7. Heat Recovery Steam Generators

- Topping cycle
- Bottoming cycle

Diagram showing the processes involved in heat recovery steam generators, including combustion (heat in) and various temperature and entropy (S) levels.
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction to HRSG</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Type of HRSGs (Horizontal vs. Vertical)</td>
<td>31</td>
</tr>
<tr>
<td>3</td>
<td>Investigation of HRSG Design Concepts</td>
<td>37</td>
</tr>
<tr>
<td>4</td>
<td>Once-through HRSGs</td>
<td>41</td>
</tr>
<tr>
<td>5</td>
<td>HRSG Performance</td>
<td>52</td>
</tr>
<tr>
<td>6</td>
<td>SCR</td>
<td>91</td>
</tr>
</tbody>
</table>
A Typical HRSG [GE]
HRSG Configuration

[ Horizontal Design ]

[ Vertical Design ]
HRSG Configuration

Combined Cycle Utility HRSG

HRSG Configuration Diagram:
- H.P. Steam Outlet
- H.P. Vent Silencer
- H.P. Steam Drum
- L.P. Steam Drum with Integral Deaerator
- L.P. Vent Silencer
- Stack
- Duct Burner
- Distribution Grid
- C.O. Catalyst
- Observation Port
- Injection Grid
- S.C.R.
- H.P. Evaporator
- H.P. Economizer
- L.P. Superheater
- L.P. Evaporator
- L.P. Superheater Outlet
- DA Pre-Heater

Thermal Fluid Techniques in Plants
7. HRSGs
HRSGs are used to convert gas turbine exhaust into useful steam for bottoming cycle.
Bottoming Cycle (Rankine Cycle)

1. Feed water heating in economizer
2. Compression of water by pumps
3. Vaporization in evaporator
4. Expansion of steam in steam turbine
5. Superheating in superheater
6. Condensation of steam
7. Steam dome
A common application of an HRSG is in a combined cycle power station, where hot exhaust from a gas turbine is fed to an HRSG to generate steam which in turn drives a steam turbine. This combination produces electricity more efficiently than either the gas turbine or steam turbine alone.

The HRSG is also an important component in cogeneration plants. Cogeneration plants typically have a higher overall efficiency in comparison to a combined cycle plant because there is no energy loss associated with the steam turbine.

Modular HRSGs can be categorized by a number of ways such as direction of exhaust gases flow or number of pressure levels.

Based on the flow of exhaust gases, HRSGs are categorized into vertical and horizontal types. In horizontal type HRSGs, exhaust gas flows horizontally over vertical tubes whereas in vertical type HRSGs, exhaust gas flow vertically over horizontal tubes.

Based on pressure levels, HRSGs can be categorized into single pressure and multi pressure. Single pressure HRSGs have only one steam drum and steam is generated at single pressure level whereas multi pressure HRSGs employ two (double pressure) or three (triple pressure) steam drums. As such triple pressure HRSGs consist of three sections: an LP (low pressure) section, a reheat/IP (intermediate pressure) section, and an HP (high pressure) section. Each section has a steam drum and an evaporator section where water is converted to steam. This steam past the saturation point then passes through superheaters to raise the temperature further.
Some HRSGs include supplemental, or duct firing. These additional burners provide additional energy to the HRSG, which produces more steam and hence increases the output of the steam turbine. Generally, duct firing provides electrical output at lower capital cost. It is therefore often utilized for peaking operations.

HRSGs can also have diverter dampers to regulate in the inlet flow into the HRSG. This allows the gas turbine to continue to operate when there is no steam demand or if the HRSG needs to be taken offline.

Emission controls may also be located in the HRSG. Some may contain a SCR (Selective Catalytic Reduction) system to reduce nitrogen oxides (a large contributor to the formation of smog and acid rain) and/or a catalyst to remove carbon monoxide.

The inclusion of an SCR dramatically affects the layout of the HRSG. NO\textsubscript{x} catalyst performs best in temperatures between 650 °F (340 °C) and 750 °F (400 °C). This usually means that the evaporator section of the HRSG will have to be split and the SCR placed in between the two sections.

Some low temperature NO\textsubscript{x} catalysts have recently come to market that allows for the SCR to be placed between the Evaporator and Economizer sections (350 °F - 500 °F (175 °C - 260 °C)).
To reduce the velocity of gas turbine exhaust gas, the inlet duct of HRSG is diffuser type in both the horizontal and vertical HRSGs, otherwise pressure drop through the HRSG would be excessive.
The function of the HRSG is to convert the thermal energy included in the gas turbine exhaust gas into steam.

After heating in the economizer, water enters the drum at slightly subcooled conditions.

From the drum, it is circulated to the evaporator and returns to the drum as a water/steam mixture where water and steam are separated.

Saturated steam leaves the drum and is forwarded to the superheater where it is exposed to the maximum heat exchange temperature of the hottest exhaust gas.

Blowdown is used to control solids build up in the steam separation drum.
D-frame is very popular for HRSG units recovering heat from small gas turbines and diesel engines.

It is a very compact design and can be shipped totally assembled.

O-frame
Evaporator Configurations [2/3]

- A-frame was popular for services with a large amount of ash, since the center area between the lower drums could be configured as a hopper to collect and remove solid particles.

- I-frame has become the most popular.

- There are numerous variations of this design where tube bundles may contain one, two, or three rows of tubes per header.
Evaporator Configurations [3/3]

Horizontal Tube

Steam Outlet

Steam Drum

Feedwater

Flue Gas Outlet

Riser

Downcomer

Circulation Pump

Forced Circulation Evaporator

Horizontal Tube Evaporator

Flue Gas Outlet

Flue Gas Inlet

Steam Outlet
Superheater Configurations

- Superheater designs would normally follow along with the evaporator type that is being used.

- Three basic superheater designs are shown above, horizontal tube, vertical tube, and I-frame.

- The horizontal tube design would normally be used for the D-frame evaporator if gas flow is vertical up at the outlet.

- This horizontal design would be expected to be used also on a horizontal evaporator design.

- The vertical tube design would generally be used with the A-frame or O-frame evaporator and with the D-frame if the gas exits horizontally.

- The I-frame superheater would be used with the I-frame evaporator, but may also be used with the other evaporator designs.
HRSG Header
The tube wall temperature tend to run quite close to the water and steam side temperatures because water side and steam side heat transfer coefficients are much higher.

Because flue gas side heat transfer rates are poor, tubes must be of small diameter, with tight spacing and be of the finned type to provide sufficient heat transfer area.

The only section of the HRSG which might not use finned tubes is the HP superheater where there might be a possibility of oxidation of the finning. (GE uses finned tube superheater)

High efficiency finning is desirable to reduce the size of the HRSG.

Fin material with a high conductivity is desirable.

Fin shape and pitch are also critical due to the need to prevent excessive pressure drop through the HRSG, otherwise gas turbine output will suffer. (the overall pressure drop across the whole HRSG should not be much more than 25 mbar)

Normally, the fin density is 5 to 7 fins per inch when natural gas or No. 2 oil use as fuels.

When the heavier fuels are used, the fin density is reduced to 3 to 4 fins per inch due to fouling.

A potential problem with finning, where different types of materials are employed, is expansion differences leading to thermal fatigue.

<table>
<thead>
<tr>
<th></th>
<th>Flue Gas</th>
<th>Water in Economizer</th>
<th>Water in Evaporator</th>
<th>HP Steam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical HRSG Heat Transfer Coefficient, W/m²·K</td>
<td>50</td>
<td>500</td>
<td>2500~10000</td>
<td>1000</td>
</tr>
</tbody>
</table>
An exhaust bypass stack is a prerequisite for phased installation of a combined cycle plant – one in which the gas turbine runs in simple-cycle operation before the steam cycle is connected.

However, this feature is less important in modern gas turbines because
- the design is expensive with gas turbine exhaust temperatures of 600°C and above.
- if the damper fails, the entire plant must be shut down.
- an exhaust damper has leakage losses with resultant losses in output and efficiency.
- the associated cost are significant.
HRSGs are gas-to-water heat exchanger systems that extract energy from the gas turbine exhaust gases to generate steam. That is, HRSGs are used to convert the energy contained in the gas turbine exhaust gas into useful steam for the bottoming portion of the combined cycle.

The steam can be generated over a wide range of pressures and temperatures for a variety of uses such as process steam, district heating, or driving steam turbine for power generation.

Many HRSG configurations may be considered when designing a combined cycle.

In many combined cycle applications, steam is generated at several pressures to make the most advantageous use of the energy available.

Reheat cycles are also feasible because of the higher exhaust gas temperatures available from advanced gas turbine technologies, such as advanced metallurgy, improved cooling technologies, and increased pressure ratio.

More steam pressure sections can be designed into the HRSG, making it more complicated and more expensive but with improved recovery of the exhaust heat.

The steam cycle design depends on the economics of the application and the project specific requirements.
The maximum temperature and pressure of the steam generated in an HRSG are governed by the gas turbine EGT (assuming that the HRSG is not supplementary fired).

The higher the EGTs, the higher steam temperatures and pressures. In the combined cycle units, the higher steam temperatures/pressure, the lower heat rates.

This is the reason why heavy duty gas turbines are more commonly used in combined cycle units.

Normally, aeroderivative gas turbines have EGTs in the range of 800 to 950°F. By contrast, current heavy duty gas turbines generally have EGTs of 950 to 1,100°F.

Exhaust heat, thermal energy contained in the exhaust gas flow, is the product of the exhaust gas flow and the exhaust gas enthalpy.

Exhaust heat can be estimated by calculating a heat balance around the gas turbine. By this method, exhaust heat is calculated as the heat input from fuel, inlet air, and injection water/steam, minus the thermal equivalent of the generator output and miscellaneous losses (including generator losses and turbine/generator bearing losses).

Some manufacturers do not guarantee exhaust flow or temperature, but they do guarantee exhaust heat. This guarantee is significant for heat recovery applications only.
Steam Cycle

Three Pressure Reheat Cycle

- Fuel
- Gas turbine
- Air
- Hot reheat steam
- Main steam
- Cold reheat steam
- IP steam
- LP steam
- Steam turbine
- Condenser
- Condensate pump
- Heat recovery steam generator
- Steam
- Water
- Fuel
- Air
A Typical HRSG Requirements

Pressure drop on the gas side should be low → diffuser type inlet duct

Low-temperature corrosion must be prevented → stack gas temp. > 80°C

Heat recovery must be high → finned tubes

The permissible pressure gradient during startup must be steep → once-through HRSG
Pinch point can be optimized by evaluating the equipment cost and operating cost. Small pinch point requires large heating surface and results in higher cycle efficiency.

**PP** = Pinch point in boiler

**ATS** = Approach temperature in superheater

**ATE** = Approach temperature in economizer
The **pinch point** is defined as the difference between the exhaust gas temperature leaving the evaporator section and the saturation temperature of the steam.

The lower the pinch point, the more the heat recovered, but this requires larger heat transfer surface area and, consequently, increases the pressure drop in HRSG and cost. Therefore, the pinch point selection can greatly affect the physical size of the HRSG.

Moreover, excessively low pinch points can mean inadequate steam production if the exhaust gas is low in energy (low mass flow or low EGT).

Pinch points are typically between 8 and 15°C (14 to 27°F), depending on the economic parameters of the plant.

The **approach temperature** is the difference between the saturation temperature of the steam and the water temperature at the economizer outlet.

The smaller approach temperature, the better heat utilization, but increased heat transfer surfaces and cost. Conservatively, high approach temperatures ensure that no steam generation occurs in the economizer.

Typically, approach temperatures are in the range of 5 to 12°C (9 to 22°F), helps to avoid evaporation in the economizer at off-design conditions.

For a drum-type HRSG, a lower limit is set on the approach temperature to minimize steaming in the economizers for off-design points. Normally, a lower limit is 5°C.
Pinch Point & Approach Temperature [3/6]

Three Pressure Reheat Cycle

Energy transfer, MW

Temperature, °C

0 100 200 300 400 500 600 700

0 50 100 150 200 240

Exhaust Gas

HP/Economizer/IP Superheater

IP Evaporator

HP/Economizer/IP Superheater

LP Evaporator

HP/Economizer/IP/LP Economizer

HP Superheater/Reheater

HP Evaporator
The surface of the evaporator increases exponentially as the pinch point decreases, whereas the increase in steam generation is linear.

For this reason, the pinch point selected is a critical factor in determining the heat transfer surface.

The lower the pinch point, the higher steam turbine output.

In order to reduce the pinch point, the surface of heat exchanger increases as the pinch point becomes zero.

HRSG having higher efficiency has the pinch point of 8~14K, but the pinch point of lower efficiency HRSG can be higher, 15~25K.

Effect of pinch point on relative steam turbine power output and relative HRSG heating surface (relative pinch point = 12K)
The flue gas leaving the evaporator enters into economizer.

If same ΔT between EGT and the water maintained, boiling would occur at the exit of economizer.

This would result in a “steaming economizer” with the possibility of the flow being blocked.

It is clear that if the water flow is blocked, all the water in the economizer would begin to turn into steam.

In this case, tubes would subject to a overheating, however, the main problems would be water hammering and tube-to-tube differential expansion.

Accordingly, the outlet water temperature in the economizer should be keep several degrees below the saturation temperature.

This can be done by cutting down the economizer heating surfaces and imposing part of the LP superheater between the HP evaporator and economizer.

The approach temperature might be 4°C, so this when added to a pinch point temperature of 8°C, would give an overall temperature differential of 12°C, greatly reducing the risks of boiling.
Current Requirements for HRSGs

- Three-pressure single reheat.
- High pressure level – the existing economic optimum is 130 bar, although the thermal optimum lies well above (180 bar) for three-pressure reheat HRSG.
- Economic optimum steam temperature is 565°C (1050°F), and above 600°C are available.
- Steam output – defined by the economic determination of the pinch point (6 to 8K) at the HP evaporator and the approach temperature at the economizer (2 to 4K), typically 74 kg/s without supplementary firing and 120 kg/s with supplementary firing.
- Finned tubes have been employed to keep the pinch point as low as possible.
- Feedwater (condensate) inlet temperature with respect to type of fuel used, above 50°C for natural gas with no sulfur content, and above 110°C for light distillate oil to ensure operation above acid or water dew point.
- Stack temperature of minimum 80°C.
- The purity of steam entering superheater is 99.9%.
- HRSG flue gas draft loss is approximately 25 mbar, 35 mbar if catalysts are required.
- The key components, those performance is critical, are high pressure steam piping headers and superheater tubes. All these components have to meet creep strength requirements, but thermal fatigue resistance and weldability are also important.
CCPP Arrangement

Single-Shaft CCPP (107FA)  
1-on-1 Configuration

Multi-Shaft CCPP (207FA)  
2-on-1 Configuration
The horizontal HRSGs are typically known as natural-circulation HRSGs because circulation through the evaporator takes place entirely by gravity, based on the density difference of water and boiling water mixtures.

The heat transfer tubes are vertical, and self-supporting on the ground.

Today, the horizontal HRSGs are preferred.
The vertical HRSGs were known as forced-circulation HRSGs because of the use of circulation pumps to provide positive circulation of boiler water through the evaporator sections.

However, the vertical HRSG no longer requires forced-circulation pumps, not even for start up, because the design of evaporator was improved.
## Horizontal vs. Vertical HRSG [1/2]

<table>
<thead>
<tr>
<th></th>
<th>Horizontal</th>
<th>Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Output and efficiency</strong></td>
<td>Equal</td>
<td></td>
</tr>
<tr>
<td><strong>Surface area for equal output</strong></td>
<td>Similar, except the reheater and superheater section which might require slightly more heating surface area mainly due to less effective flue gas distribution</td>
<td></td>
</tr>
<tr>
<td><strong>Plan area for equal output</strong></td>
<td>Up to 30% more, mainly due to the opening angle of the inlet duct and the stack, and if supplementary firing systems, SCRs, CO catalysts, etc. are required</td>
<td></td>
</tr>
<tr>
<td><strong>Emission control</strong></td>
<td>Requires more HRSG length</td>
<td>Requires more HRSG height, cleaning of downstream fouled surfaces has to be carried out carefully, not to poison the catalyst</td>
</tr>
<tr>
<td><strong>Supplementary firing</strong></td>
<td>Readily installed in the HRSG inlet duct or within the boiler surface area</td>
<td>Readily installed in the HRSG inlet duct, difficult to install within the boiler surface area</td>
</tr>
<tr>
<td><strong>HRSG enclosure / Boiler house</strong></td>
<td>Free standing, self supporting enclosure</td>
<td>Attached to and supported by the HRSG structure, light enclosure</td>
</tr>
<tr>
<td><strong>Circulation</strong></td>
<td>Natural</td>
<td>Forced (Natural type is available)</td>
</tr>
</tbody>
</table>
## Horizontal vs. Vertical HRSG

<table>
<thead>
<tr>
<th></th>
<th>Horizontal</th>
<th>Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Modularized</strong></td>
<td>Typical</td>
<td></td>
</tr>
<tr>
<td><strong>Erection area,</strong></td>
<td>Equal, though more crane area is required for pressure parts mounting which</td>
<td>Equal, though heavy transportation (120 tons) may be required on site,</td>
</tr>
<tr>
<td><strong>prefabrication on</strong></td>
<td>typically lasts 5 weeks for large GT CCPP</td>
<td>typical time needed for boiler surface mounting: 3 weeks for large GT</td>
</tr>
<tr>
<td><strong>site</strong></td>
<td></td>
<td>CCPP</td>
</tr>
<tr>
<td><strong>Cycling</strong></td>
<td>State of the art design experiences severe cycling problems at superheater</td>
<td>Less vulnerable if properly designed</td>
</tr>
<tr>
<td></td>
<td>and reheater stages, design considerations cost effective</td>
<td></td>
</tr>
<tr>
<td><strong>HRSG cost (ready to</strong></td>
<td></td>
<td>Equal</td>
</tr>
<tr>
<td><strong>run)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>O&amp;M cost</strong></td>
<td>Higher number of and larger textile expansion joints, boiler surface</td>
<td>Replacement and blocking of tubes possible</td>
</tr>
<tr>
<td></td>
<td>replacements not possible, repair by blocking of tubes, cost effective</td>
<td></td>
</tr>
<tr>
<td><strong>Regular inspections</strong></td>
<td>Inspection of headers and surfaces is not easy</td>
<td>Inspection of header and surface can be performed easily because of easy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>accessing through manholes</td>
</tr>
</tbody>
</table>
3. Investigation of HRSG Design Concepts
HRSG should absorb the rapid thermal expansion caused by quick startup of the gas turbine.

The main constraint of the loading gradient is often governed by the drum.

The walls of the drum should be as thin as possible for shorter startup times.

However, advanced gas turbines have higher EGT than older ones, therefore, higher steam pressures are more attractive and this results in longer startup times.

Once-through HRSGs eliminate the thick high pressure drum, which is the main obstacle for shorter startup times in high pressure HRSGs.

Another concern is the volumetric change in the evaporator during startup.

The large difference in specific volume between steam and water at low and intermediate pressures cause large amount of water to be expelled from the evaporator at the onset of the evaporation process.

If the drum cannot accommodate most of this water, a large amount of water would be lost through emergency drain of the drum during every startup, or an undesired emergency trip of the unit would be required to prevent water carryover into the steam system.
HRSG Design [2/3]

- HRSG is operated in sliding-pressure mode to improve part load efficiency.
- In a system with two gas turbines and two HRSGs feeding a common steam turbine, half-load of the whole power station can be accomplished with only one of the gas turbines running at full load.
- In sliding-pressure mode, the steam pressure is at 50% of the pressure at full load.
- The steam volumes in the evaporator, superheater, and steam lines of the HRSG in operation are doubled.
- HRSG flue gas draft losses: approximately 25 mbar, 35 mbar if catalysts are required.
- Stack temperature: $\geq 80^\circ$C (to avoid corrosion due to corrosion elements having lower dew points).
- Rankine cycle: triple pressure single reheat.

- Once-through boilers are subject to FAC (Flow Assisted Corrosion).
- In order to avoid to deposition of solids in the evaporator, once-through boilers have to use as AVT (All Volatile Treatment).
- Tube surfaces are then susceptible to erosion by two phase, high velocities, leading to FAC, as can occur in the low pressure units of the HRSG.
### Key Factor

<table>
<thead>
<tr>
<th>Key Factor</th>
<th>Unit</th>
<th>Value</th>
<th>Limiting Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main steam temp.</td>
<td>°C</td>
<td>567</td>
<td>Steam turbine</td>
</tr>
<tr>
<td>Operating steam pressure</td>
<td>Bar</td>
<td>170</td>
<td>Start-up time &lt; 60 min</td>
</tr>
<tr>
<td>HP evaporator pinch points</td>
<td>K</td>
<td>6</td>
<td>Economics, accuracy of thermal design</td>
</tr>
<tr>
<td>HP economizer approach point</td>
<td>K</td>
<td>3 (0)</td>
<td>Horizontal (vertical, due to the height benefit)</td>
</tr>
<tr>
<td>HP superheated steam vel.</td>
<td>m/s</td>
<td>70</td>
<td>Sound, economics</td>
</tr>
<tr>
<td>HP saturated steam vel.</td>
<td>m/s</td>
<td>20</td>
<td>Erosion, corrosion, economics</td>
</tr>
<tr>
<td>Two-phase velocity</td>
<td>m/s</td>
<td>10</td>
<td>FAC, economics</td>
</tr>
<tr>
<td>Water velocity</td>
<td>m/s</td>
<td>2-4</td>
<td>FAC, economics</td>
</tr>
<tr>
<td>Noise</td>
<td>dbA</td>
<td>90</td>
<td>GT emission, sound enclosure</td>
</tr>
<tr>
<td>Supplementary firing</td>
<td>%</td>
<td>+50</td>
<td>Flow distribution and properties, flue gas temperature in case of the vertical type HRSG</td>
</tr>
<tr>
<td>Cold starts</td>
<td>-</td>
<td>Weekly</td>
<td>Gradients of thick walled components</td>
</tr>
<tr>
<td>Cycling rate</td>
<td>MW/ min</td>
<td>None</td>
<td>GT load changes</td>
</tr>
</tbody>
</table>

FAC: Flow Assisted Corrosion
<table>
<thead>
<tr>
<th></th>
<th>Description</th>
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<td>SCR</td>
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</tbody>
</table>
In a once-through steam generator, the economizer, evaporator, and superheaters are basically one tube, eliminating the drum and circulating pumps.

This design has advantages at higher steam pressure because the drum does not impose limits during startups and load changes.

Both horizontal and vertical HRSGs can be built with once-through type.

There are two primary concerns in terms of HRSG design for fast start:

1. Component failure
   a. High steam conditions require thick component walls
   b. Fast start-up results in high thermal gradients in the walls
   c. Component fail after fatigue life is consumed

2. Drum level control
   a. Gas turbine start-up produces rapid boiling in the evaporator
   b. If water level in the drum rises to the separators, water carry over into the superheater may occur
   c. The typical response to this is to either trip or slow gas turbine load ramp

Once-through HRSG eliminates the thick wall HP drum and allows an unrestricted gas turbine start-up
Drum Type vs. Once-through

**Drum-type HRSG**
- Thick-walled HP drum limits operating flexibility due to high thermal stresses
- Natural circulation principle

**BENSON® Once-Through**
- Eliminates HP drum, thereby enhancing operating flexibility
- Maintains natural circulation flow characteristics

Exhaust gas flow

Superheater

Evaporator

Separator

Superheater

Evaporator
The term Benson boiler is a design that is capable of operating on a variable pressure ramp and is capable of start up from zero pressure at initial firing and up to supercritical pressure at higher load.

Benson boiler has a better operational flexibility.

Question: Why fast startup is important in terms of emission?
There has also been a debate over the years whether the once-through HRSG technology should be better off than drum boilers in terms of cycling.

| GE     | Detailed transient analysis showed that the majority of fatigue life consumption occurs at the hottest high pressure superheater and reheater during fast gas turbine loading, regardless of whether the HRSG uses high pressure drum or once through technology.  
|        | The HRSG stack is equipped with an automatic damper that closes upon plant shutdown to reduce HRSG heat loss and the time required for next plant start-up, as well as reduce the cyclic stress of the start. |

| Siemens | Once-through HRSG eliminates the thick wall HP drum and allows an unrestricted gas turbine start-up  
|         | a. gas turbine start-up produces rapid boiling in the evaporator  
|         | b. if water level in the drum rises to the separators, water carry over into the superheater may occur  
|         | c. the typical response to this is to either trip or slow gas turbine load ramp |

It is hard to conclude that which one is better in terms of operating flexibility.
Most once-through designs for CCPP are subcritical.

Steam bubbles are generated in the evaporator.

During base load operation the steam existing the evaporator section will have a mild degree of superheat and should enter the superheater in a completely dry condition.

During startup, the steam from the evaporator will not only be saturated but also will superheated.

This needs to be removed in a separator.
Once-through HRSG

Steam separator
- Replaces internal drum separators

Surge bottle
- Manages evaporator swell during start-up
Advanced HRSGs are of a three-pressure reheat configuration with high-pressure section in a once-through design, and intermediate- and low-pressure sections as drum-type evaporators.
Water consumption in the water/steam cycle can be reduced by the employment of once-through HRSGs.

- In a drum type HRSG, some amount of water need to be blown down out of the drums to achieve the required steam purity.
- This water needs to be replaced by demineralized water.
- The once-through HRSG, which does not have drums, the cleaning is done by a condensate polishing plant. Therefore, the amount of water wasted is much less.
Once-through HRSG

This cycle has no feedwater tank, so deaeration takes place in the condenser.

Flow diagram of a high-pressure reheat cycle with a HP once-through HRSG and a drum-type LP section.
Once-through HRSG

국내 설치 현황 (Units): GS EPS, 당진 (1); SK E&S, 장문 (4); 포스코에너지 (3); 대구그린파워 (1); S-Power, 안산 (2); 남부발전, 안동 (1)
1. Introduction to HRSG
2. Type of HRSGs (Horizontal vs. Vertical)
3. Investigation of HRSG Design Concepts
4. Once-through HRSGs
5. HRSG Performance
6. SCR
Energy Flow Diagram

Three Pressure Reheat Cycle

Fuel Energy
100%

GT
37.6%

Loss
0.5%

ST
21.7%

Condenser
31.0%

Stack
8.6%

Loss in HRSG
0.3%
The power output and efficiency of the gas turbine is strongly affected by its backpressure.

Therefore, the pressure loss occurred in the flue gas side of HRSG should be minimized.

Lower pressure losses can get through lower flue gas velocities around the tube bundle leading to larger HRSG surface.

Typical pressure losses on the flue gas side are between 25 to 30 mbar.
EGT increases with TIT. The HRSG efficiency increases with EGT.

Figure 5–13 Steam turbine output and HRSG efficiency versus gas turbine exhaust temperature for a single-pressure cycle
Low Temperature Corrosion

- The corrosion, caused by water vapor and sulfuric acid in the exhaust gas, occurs whenever the gas is cooled below the acid dew point of these vapors.

- All surfaces that come into contact with the exhaust must be at a temperature above or slightly below the sulfuric acid dew point.

- The tube surface temperature on the exhaust gas side is approximately the same as the water or steam temperature because the heat transfer on the exhaust gas side is inferior to that on the steam or water side.

- Therefore, if tubes are to be protected against an attack of low temperature corrosion, feedwater temperature must remain approximately as high as the acid dew point.

- If the feedwater temperature is too low, a high stack temperature for the exhaust gases does not helpful.

- Low temperature corrosion can also occur even when fuel containing no sulfur if the temperature drops below the water dew point, that is between 40 and 45°C.

- In case of gas fuel with very low sulfur content (<3ppm sulfur in fuel), a feedwater temperature is around 60°C.

- Oil tends to have higher sulfur, resulting in feedwater temperatures of around 120 to 160°C.

- For high sulfur fuels (normally backup fuels), the economizer is bypassed and the water enters directly into the low-pressure drum.

- Sulfur oxides in combination with excess air raise the dew point temperature very significantly, producing liquid sulfuric acid at well above the dew point temperature. Gas turbine exhaust ducts and HRSGs can be quickly corroded in this way.
**Acid Dew Point of Flue Gas**

Maximum flue gas dew point versus percent $\text{H}_2\text{S}$ in typical gas fuels

<table>
<thead>
<tr>
<th>% Excess Air</th>
<th>Dew Point ($^\circ\text{F}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>138</td>
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<tr>
<td>10</td>
<td>135</td>
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<tr>
<td>20</td>
<td>131</td>
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</table>

Dew Points for Sulfur Free Flue Gas

Excess Air Range 5~20%

Graph showing the relationship between weight percent $\text{H}_2\text{S}$ in fuel gas and dew point temperature. The graph indicates an increasing trend with higher $\text{H}_2\text{S}$ concentrations.
Acid Dew Point of Flue Gas

Maximum flue gas dew point versus percent sulfur in typical oil fuels

Dew Points for Sulfur Free Flue Gas

<table>
<thead>
<tr>
<th>% Excess Air</th>
<th>Dew Point (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>116</td>
</tr>
<tr>
<td>15</td>
<td>112</td>
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<td>30</td>
<td>108</td>
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</table>

Excess Air Range 10~30%
Three Pressure Reheat Cycle

1. Dual HP superheater/reheater
2, 4, 6. HP, IP, LP evaporators
3. HP economizer/IP superheater
5, 7. Dual HP/IP economizer
8, 9, 10. HP, IP, LP drums
11. HP steam turbine
12. IP/LP steam turbine
13, 14, 15. HP, IP, LP steam bypasses
16. Condenser
17. Condensate pump
18. Deaerator
19, 20. IP, HP feedwater pumps

Natural gas
Heat Balance

Single Pressure

Gross Power Output = 272.8 MW
Gross Efficiency (LHV) = 57.7 %
Single Pressure (GE)

- Single pressure system does not produce the highest efficiency.

- Economical election:
  - when fuel is inexpensive
  - when applied in peaking type service
  - when burning ash-bearing fuel with high sulfur content

- The HRSG stack gas temperature with this steam cycle is approximately 171°C.
Heat Balance

Two Pressure

Gross Power Output = 277 MW
Gross Efficiency (LHV) = 58.6%
Three Pressure Non-reheat Cycle

- Two- or three-pressure cycles achieve better efficiency than single pressure systems, but their installed cost is higher.

- Economic choice when fuel is expensive.

- The HRSG stack gas temperature is range of 93°C to 127°C.
Three Pressure Non-reheat Cycle

1. Compressor
2. Gas Turbine
3. Dual HP/IP Superheater
4, 6, 8. HP, IP, LP Evaporators
5. HP Economizer/HP Superheater
7, 9. Dual HP/IP Economizer
10, 11, 12. HP, IP, LP Drums
13. Steam Turbine
14, 15, 16. HR, IR, LP Steam Bypasses
17. Condenser
18. Condensate Pump
19. Feedwater Tank/Deaerator
20, 21. IP, HP Feedwater Pumps

Flow Diagram
Steam Cycle

Three Pressure Non-reheat Cycle (GE)
Heat Balance

Three Pressure Reheat Cycle

Gross output = 280.5 MW
Gross effi. (LHV) = 59.3%
Three Pressure / Reheat Cycle

- The higher exhaust gas temperature of 1100°F/593°C or higher provides sufficient high temperature energy to the HRSG to make the reheat steam cycle practical.
- Fuel gas heating to approximately 185°C, using water supplied from the HRSG IP economizer discharge.
Heat Balance

Single Pressure Supplementary Firing

Gross Power Output = 303.5 MW
Gross Efficiency (LHV) = 57.9 %
## Comparison of Cycle Performance [1/3]

<table>
<thead>
<tr>
<th>Energy flow</th>
<th>Unit</th>
<th>1-Press</th>
<th>2-Press</th>
<th>3-Press/Non-reheat</th>
<th>3-Press/Reheat</th>
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<tbody>
<tr>
<td>GT</td>
<td>%</td>
<td>37.6</td>
<td>37.6</td>
<td>37.6</td>
<td>37.6</td>
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<tr>
<td>ST</td>
<td>%</td>
<td>20.1</td>
<td>21.0</td>
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<td>Condenser</td>
<td>%</td>
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<td>Stack</td>
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<td>178</td>
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<td>99.0</td>
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<td>565</td>
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<tr>
<td></td>
<td>Unit</td>
<td>1-Press</td>
<td>2-Press</td>
<td>3-Press</td>
<td>3-Press/Reheat</td>
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<td>------------------------</td>
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<tr>
<td>GT Fuel Input (LHV)</td>
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<td>473</td>
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<tr>
<td>ST Output</td>
<td>MW</td>
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<td>99</td>
<td>99.7</td>
<td>102.5</td>
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<td>Gross Plant Output</td>
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<td>Gross Efficiency (LHV)</td>
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<td>Net Efficiency (LHV)</td>
<td>%</td>
<td>56.8</td>
<td>57.6</td>
<td>57.8</td>
<td>58.3</td>
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<td>Net Heat Rate (LHV)</td>
<td>kJ/kWh</td>
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<td>Total Relative Plant Cost</td>
<td>%</td>
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</table>
Comparing two-pressure cycle with single-pressure cycle, the two-pressure cycle makes better use of exhaust gases in the HRSG, resulting in a higher steam turbine output.

Comparing three-pressure cycle with two-pressure cycle, the three-pressure cycle has a only slightly higher steam turbine output. This is because IP flow is very small.

In a three-pressure HRSG, the HP flow is 72.5 kg/s. However, the IP and LP flows are very small, only 3.1 kg/s and 3.0 kg/s, respectively. This fact is the same as in two-pressure HRSG.

Three-pressure reheat cycle has an advantage of a reduced moisture content and an improvement in the performance.
### Performance Variation

<table>
<thead>
<tr>
<th>STAG 207EA</th>
<th>NET PLANT OUTPUT (%)</th>
<th>NET PLANT THERMAL EFFICIENCY (%)</th>
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<tbody>
<tr>
<td>STEAM CYCLE</td>
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</tr>
<tr>
<td>THREE PRESSURE, REHEAT</td>
<td>+0.7</td>
<td>+0.7</td>
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<tr>
<td>THREE PRESSURE, NON-REHEAT</td>
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<td>TWO PRESSURE, NON-REHEAT</td>
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<tr>
<td>SINGLE PRESSURE, NON-REHEAT</td>
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<table>
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<tr>
<th>STAG 107EA</th>
<th>NET PLANT OUTPUT (%)</th>
<th>NET PLANT THERMAL EFFICIENCY (%)</th>
</tr>
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<tr>
<td>STEAM CYCLE</td>
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</tr>
<tr>
<td>THREE PRESSURE, REHEAT</td>
<td>BASE</td>
<td>BASE</td>
</tr>
<tr>
<td>TWO PRESSURE, REHEAT</td>
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<td>THREE PRESSURE, NON-REHEAT</td>
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<td>TWO PRESSURE, NON-REHEAT</td>
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<td>-2.0</td>
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</tbody>
</table>
Comparison of Cycle Performance

Three Pressure Reheat Cycle
Three Pressure Non-reheat Cycle

Saturation Line

(1-x)=10%
(1-x)=16%
An increase in the HP pressure leads to an increase in the cost of the HRSG, feedwater pumps and piping, which is often the limiting factor when determining the optimum pressure.

There will also be an increase in the auxiliary consumption of the feedwater pumps as the HP pressure rises, which means that the benefit in the net power output is slightly less than shown in the curve.

At lower live-steam pressures a lower reheat pressure is advantageous because the enthalpy drop in the HP steam turbine is bigger.

Normally, the higher HP pressure, the higher reheat pressure is preferable.
Deaeration is the removal of noncondensable gases from the water or steam.

High oxygen content is in the water can cause erosion and corrosion of the components and piping that contacting with water.

Typically, an oxygen content of less than 20 parts per billion (ppb) in the feedwater is recommended.

Deaeration must be done continuously because small leakages of air at flanges and pump seals cannot be avoided.

Deaeration takes place when water is sprayed and heated (boiled), thereby releasing the dissolved gases.

Generally, the condensate is sprayed into the top of the deaerator.

Heating steam, fed into the lower part, rises and heats the water droplets to the saturation/boiling temperature, releasing incondensable gases that are carried to the top of the deaerator and evacuated.

The feedwater tank is filled with saturated and deaerated water, and steam buffer above it prevents any reabsorption of air.
Deaeration will also partly take place in the condenser.

The steam turbine exhaust steam condensates and collects in the condenser hotwell, while the noncondensable gases are extracted by means of evaluation pump.

A steam cushion separates the water in the hotwell so that reabsorption of the air cannot take place.

Often, levels of deaeration in the condenser can be achieved that are comparable to those in the deaerator.

Therefore, the deaerator and feedwater tank can sometimes be eliminated from the cycle, and the condensate is fed directly from the condenser into the HRSH drum.

In these cases the makeup water must be admitted to the cycle through the condenser.
Deaerator [1/3]
보일러 급수계통은 급수에 포함되어 있는 용존산소와 이산화탄소에 의해서 가장 많이 부식된다.

용존산소는 이산화탄소에 비해서 5~10배 정도 부식성이 강하며, 급수온도가 17°C 증가할 때마다 부식성이 2배 이상 강해진다.

급수에 포함되어 있는 산소와 이산화탄소는 deaerator에서 제거된다.
Deaerator [3/3]
Transition duct and HRSG inlet duct
RNG k-e turbulence model
Velocity Magnitude Distribution

Side view

Plan view
Swirl vanes are located after the gas turbine as the exhaust gas will tend to corkscrew up the duct with some force particularly when the gas turbine is working under off-design conditions.
Flow Correction Device

FCD: make the exhaust gas flow uniform at the inlet of duct burner or superheater tube bundle for efficient combustion at duct burner or efficient heat exchange at superheater.
A Typical HRSG

- Drum and evaporator
- Superheater
- Membrane walls
- Supplementary-firing burners
- Distribution plate
- Economizer
- DH-cooled economizer
- Flue gas to stack
- Cold DH water
- Hot DH Water
- Condensate
- Superheated steam to steam turbine

Hot flue gas from GT
Generally required velocity criteria (Top-to-bottom and side-to-side)
Superheater: ± 50%
Duct burner: ± 15%
Grid System for the Design of FCD

Without FCD

With FCD
Investigation of Velocity magnitude

Uniform Inlet Velocity Profile

Non-uniform Inlet Velocity Profile

W/O FCD

With FCD

Uniform Inlet Velocity

Non-uniform Inlet Velocity

With FCD
Combined Cycle Performance

1. Combined cycle with unfired steam cycles
   - The most efficient power generation cycles are those with unfired HRSGs having modular pre-engineered components.
   - These unfired steam cycles are the lowest in cost.

2. Combined cycle with supplementary-fired steam cycles
   - These are provided for customer specific applications.
   - These give an increased power, however, reduced thermal efficiency.

3. Combined cycle with fully-fired steam cycles
   - The most efficient cycles for cogeneration applications are those with fully-fired HRSGs.
   - These give maximum thermal energy output.
   - These are high in cost because of their water wall construction and need for field erection.
   - These may add to emission considerations.
1. Introduction to HRSG
2. Type of HRSGs (Horizontal vs. Vertical)
3. Investigation of HRSG Design Concepts
4. Once-through HRSGs
5. HRSG Performance
6. SCR
HRSG with SCR [1/5]

- SCR is an exhaust gas NO\textsubscript{x} reduction system that uses ammonia to react with NO\textsubscript{x} over a catalyst that converts NO\textsubscript{x} into molecular nitrogen and water.
- This system increases plant installation and operating cost.
- Typically, the SCR catalyst operates under temperature range of 570°F/300°C and 750°F/400°C, therefore, the catalyst is typically installed within the high pressure evaporator.
HRSG with SCR [2/5]
NO\textsubscript{x} level less than 9 ppmvd can be obtained at 15% oxygen for all combined cycle plants with selective catalytic reduction (SCR) systems.

- SCR is the most effective and proven technology to reduce NO\textsubscript{x} emissions, greater than 90%.
- NO\textsubscript{x} contained in the gas turbine exhaust gas is converted into harmless molecular nitrogen and water on the catalyst bed by the reaction with ammonia.

- Conventional SCR technology operates in a narrow temperature range (288°C-399°C).
- The equipment is comprised of segments stacked in the exhaust duct. Each segment has a honeycomb pattern with passages aligned to the direction of the flow.
- A catalyst such a vanadium pentoxide is deposited on the surface of the honeycomb.
- For a GE turbine MS7001EA an SCR designed to remove 90% of the NO\textsubscript{x} has a volume of 175 m\textsuperscript{3} and weights 111 tons.
- The cost of the system, the efficiency penalty due to the pressure drop introduced by the catalyst, and the potential for NH\textsubscript{3} slip are the major disadvantages of this system.
- A certain amount of ammonia, that is excess ammonia, may pass through the catalyst unreacted and emitted into the atmosphere as “ammonia slip”.
- Both NO\textsubscript{x} and ammonia are acutely toxic, and they contribute to fine particle formation, acidifying deposition.
- In most cases, ammonia slip is currently limited by permit condition to either 5 or 10 ppm at 15% O\textsubscript{2}, because ammonia is a hazardous material.
Ammonium hydroxide (수산화 암모늄) solution sprayed over a mesh containing titanium and vanadium oxide catalysts reacts with the NOₓ to form nitrogen and water.

The reaction rate shows peak level at around 350°C, and this temperature is appeared between the evaporator and economizer sections of HRSG.

This systems are relatively expensive to install and maintain.

However, when the NOₓ emission should be controlled less than 10 ppm, this system can be used with the combination of water injection.

Anhydrous ammonia (NH₃) is the most cheap reagent.

Aqueous ammonia (NH₄OH) is a safer to transport, handle and store than anhydrous ammonia. For these reasons, many end-users and operators use it.

SCR systems are sensitive to fuels containing more than 1000 ppm sulfur.

Ammonia can lead to fouling of HRSG tubes downstream of the SCR if moderate quantities of sulfur are present in the flue gas.

Ammonia and sulfur react to form ammonium bisulfate, a sticky substance that forms in the low temperature section of HRSG (usually the economizer).

The deposited ammonium bisulfate is difficult to remove and can lead to a marked increase in pressure drop across the HRSG.
SCONOX is a post-combustion catalytic system that removes both NO\textsubscript{x} and CO from the gas turbine exhaust, but without ammonia injection.

The catalyst is platinum and the active NO\textsubscript{x} removal reagent is potassium carbonate.

Currently, SCONOX is used for only LM2500.

SCONOX is very sensitive to sulfur, even the small amount in pipeline natural gas.

The initial capital cost is three times the cost of SCR.

It has moving parts, reliability and performance degradation due to leakage may be significant issues.

Use of any exhaust gas treatment technology (SCR or SCONOX) results in pressure drop that reduces gas turbine efficiency.
질의 및 응답