temperature of ~600°C. However, by incorporating supplementary firing into a standard HRSG this temperature can be raised to ~815°C. HRSG inlet temperatures higher than 815°C are achievable when firing with duct burners, but the walls of the HRSG will then need to be lined with refractory for protection of the steel casing. Furthermore, at temperatures above around 1100°C water cooled walls may be necessary. This increase in exhaust gas temperature to ~815°C is associated with an almost doubling of steam production and thus provides a mechanism of altering steam production by means that are independent of the gas turbine operation.

2.5.2 Auxiliary Firing Mode

Auxiliary fired HRSGs allow steam to be generated in the HRSG when the gas turbine itself is not in operation. The main advantage of this mode is the flexibility it provides operators, allowing maintenance to be undertaken on the gas turbine whilst still generating electricity with the steam turbine.

Disadvantages of this mode are that firing is therefore undertaken with air at a lower initial temperature than that supplied previously by the gas turbine exhaust gas. Therefore the fuel input required to obtain full steam output is greater than for the case where the gas turbine is in operation. For auxiliary firing mode, a system is therefore required which allows sufficient airflow into the HRSG when the gas turbine is not in operation. This usually consists of an arrangement whereby the duct from the gas turbine exit is isolated when the turbine is off-line and the combustion air is introduced into the HRSG either via a separate upstream forced draft fan or an induced draft fan positioned downstream of the HRSG.

2.6 Industrial Scale HRSG Technology

A wider variety of operating conditions and applications gives rise to a variety of designs and specialised equipment additions for industrial scale HRSGs as compared to utility units.

As at the utility scale, the driving force for the development of the industrial scale HRSG is the desire to improve the overall efficiency of fuel use. For example industrial scale HRSGs are commonly used in combined heat and power (CHP) schemes. In 2001 the average electrical efficiency of all operating UK CHP schemes was 20% (GCV) and the average heat efficiency was 54% giving an overall efficiency of 74% [7]. For comparison in 1998 the mean efficiency of fossil fuelled electricity generation before transmission loses was 40% and the efficiency of typical UK boiler stock was around 75% (GCV). Based on the above efficiencies, compared to separate generation of electricity and heat, the CHP scheme would use only 81% of the energy input [8].

In addition, in some industrial applications there is in any case a process need to cool a fluid flow, and the HRSG allows some use to be made of the rejected heat.

2.6.1 Water Tube Designs

Many industrial HRSGs are broadly similar in design to utility scale units and the same design criteria as discussed above apply. They are usually simpler, often having just a single working pressure and no reheat. Some units supplying steam to a steam turbine may have a second pressure level to allow improved heat recovery with the lower pressure steam being admitted to the turbine part way down the casing at the appropriate pressure level. As with the larger units, they may have a horizontal or a vertical gas path, with hot or cold casing and natural or forced circulation. In some applications, water wall designs are used. This avoids the need for a refractory lining and is particularly advantageous in applications where the exhaust gas is corrosive and would attack a refractory lining. It is also sometimes used in units with a high degree of supplementary firing.

2.6.2 Smoke Tube Designs

In some applications in which pressures and flows are lower, it is possible to use the ‘smoke tube’ (also known as ‘fire tube’ or ‘shell boiler’) design in which the hot gas is circulated through tubes within a water /steam filled shell.

The smoke-tube design has the advantage of simplicity, ease of construction and lower capital cost. It removes the need for a separate steam drum and the need to consider circulation and the provision of boiler circulation pumps. It is therefore favoured in many smaller scale applications, especially in small scale CHP schemes. Smoke tube HRSGs are available as factory built package units, but these packages are usually limited to steam pressures of around 18 bar_g. The smoke tube design is also favoured in process applications where there is a high gas side pressure.

However smoke tube designs are limited to the production of saturated steam as the water and steam always exist within the same compartment (although a separate superheater could be fitted). The stress in the shell due to the internal pressure increases with diameter. Smoke tube designs are therefore limited in their steam flow and pressure capabilities compared to the water tube design.

The multitude of small diameter gas passes means that they are not easily cleaned and are prone to dust fouling. They are therefore not well suited to applications where there is a high dust load in the gas. High gas velocities may be experienced, especially if some tubes start to block increasing the flow through the remaining tubes, which can lead to erosion problems.

Care needs to be taken in designs for higher temperature use. Steam blanketing may occur in the upper regions of the shell reducing the cooling flow of the water / steam. This is especially true in a vertical design where a steam blanket can form over the bottom surface of the top tube plate. This can allow high temperatures to occur in the top tube plate. This is dangerous if such high temperatures have not been taken into account in the design of and material selection for the top tube plate.

2.6.3 Once Through Steam Generators

Once through steam generators (OTSGs) are available at the industrial scale as well as the utility scale and in some markets have achieved reasonable penetration. The main supplier has been Innovative Steam Technologies (IST), who have installed 65 units, mainly in the US [9]. However with four notable exceptions, these have generally been on GTs of 50MW or less, and on the >50MW plants, steam pressures have been relatively low (< 40 bar). The IST design is not widely used in Europe yet. The IST design makes extensive use of high temperature rated alloys that allow it to stand exposure to full GT exhaust temperature when dry. The advantages of IST’s OTSG technology are perceived as being [9]: -

- Cheaper erection costs and quicker erection (for units less than ~50MW) because all pressure welds can be done in the factory and there is no welding of drums etc. to carry out on site. IST suggest that an OTSG can be erected in only 25% of the erection time of a conventional HRSG.
- Typically HRSGs will be equipped with a bypass damper/stack to allow the GT to continue running if the HRSG trips. This is not needed with the OTSG as the unit can run dry – the tubes are able to withstand the full GT exhaust temperature without cooling. The absence of a bypass stack and damper gives a saving in capital cost. It will also give a slight efficiency improvement as there is no GT exhaust gas loss through damper (normally 0.3 – 1.0% of exhaust gas gets lost through the damper and out of the bypass stack).
- There is no blowdown in the OTSG design, so there are no blowdown losses, resulting in a higher efficiency.
- Fewer parts, requiring less control and instrumentation – typically only 50% of the valves that a conventional HRSG would need. This can result in improved reliability and lower maintenance requirements.
- The OTSG can be designed for fast maintenance with a single door for access and fabricated entirely with single pass welds which are close together for ease of access.
- Remote operation as the unit is more robust - it will not be damaged if it runs dry.
- The nickel alloy tubes employed in the design are resistant to corrosion. Carbon steel finning may suffer corrosion or the build up of deposits. However these can be removed by running dry to bake them off. This obviates the need for periodic acid cleaning. Alternatively corrosion resistant alloys can be used for the finning as well.
- The OTSG has a low water demand. It only uses around 16% of the water that a conventional HRSG uses. This suits it to applications where good quality water is not readily available e.g. areas of the Middle East. This also allows a faster start up / shut down as there is a smaller reservoir of water to heat up.
- The OTSG has only ~40% of the weight of a conventional HRSG (implications for transport costs and structural steelwork).
- Smaller diameter and therefore thinner section components are used. Thermal stresses are lower on start up, shut down and load varying. Higher heating / cooling rates are acceptable. IST suggests that one of their dual pressure OTSGs behind a 40 MW_e GT could start from cold in under one hour. The design is well suited to cyclic operation.
- The material can handle a feedwater temperature as low as 15°C (compared to ~60°C for carbon steel). This means that a plant can run with a lower de-aerator temperature and feedwater temperature, which gives higher boiler efficiency. However, it should be noted that any type of HRSG can have material upgrades in the preheater if necessary or other provisions for protection against cold end corrosion.
- As the de-aerator can run at a lower temperature, vacuum de-aeration can be employed, which uses less steam and at a lower pressure – so giving greater overall plant efficiency.

There are also a number of perceived disadvantages: -

- The advanced finning and construction techniques involved in the factory fabrication of OTSG designs mean that few facilities are capable of making them. This in turn means that the cost of transport to site may be higher as manufacture cannot be carried out locally.
- The extensive use of high temperature alloys increases capital cost.
- One of the key advantages of the OTSG design is the fact that a bypass duct is not needed, but the absence of one means that the GT must be shut down in order to carry out HRSG maintenance.
- The tube diameter is usually smaller to allow adequate strength at the elevated temperatures that an OTSG may experience. This results in a higher water side pressure drop and therefore a requirement for larger feedwater pumps, which impose a larger parasitic load.
- As impurities may not be blown down from a steam drum, the control of water quality becomes more critical. A polisher is required in the circuit adding to capital and operational costs.
- The capital cost of OTSG designs may be slightly higher than conventional drum designs.

Although once through designs have existed for many years now they are still perceived as being novel with a higher risk than the conventional drum design. This is especially true in Europe where there is little reference plant. The design has been more widely used in the US, although they still form a very small proportion of the total market. Many plants are now built under turnkey contracts. Many of the advantages of the OTSG design are operational whereas the capital cost may be slightly higher. This means that turnkey contractors whose principal concern is normally capital cost rather than operational advantage tend not to favour the design.

2.6.4 Design Aspects

Beside the thermodynamic design factors detailed above for utility HRSGs, the design of the industrial scale HRSG is controlled by factors such as:-

- The dust load of the hot gas stream and its chemistry: in some process applications the hot gas may have a high dust load and the dust chemistry will influence the degree to which deposits build up on tube surfaces. In such cases, means of online removal of deposits will be required, such as rapping devices, sonic horns or soot blowers. Allowances for the reduction of heat transfer rate due to the build up of deposits must be factored in to heat transfer calculations by the inclusion of fouling factors.
- The composition of the hot gas stream: compatible construction materials may be needed (e.g. materials resistant to a corrosive gas stream).
- Pressure of the gas stream: whilst for utility scale combined cycle applications the hot exhaust gas is always at a low pressure to minimise the back pressure on the gas turbine, in a process integrated application the hot gas stream may be at high pressure. In such circumstances, and if a high steam pressure is not required, it may be preferable or necessary to use a smoke tube design.

- Exhaust gas temperature: current GT exhaust temperatures tend to be in the range 450-600°C. Process exhaust gas temperatures may be far higher necessitating the use of refractory linings or membrane panel water walls.
- Steam requirement: the steam conditions produced from the HRSG may be dictated not by the most efficient operating point of the HRSG, but by the requirements of the process utilising the steam. Achieving the required steam flow may also require supplementary firing.
- Guaranteed availability of steam production: if a very high availability of steam production is required to keep a downstream process running, the design will be affected e.g. auxiliary firing may be provided to allow full steam production to be maintained in the event of a gas turbine trip.

3 CURRENT STATUS OF HRSG TECHNOLOGIES

3.1 Introduction

This section covers the current design of HRSGs. It also discusses problem areas, operational experience and typical costs. It is based on the experience of users in specifying and operating both CHP and utility CCGT plant, and on discussions with major equipment suppliers. Other applications of industrial scale HRSGs are also discussed.

3.2 Specification and Design of HRSG Plant

The recent trend has been for the CCGT plant to be built under a ‘turnkey’ contract, to a functional specification with one overall contractor being responsible for supplying the whole plant. Whilst this does have advantages to the end user in terms of accountability, it does tend to mean that the choice of HRSG supplier is often outside the users control.

An example of the role of the turnkey contractor is given by Siemens [10]. Siemens would typically carry out the overall thermal calculations and supply the steam boundary conditions, customer requirements in terms of starts and cycles and the number of pressure levels to the HRSG supplier, who then carries out the detailed HRSG design. Siemens would also specify whether the HRSG should be vertical / horizontal, fired / unfired and, if fired, whether this should be supplementary / auxiliary. Siemens would then check the design, ask the HRSG supplier to explain the rationale behind it and check the calculations to make sure that it can perform theoretically. Siemens would also thoroughly check the design of any non-standard plant with which the HRSG supplier is unfamiliar.

Different turnkey contractors have different philosophies regarding erection. For example, some use a single erection contractor for all plant items. The Siemens approach [10] requires the contractor to design, manufacture and erect the HRSG as they have knowledge, familiarity and experience of their own plant and can install it correctly. This also means that responsibility is clearly established. The boiler steel structure is also regarded as part of the boiler and is included in the boiler supplier’s scope.

The user can regain some control over the HRSG design through the functional specification, although if this contradicts the suppliers standard design philosophy, additional costs may result. The aim, therefore, is to allow the supplier to provide his standard design as far as possible, whilst ensuring that a minimum number of essential design features are incorporated into the design. This will often involve meeting with the supplier at an early stage in the tendering and/or design process to discuss the HRSG design and how the required features can be incorporated.

Since the market for HRSGs is very competitive, most suppliers will provide only the basic design unless otherwise required by the specification. In addition, the supplier's warranty period will normally be limited to 1-3 years, so the HRSG supplier will not always be focussed on the long-term performance of the plant. In this respect, it is often the turnkey contractor (who may supply a warranty of up to 5 years) or end user that dictate design improvements, usually on the basis of previous experience.

Some of the main issues raised at the design/construction phase are: -

3.2.1 Design Code

The Powergen requirement is normally that the HRSG be designed to an agreed internationally recognised code. The preference would normally be for the use of British Standards, EN Standards or TRD, principally due to their recognition of fatigue as a damage mechanism, linkage of design stress to design life and generally lower component wall thickness. However the majority of HRSG suppliers provide their HRSGs to ASME (American Society of Mechanical Engineers), and it often proves less problematic to stay with the manufacturers standard practice and to concentrate on attaining specific mechanical design features within that code. As implied above, ASME Section 1 excludes any reference to low cycle fatigue as a damage mechanism [11], so if this code is to be accepted, fatigue needs to be separately assessed at the design phase, particularly if cyclic operation is envisaged.

Siemens experience also reflects this [10]. They regard ASME as a somewhat over-conservative code that results in thicker components, and flexible plants are therefore best designed to TRD (German Technical Rules for Boilers), BS (British Standards) or EN (Euronorm). They also noted that inspectors are involved in design and manufacture with the European codes, giving an extra quality check, whereas ASME only requires sample designs to be checked. Having said this, Siemens preference is for ASME as it is familiar to all boiler manufacturers (European codes in particular are not familiar to Asian manufacturers). As Siemens are under pressure to reduce delivery times (Killingholme B was completed in 36 months but would now be done in around 22), the use of unfamiliar codes can slow projects down. As a result, no overseas Siemens projects have been designed to TRD. Occasionally the choice of code is specified by the end-user. Another issue is that ASME only allows the use of ASME materials and negotiations have to be made with the inspector when other materials are wanted.

Similarly to Powergen, Innogy [12] is not prescriptive in its specification of design codes (the description given is simply 'BS or equivalent'). They also recognise the fact that ASME has an inertia behind it and dominates, even in Europe. The European codes have been written to exclude the legislative aspects, as they are included in the PED (Pressure Equipment Directive). ASME on the other hand is 'all encompassing'. In retrospect, Innogy felt they may have preferred to put more investment into HRSG projects up front (i.e. improve the specification) to reduce operational problems experienced further down the line. However, they did feel that it is sometimes more cost effective to rectify issues early in a plant's life than to change the specification in the project development stage. As discussed above, this is because standardisation from HRSG to HRSG allows turnkey contractors to save money and additional features requested by the client deviate away from the turnkey contractor's norm.

As far as suppliers are concerned, opinion is divided. Nooter/Eriksen [13] carry out all design to ASME unless specifically requested by the customer. NEM [14] fix the design code to the customer's requirements, although once again, they state that ASME has been the tendency over recent years. Standard Fasel Lentjes have no preference, except for two-shift operation, where TRD is preferred.

3.2.2 Quality of Supply

Quality of supply has become one of the major issues to the user. As the HRSG market has become more competitive, fabrication has shifted to areas where labour costs are low. The actual boiler fabricator is therefore often several steps removed from the turnkey contractor, and in the worst case may not have experience in HRSG fabrication. This means that the management of quality by the turnkey contractor or main HRSG supplier is increasingly difficult, and that changes to design agreed with the turnkey contractor may take some time to filter down to the shop floor. The same problems can occur on site, particularly if the HRSG erector did not supply the HRSG.

Siemens experience reflects this [10]. They do not tend to encounter problems with the design of standard drum-type HRSG plant anymore - it is fabrication / erection quality that causes greater concern and shop/site supervision is therefore seen as crucial. For example, incorrectly installed baffle plates have resulted in low thermal performance in the past due to gas bypassing. Site welds are considered a particularly high-risk area. They also prefer to use established designers – although a boiler design may work thermodynamically from a theoretical point of view, practical details can be critical and therefore great emphasis is placed on experience.

Powergen experience is similar, and importance is placed on Powergen personnel carrying out independent QA inspections during HRSG fabrication and installation. This is believed to result in significant overall benefits in terms of long term plant reliability.

3.2.3 Pressure Part Materials

HRSGs generally (but not always) operate at lower conditions than conventional direct-fired boiler plant. The pressure parts are therefore normally fabricated from well-proven materials. Modified 9%Cr (P91) and 12%Cr are now commonplace in HRSG design. P91 is the newer material, having been in use in power plant for some 13 or so years and in HRSGs for slightly less than this. P91 has excellent high temperature creep properties and this is particularly beneficial in reducing the wall thickness of high temperature components. This is often the driver for the use of this material, particularly for headers, where design for cyclic operation is required.

Siemens [10] view was that materials are not really an issue, as higher temperatures have been successfully handled on coal plant. It is also possible to make a boiler more or less flexible with the same material by changing the number of stubs into each header, for example. They believe the main issue with materials is now quality of supply.

Nooter/Eriksen [13] use ASME materials as standard, subject to availability - P91 is used as standard on high temperature pressure parts and they otherwise tend to use commonly available materials. Standard Fasel Lentjes [15] and NEM [14] give similar comments.

From an operator's perspective, there are still some issues with P91, mostly relating to the long-term life of the welds and inspection strategies to manage this. Significant research / investigation is ongoing in this area.

3.2.4 Seamless Pressure Part Components

Powergen's standard is for all tubes, pipes and headers to be fabricated from seamless material, due to the perceived inherent risk in seam welded components, in which the weld is subjected to the full hoop stress due to internal pressure. This is particularly applicable in the creep range, where the long term properties of the seam weld come into play.

Innogy [12] have likewise always used seamless headers. They have, however, used ERW (electric resistance welded) tubing and have seen ERW tube failures on some international projects. However, they believe that the specification for ERW has since been tightened and that it is probably not much cheaper than seamless (apparently only three companies world-wide supply ERW). Innogy's (now sold) Killingholme A plant contains ERW and they acknowledged that the reliability of ERW is very sensitive to quality.

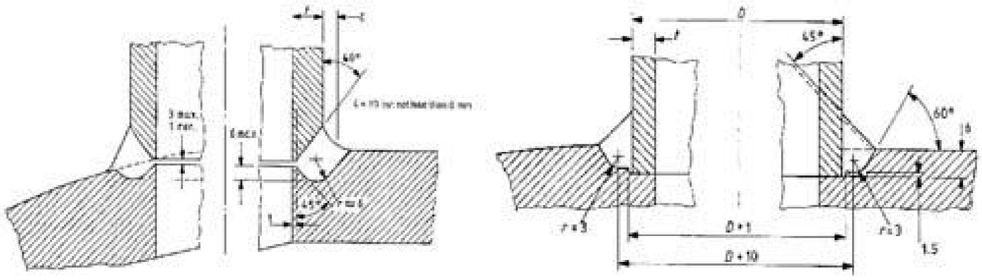
Siemens's approach [10] agrees with this. They prefer seamless headers and if a manufacturer wants to use seam welded pipework, special requirements are imposed. Siemens have not accepted a seam-welded header to date.

As far as suppliers are concerned, the situation is as follows. Nooter/Eriksen's standard [13] is to use seamless tubes for chrome alloy tubes and seamless or welded ERW tubing for the carbon steel sections, with all headers being seamless. However, in the UK, seamless tends to be used throughout due to negligible difference in cost compared to seam-welded components. Standard Fasel Lentjes [15] use seamless throughout. NEM use seamless in the creep range and seamless or seam-welded below these temperatures.

3.2.5 Stub to Header Weld Detail

If incorrectly specified and executed, stub to header welds can be a major source of long term unreliability. This is principally due to their great number, difficulty of access (especially in horizontal HRSGs) and that fact that they are usually required to accept bending stress as well as internal pressure stress. As such, this is regarded as a key pressure part design feature.

Powergen normally require full penetration welds, particularly for cycling plant (Figure 9a). Partial penetration welds (Figure 9b) are more susceptible to corrosion fatigue cracking initiating at the unfused internal land. Whilst there are plants operating flexibly with partial penetration welds, they are generally best avoided other than for base-load operation, where starts are limited and chemistry is well controlled. The use of full penetration welds can cause problems for some manufacturers if it is not their standard, however in real terms, there is little cost penalty in including this feature.



(a) (b)

Figure 9: Full (a) and partial (b) penetration welds (Courtesy of Power Technology).

Siemens [10] also prefer full penetration header welds, particularly if heavy cycling is required. They believe that partial penetration welds are a risk as acid can get trapped in the gaps following acid clean and cause corrosion. A different cleaning procedure is therefore required. The unfused area can also act as a site for corrosion fatigue cracking under cyclic operation (as mentioned above). Siemens prefer fully penetrated stub welds that are actually drilled afterwards to remove any protruding weld material. However, this is more expensive. At one project, special welding equipment was developed to ensure a consistent weld around its full circumference, despite the stub not being normal to the header. Siemens stated that if full penetration welding is not used then special requirements are imposed.

Innogy [12] has experienced corrosion fatigue failures where partial penetration welds have been used and the headers have not been heat-treated. This has resulted in header replacement. They are also aware of another project (not one of their own) where this resulted in 5% failure on the site hydro test when it had passed the same test in works. They have also seen inadequate provision for differential expansion, which resulted in stub to header weld failures. In this case the headers and tube-sheet in question were relatively close together and the header pulled apart the tube-sheet on expansion.

Nooter/Eriksen [13] standard for all header connections is for set-on branch connections with full penetration welds. This was upgraded in recent times due to defects found between 1992 and 1996. The revised weld procedures have proved successful. They have also moved to a straight through tube design (i.e. no bends in the stubs) where flexible operation is required as this is claimed to reduce bending moment to zero.