ABSTRACT

Combustion turbine combined cycle plants continue to increase their role in worldwide power generation. Advanced combined cycle plants provide:

- high efficiency, often in excess of 50%
- short project schedules
- reasonable cost with minimum environmental considerations

For reliable operation of these facilities, it is essential the Heat Recovery Steam Generator (HRSG) design adequately address issues to include:

- required load rangeability
- transient operation, particularly start-up and shutdown
- low life cycle costs through high availability

This paper will address the more detailed aspects of the design configuration of large HRSG units.

INTRODUCTION

Combustion turbine (CT) combined cycle plants continue to experience strong acceptance as the technology of choice for many power plants worldwide. CT combined cycle plants offer many advantages over competing technologies including:

- Low capital cost
- Short project schedules
- High thermal efficiency, often exceeding 50%
- Low environmental emissions
- High operating flexibility
- High availability, in excess of 90%

These combined cycle plants can also be designed for the future addition of coal gasification for fuel gas generation.

Large combustion turbine combined cycle plants in cyclic service present extreme operational transient conditions. These transient conditions are the result of a number of factors which may include:

- the fast starting and shutdown characteristics of combustion turbines,
- associated heating and cooling ramp rates of critical components in the heat recovery steam generator (HRSG),
- introduction of cold condensate into hot economizer headers of the HRSG upon a system restart after planned shutdowns such as overnight, and,
- the required warm-up time of steam cycle equipment.
These conditions or limits must be considered in the “Balance of Plant” component selection, particularly the HRSG. The evaluation of low cycle fatigue and creep are now beginning to gain the required design attention relative to life cycle analysis.

Balance of plant component selection difficulty is increased due to the increases in steam cycle operating pressures. Pressure increases result in thicker drum shells, turbine casings, pump casings, and other associated components. Special consideration must be given to the effect selected start-up and shutdown rates have on HRSG metal temperatures and even more importantly, temperature gradients. Thicker component cross sections result in longer and usually non-linear transient thermal responses, which may adversely affect the equipment life cycle. These temperature gradients may place constraints on allowable start-up or shutdown times to achieve acceptable component life. Each manufacturer should establish temperature and temperature gradient limits for the various components that will allow long-term continuous and reliable operation. These restrictions must be carefully considered when defining the combined cycle plant operating parameters.

The HRSG is a critical component in the CT combined cycle. HRSG technology has advanced significantly from the units of the 1960's. For reliable operation today, it is essential the HRSG selection process adequately address issues to include:

- Transient operation, particularly start-up and shutdown cycles
- Required load rangeability including effects of:
  - operation dispatch requirements and associated thermal cycling
  - peaking service
  - spinning reserve capability
- Impact of environmental equipment such as Selective Catalytic Reduction (SCR) systems for NOx removal
- Low life costs through high availability
- Other design requirements such as freeze protection and far field noise limits

**THERMAL DESIGN**

The design of a modern HRSG unit must, therefore, optimize, in accordance with the end user's needs, a combination of factors to include:

- Thermal efficiency
- Availability
- Operating flexibility, and
- Life cycle costs

Combined cycle HRSG thermal design for new facilities is basically a trade-off between:

- Amount of required heat transfer surface (capital investment)
- Cycle efficiency (operating and fuel cost)
- Duct burner fuel input (overall steam generation and power production for supplemental fired designs)

The HRSG configuration and performance is, therefore, strongly influenced by the plant load factor, electricity value, and overall rate of return criteria.

For applications with high load factors and electricity values, three pressure level HRSG configurations optimized for high thermal efficiency are the typical design choice. These HRSG units incorporate minimum pinch temperature differences and approach temperatures for each boiler level to maximize steam production and corresponding steam turbine power output. Utility repowering and other dispatchable applications may not require high efficiency HRSG designs due to factors such as limitations related to:

- Capacity and configuration of existing steam turbines
- existing thermal discharge and environmental permits
- Low or moderate load factors

Figure 1 illustrates a three pressure, reheat HRSG configuration typical of a high efficiency combined cycle plant. These reheat HRSG units can be characterized by:

- Three levels of steam generation for use in steam turbine power generation:
  - HP Steam: 1200-1800 psig/900-1025°F (8375-12512 kPa/482-552°C)
  - Combined Reheat and IP Steam: 250-350 psig/900-1025°F (1825-2500 kPa/482-552°C)
  - LP Steam: 15-100 psig/400-500°F (200-790 kPa/200-260°C)
- Low stack temperature during natural gas operation, typically below 199°F (93°C)
- Sliding pressure operation for load following applications
During light oil operation being used as standby fuel, HRSG operation is changed to a less efficient mode to avoid acid dewpoint corrosion problems. For applications with lower load factors, often a simpler, lower cost HRSG may be justified in form of a reduced efficiency (relative to power generation), two pressure HRSG design. Table 1 compares performance differences between two recent utility applications to illustrate three differences.

SCR INTEGRATION

With the growing concern for the environment, the reduction of nitrogen oxide emissions are receiving increased attention worldwide. For combined cycle plants, the integration of a SCR catalyst unit into the HRSG is gaining growing use. The operating temperature range (600-750°F/315-399°C) for conventional SCR catalyst normally requires splitting of the HP evaporator (or boiler) section to accommodate the SCR catalyst as shown in Figure 2. Although SCR systems have accumulated significant experience for natural gas operation - little experience

TABLE 1: PERFORMANCE COMPARISON
has been collected for operation with higher sulfur liquid fuels in
gas turbine combined cycle plants. One key to successful use of
SCR units with liquid fuels or other sulfur bearing fuels will be
avoiding corrosion of the heat transfer components downstream
of the SCR. Issues which need to be addressed for dual fuel
flexibility with SCR systems include:

1. **Water Washing Capability**: The horizontal gas flow
configuration of natural circulation HRSG design
provides an easy method of water washing of the highly
soluble ammonia compounds formed downstream of the
SCR when operating with a sulfur-bearing fuel. A
major deficiency of forced or assisted circulation HRSG
designs with their vertical gas path arrangement is the
lack of a procedure to water wash deposits from
downstream of heat transfer surface without damage to
the SCR catalyst.

2. **Quantity of Ammonia Compounds Formed**: The quantity of ammonia compounds formed in the HRSG
is related to the SO$_3$ present in the CT exhaust gas.
SO$_2$ to SO$_3$ conversion occurs:

   - In the gas turbine and HRSG boiler sections,
   - By reaction in a CO catalytic convertor, (if
     present),
   - By reaction in the SCR catalyst section

3. The CO convertor (being an oxidizing catalyst) when
   present, will contribute the largest portion of the SO$_3$
   formed.

   To minimize the quantity of ammonium compounds
   formed downstream of the SCR, one needs to consider
   a departure from the current practice of only measuring
   "excess or slip" ammonia in the HRSG outlet stack.
   An alternate measurement of "excess or slip" ammonia
   immediately downstream of the SCR would be effective
   in minimizing the quantity of NH$_3$ available for reaction
   with the SO$_3$. This approach would minimize the
   quantity of ammonium compounds formed and the NH$_3$
in the outlet stack gas stream. The deficiency
   associated with the measurement only of NH$_3$ in the
   outlet stack is that NH$_3$ is then measured only after the
   NH$_3$-SO$_3$ reactions have occurred.

   If NH$_3$ is only analyzed in the HRSG outlet stack, one
   must then consider the best way to effectively produce
   the least corrosive ammonium compounds. For most
cases, this is achieved by operation near maximum
ammonia slip levels to promote formation of
ammonium sulfate.

   Principally, either ammonium sulfate (NH$_4$)$_2$SO$_4$
or ammonium bisulfate NH$_4$HSO$_4$ will be formed by the
reaction of SO$_3$ and excess NH$_3$ downstream of the
SCR catalyst. In general, ammonium sulfate is
considerably less corrosive than ammonium bisulfite.
Figure 3 illustrates the equilibrium distribution of
Minimizing Corrosion: To minimize corrosion, one must consider first, producing the least corrosive combination of ammonia compounds, and, secondly, incorporating operating procedures to avoid corrosion during changes in HRSG operation. Important operating options relative to avoiding corrosion during extended shutdown include either immediate HRSG cooldown and water washing, or maintaining the HRSG in a warm, standby condition. For short-term shutdowns it is important to maintain the HRSG in a warm standby condition by use of stack dampers and standby heaters, as needed. Shutdown and isolation of the HRSG after oil firing should be avoided if the HRSG is allowed to cool down. This sequence should be avoided because of the higher sulfur content in the flue gas and the potential for acid dewpoint corrosion upon cool down. When changing from oil to gas fuel firing consider water washing of ammonium compounds from the system after fuel switchover, or avoiding operation of heat transfer components below the water dewpoint until a water wash stop has been completed.

CYCLIC SERVICE

In recent years, the combined cycle plants in the U.S. are shifting from base load applications to more dispatchable and peaking service. These different modes of cyclic service impose significantly more severe operating conditions on the HRSG and remainder of the combined cycle plant. As with any boiler, start-up and shutdown represent operations requiring the most detailed considerations. For cyclic operation, several areas which require careful review include:

- **Water Chemistry**
  Excursions can significantly impact the HRSG operating life and maintenance costs. Detailed operating procedures should be developed to minimize and eliminate these excursions, particularly during start-up.

- **Welding**
  All full-strength welded construction provides better availability when compared to designs incorporating rolled or rolled and seal welded construction for the evaporator components. Weld details need to be fully evaluated for cyclic operating HRSG units.

- **Steam Drum Size**
  Adequate steam drum size needs to be evaluated to accommodate expected load following and cyclic service requirements. Regardless of HRSG design philosophy, for either natural or forced/assisted circulation HRSG units, the steam drum sizing is primarily dictated by external operating factors and transients. Be sure adequate steam drum size is provided.

- **Supplemental Firing**
  Supplemental firing through the use of duct burners should be considered where either an improvement in steam supply reliability or an increase in peak steam generating capacity is a facility need. Multiple gas turbine/HRSG installations can use duct burners to maintain overall steam production when one gas turbine train is shutdown. A typical natural gas duct burner is pictured in Figure 4.

- **Restart Time**
  Use of stack isolation dampers or other means to minimize HRSG cooldown rates during short shutdowns (such as overnight periods) can help minimize restart time. Measures to safely reduce restart time need thorough evaluation.

- **HRSG Metal Temperature Heatup and Cooldown Rates**
  Temperature gradients generated during start-up and shutdown are an important parameter in the evaluation
In cyclic service applications, natural circulation HRSG technology in the United States has demonstrated its ability to effectively handle rapid load changes and wide operating ranges. The use of vertical heat transfer tubes and elimination of recirculation pumps for natural circulation HRSG designs eliminates many of the concerns associated with flow separation sensitivity, erosion and other concerns associated with the horizontal tube configurations found in forced or assisted circulation HRSG units. Figure 5 provides an aerial photograph of a New England Independent Power Production facility which includes:

- Four 84 MW gas turbines
- Four three-pressure, non-reheat HRSG units
- Two condensing steam turbines
- SCR systems using aqueous ammonia
- Extensive sound attenuation
- Duct burners for peaking needs

This power generation facility is designed for dispatchable operation and load capacities of 60-100% of the electrical output.

START-UP CONSIDERATIONS

As noted previously, cold and warm start-ups will normally impose the most severe conditions for any boiler operation. HRSG start-up considerations in many respects clearly resemble conventional boilers (except HRSG start-up times are much shorter). Factors of significant importance for evaluation during any start-up analysis include:
1. **Temperature lag of HP steam drum shell.** For large combined cycle HRSG units with HP steam pressures of 1500 psig (10,443 kPa) or greater, the temperature difference between the inside of the steam drum and outside drum wall is an important constraint in terms of relative start-up rate. Any start-up procedure must properly account for and minimize "stress intensification" which occurs as a result of this metal temperature lag through the HP steam drum wall. Figure 6 illustrates a typical stress curve as a function of start-up rate and resulting steam drum metal temperature.

![Typical HRSG High Pressure Start Up Ramp](image)

**FIGURE 6: START-UP TIME AFTER CT GAS FLOW**

2. **Metal temperature gradients and maximum temperatures.** Maximum metal temperature excursions are typically an important design and start-up consideration for reheater components. The metal temperature gradients generated during start-up and shutdown are an important variable to determine cumulative damage factors for low cycle fatigue analysis. An important issue is the magnitude and non-linearity of the temperature gradients and not necessarily the temperature range where they occur. For example, the potential for header cracking should be analyzed for economizer inlet headers which operate in cyclic service.

3. **HRSG/steam turbine arrangement.** Multiple HRSG/single steam turbine arrangements can have an impact on HRSG operating range and the sequencing of plant start-up.

4. **Required plant operating modes.** The need for simple cycle operation through use of bypass diverters, steam bypass capability or dry operation of heat transfer components should also be considered.

In general, all HRSG technologies provide similar start-up times for large, high efficiency combined cycle plants. This is due in great part to the fact all designs must address the same type of mechanical design constraints. However, natural circulation HRSG designs offer a number of advantages compared to forced/assisted circulation units relative to start-up. Particularly for warm starts, the vertical readily-drainable superheater/reheater arrangement in natural circulation designs eliminates concerns over condensate carryover and impingement on hot headers/piping as possible in horizontal tube superheaters/reheaters of forced/assisted circulation designs. Natural circulation designs also eliminate the possible effects of transient flow separation by use of vertical evaporator tubes and provide a self-balancing, responsive evaporator design.

With the trend towards quality in worldwide industry, the issues of equipment availability and lowest life cycle costs are moving to the forefront of equipment selection for combined cycle power generation. Higher availability provides the capability of keeping the lowest cost producers on-line while deferring a portion of new capacity.

The importance of HRSG availability is illustrated in Figure 7, which shows the relative source of unscheduled outage hours as a function of the major combined cycle components. Although as expected, the gas turbine is the leading contributor to unscheduled outages, the HRSG is an important element in achieving high plant availability.

![Contribution to Availability Loss](image)

**FIGURE 7: UNSCHEDULED OUTAGE CAUSES**

**CONCLUSION**

The proper selection of HRSG technology and design integration of the overall plant operating requirements are key factors to assure high plant availabilities. The choice of HRSG technology is, not only a decision between natural circulation or forced/assisted circulation, but also an issue of the strong advantages for the use of vertical heat transfer tubes rather than...
horizontal tubes. It is also of paramount importance the end user provide a thorough definition of the intended operating modes for the facility during initial design stages.

REFERENCES


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