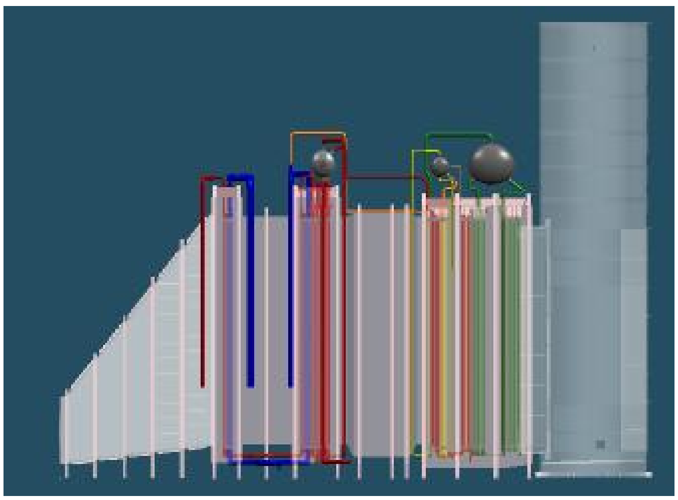
1.0 INTRODUCTION

A Heat Recovery Steam Generator (HRSG) or waste heat boiler, is the standard term used for a steam generator producing steam by cooling hot gases. Waste heat is obviously a very desirable energy source, since the product is available almost operating cost-free, and increases the efficiency of the cycle in which it is placed, either for process steam generation or for incremental power generation.



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HRSGs can regain energy from any waste-gas stream, such as incinerator gases, furnace effluents, or most commonly, the exhaust of a gas turbine set (GT).

2.0 FUNDAMENTAL PARTS of the HRSG

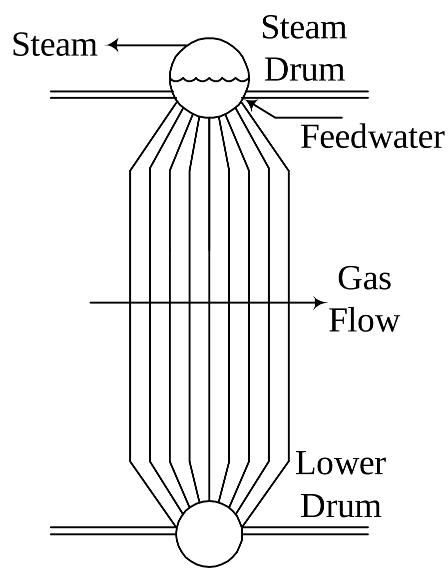
HRSGs can be made up from a number of components, including evaporators, economizers, superheaters, reheaters, integral deaerators and preheaters.

Each of these heat-transfer sections performs a specific task, and the ones that are selected are generally dictated by the required steam conditions for process use or power generation, the type of power generation cycle and/or the efficiency requirements, weighed against HRSG costs.

2.1 Evaporators

HRSG evaporator or boiler sections act to vaporize water and produce steam in one component, like the kettle in the kitchen.

A bank of finned tubes is extended through the gas turbine's exhaust gas path from a steam drum (top) to a lower (mud) drum. Boiler feedwater is carefully supplied at the appropriate pressure to the upper drum below the water level, and circulates from the upper to lower drum by external downcomers, and from the lower drum back to the upper drum by convection within the finned tubes.



In the steam drum, a "water level" is carefully maintained in the middle of the cylinder – virtually dry steam rises from the water surface, and exits the steam drum through moisture separators and cyclones – delivering essentially 100% dry, albeit saturated steam.

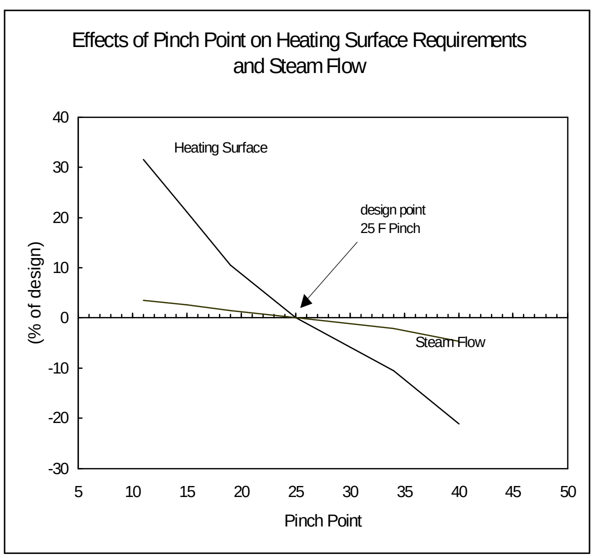
The amount of heat absorbed by the water, and the amount of heat released from the GT exhaust gas to generate steam is the product of the gas mass flow rate, average gas specific heat capacity (C_p), the temperature difference (dT) across the evaporator and the amount of heat transfer surface area installed.

Water vaporizes and boils at a constant temperature, known as the saturation temperature, which is unique for every steam pressure.

If an infinite amount of surface is installed, the gas temperature leaving the evaporator will equal the saturation temperature of the steam – and maximum heat recovery will be achieved in this component. However, infinite surface is obviously neither practical, economical nor good for the gas turbine (resulting in very high exhaust pressure loss and thus reduced power output).

Accordingly, a "reasonable" amount of surface is installed, as dictated by economic considerations – as a result the gas temperature leaving the evaporator section is higher than saturation. This difference between the saturation temperature and the gas exit temperature is called the "pinch point". The lower the pinch point, the more surface that has been installed, the more steam that is produced and the higher the capital cost of the HRSG, and vice versa.

The amount of surface required to reduce the pinch point increases dramatically as the pinch point drops. As the typical figure below indicates, moving from a pinch point of 25 deg F to 10 deg F requires approximately 30% more surface area for an increase in steam flow of less than 5%. For unfired HRSGs, the optimum pinch point ranges from 10 F to 30 F.

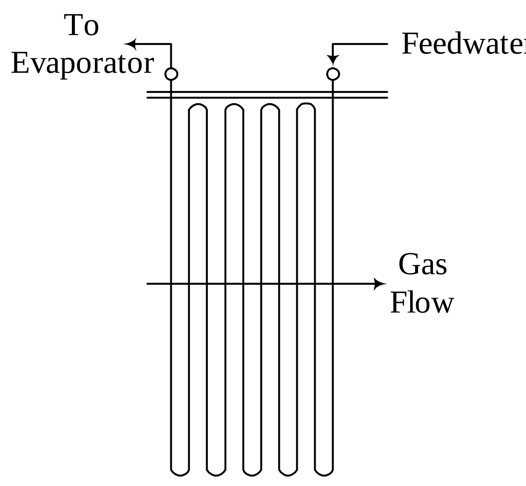


For multi-pressure natural-circulation HRSGs, an evaporator is installed for each pressure level.

2.2 Economizers

The gas temperature leaving an evaporator varies from 300 ~ 600 deg F, depending upon the steam pressure being produced. If no other heat transfer component is installed downstream, this remaining energy is wasted.

Accordingly, economizers are frequently installed downstream (with respect to gas flow) of the associated evaporator, and lower gas temperatures further, thus increasing heat recovery. Economizers are serpentine finned-tube gas-to-water heat exchangers, and add sensible heat (preheat) to the feedwater, prior to its entry into the steam drum of the evaporator.



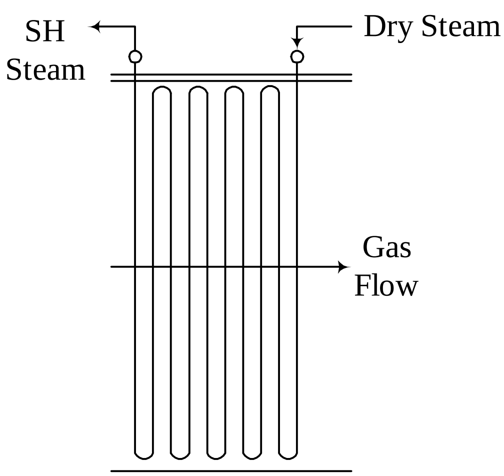
Instead of pinch point, the amount of surface area in an economizer is quantified by the "approach temperature", i.e. the difference between the feedwater temperature leaving the economizer, and the saturation temperature in the drum to which it is delivered. For most HRSGs, it is desirable to maintain a discreet approach temperature under all operating conditions (i.e. considering fired, unfired and part-load GT situations), in order to prevent the generation of steam directly in the economizer – where it doesn't belong. Typical approach temperatures are approximately 25 ~ 40 F.

In a single pressure HRSG, the economizer will be located directly downstream (with respect to gas flow) of the evaporator section. In a multi-pressure unit the various economizer sections may be split, and be located in several locations both upstream and downstream of the various evaporators.

2.3 Superheaters

While the evaporator produces dry-saturated steam, this is rarely acceptable for large steam turbines, and is frequently not the appropriate condition for process applications.

In these cases, the saturated steam produced in the evaporator is sent to a separate serpentine tubed heat exchanger referred to as a superheater, which is located upstream (with respect to gas flow) of the associated evaporator. This component adds sensible heat to the dry steam, superheating it beyond the saturation temperature.



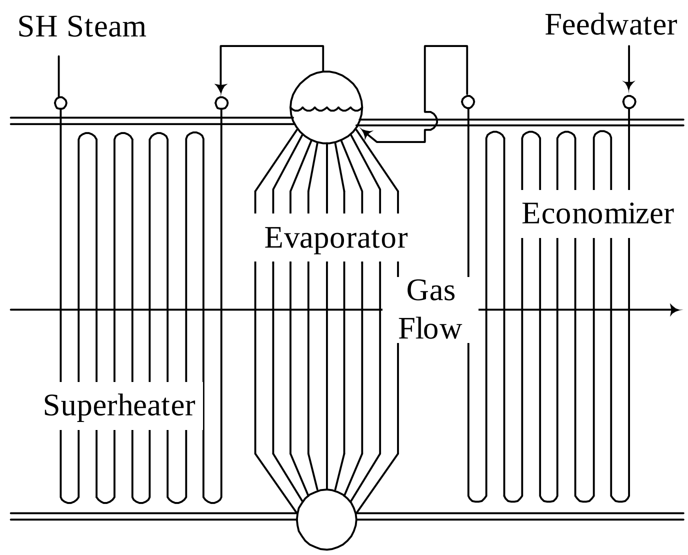
The superheater can consist of either a single heat exchanger module or multiple heat exchanger modules. The final steam outlet temperature will vary depending upon the gas turbine exhaust and/or duct burner conditions, unless controlled.

For single modules, a temperature controlling desuperheater can be located outside the HRSG, to adjust the final outlet temperature.

If two superheater modules are installed, the temperature controlling desuperheater is generally mounted between the two discreet modules, i.e. interstage attemperation, allowing more precise steam temperature control and eliminating the risk of having water droplets enter the steam turbine.

Superheaters can be either bare tubes or finned tubes, depending upon material and inlet gas temperature considerations.

The three primary heat transfer components discussed above, i.e. the economizer, evaporator and superheater, are included in all power generation HRSGs, and most process steam HRSGs.



Other HRSG heat transfer components can be installed, depending upon economics, cycle considerations and/or process steam requirements.

2.4 Reheaters

Reheaters are a heat transfer component similar to superheaters, and are employed in advanced multi-pressure power generation cycles. They accept superheated or semi-saturated steam at a low pressure from a steam turbine after it’s first section of expansion, and re-superheat or “reheat” the steam back towards the original superheater’s outlet temperature. Accordingly, reheaters are generally interspersed among the superheater sections in the HRSG, so that the same outlet temperatures can be achieved.

In general, reheat systems are very expensive due to the high temperature, large-diameter HRSG tubing and external piping systems required, and complicate startup, operation and load adjustment. Reheaters appear to be justified only in the largest combined-cycle plants where the highest efficiency is prime.

In general, there will only be one reheat section in an HRSG, irrespective of how many steam pressure levels are employed in the unit.

2.5 Integral Deaerators

All power plant cycles employ a deaerator to control oxygen levels in the feedwater. Heating steam is provided to strip oxygen from the condensate falling through the pressurized deaerator's tray systems.

Normally, this deaerating steam is a parasitic loss from such a cycle. In some HRSG's, the deaerator can instead be mounted on the HRSG in the final portions of its gas path, with a finned or bare tube bank extended into the gas stream. The pegging steam is produced from the tube bank and provided directly to the deaerator mounted above.

The result is decreased stack temperature, i.e. improved heat recovery, and decreased piping and equipment cost.

2.4 Preheaters

Typically, preheaters are located at the coolest end of the HRSG gas path, and absorb energy from the gas stream to preheat liquids such as condensate, makeup water, water/glycol mixtures or proprietary heat exchange fluids, e.g. Dowtherm.

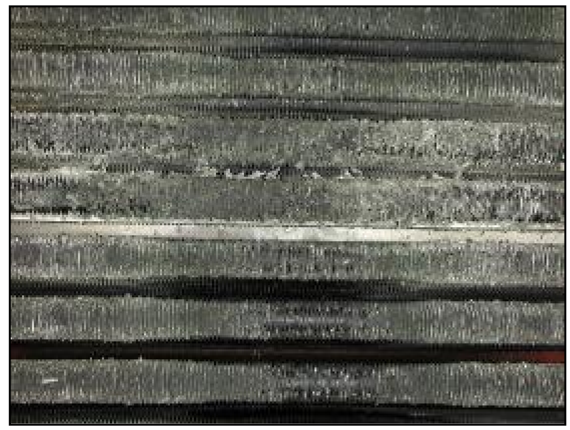
The most common application is to preheat condensate prior to entry into the deaerator, which reduces the amount of deaeration steam required.

Due to the low gas and fluid temperatures associated with integral deaerators and preheaters, there can be concerns related to water dewpoint corrosion and acid dewpoint corrosion.

a) **Water dewpoint corrosion** can occur when the preheater metal temperatures are below the water dewpoint, leading to accelerated corrosion of carbon steel and some stainless steel heat transfer surfaces, tubes and/or fins. This form of corrosion is especially a concern when the GT is steam or water-injected.

b) **Acid dewpoint corrosion** occurs when trace quantities of sulfur in the fuels form sulfur trioxide SO_3, and can lead to localized sulfuric acid corrosion in colder sections of the preheater. Materials must be carefully selected to operate in this environment.

Dewpoint corrosion can lead to deposits forming on the finned tubes. These deposits can lead to accelerated corrosion and loss of performance.



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To avoid these forms of corrosion in the HRSG, it is sometimes economically justifiable to incorporate external water-to-water preheaters. The boiler feedwater leaving the deaerator can be used to preheat the incoming makeup water.

3.0 TYPES OF HRSGs

HRSGs types can be classified on whether they are a natural-circulation (NC), forced-circulation (FC) or a once-through (OT) design.

3.1 Natural Circulation HRSG

In natural-circulation HRSG units, the turbine gases flow horizontally past vertical tubes.

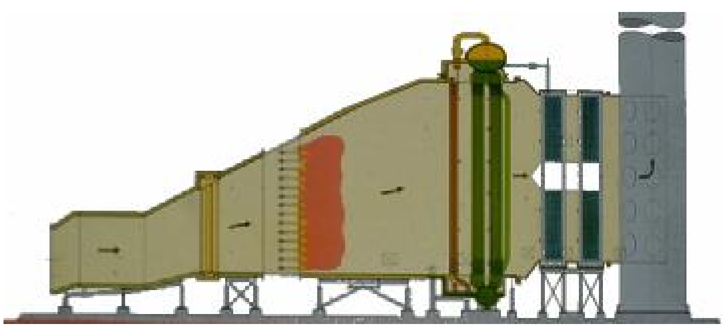
In the vertical evaporator tubes (as per the diagram in section 2.1), the density difference between water in the external downcomers and the water-steam mixture in the evaporator tubes is responsible for the circulation through the evaporator system.

Proper selection and sizing of evaporator tubes, downcomer, feeders & risers is required to ensure good circulation rates for the full range of GT, duct burner and HRSG operation that is expected.

In most natural circulation HRSG units, the economizer, superheater, reheater, preheater and integral deaerator sections (as applicable) are all supported and hung from the top of the HRSG structure. As the tube bundles grow thermally, they are allowed to expand vertically down.

Because of this construction and support method, the various sections of the HRSG can frequently be prefabricated in the shop, and shipped to site as a single component, minimizing field erection time and complexity.

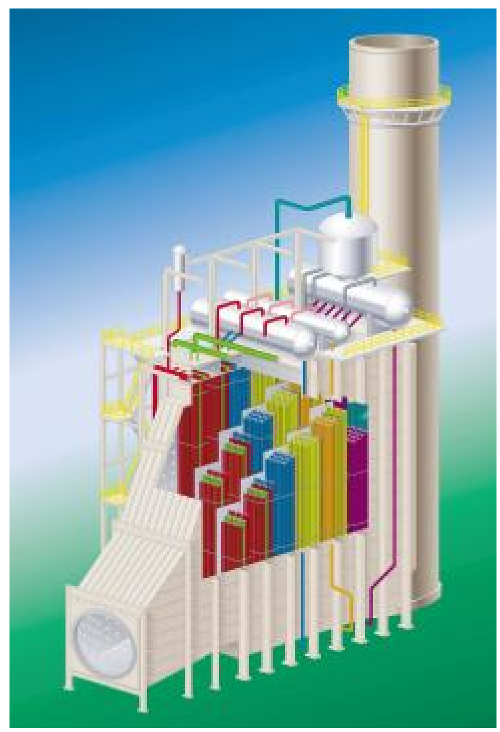
Often, NC HRSGs for GT's up to about 40~50 MW incorporate integral steam drums and internal downcomers, again minimizing field erection.



Foster Wheeler Limited

For larger NC HRSGs, the length of the steam drum dictates that the drum be shipped separately, and be erected at site. In this case, the evaporator tube banks will be located between top and bottom headers, and the drum is connected to the headers with risers to release steam, and with downcomers to be fed with water. Instead of a bottom drum, the bottom headers are interconnected with jumpers.

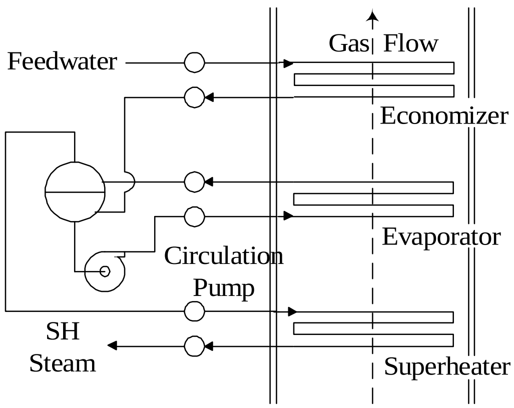
For the largest HRSGs, the width of the gas path dictates that each module be fabricated and shipped in multiple sections, i.e. a right-hand, middle and left-hand section. These sections are then connected at site to each other to form a complete box structure. Several sections or modules will usually be required to complete each evaporator, superheater and economizer, etc.



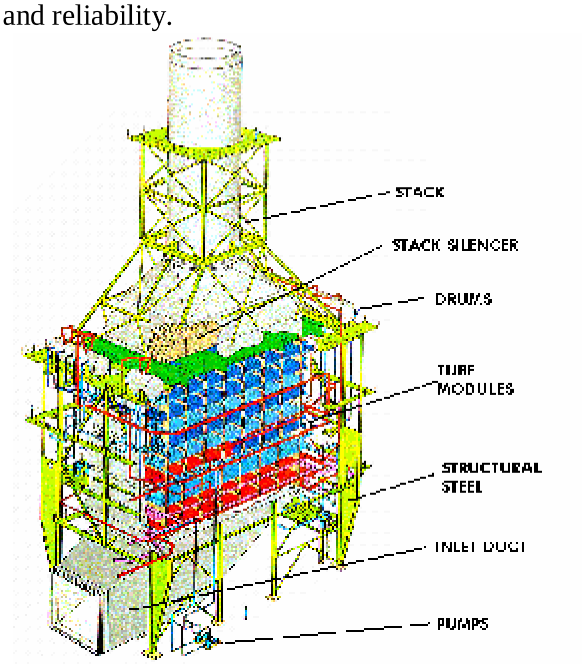
Vogt Power International

3.2 Forced Circulation HRSG

In a forced circulation HRSG, the gas turbine exhaust flows vertically past horizontal tubes. Steam-water mixture circulation through the evaporator tubes, and to the and from the drum is maintained with a “forced circulation” pump.



Traditionally, most HRSGs in Europe have been specified as forced circulation. The claimed advantages of these units include decreased space requirements and faster start-up capabilities. However, their main disadvantage is the complex circulating pumps and their impact on operating costs and reliability.



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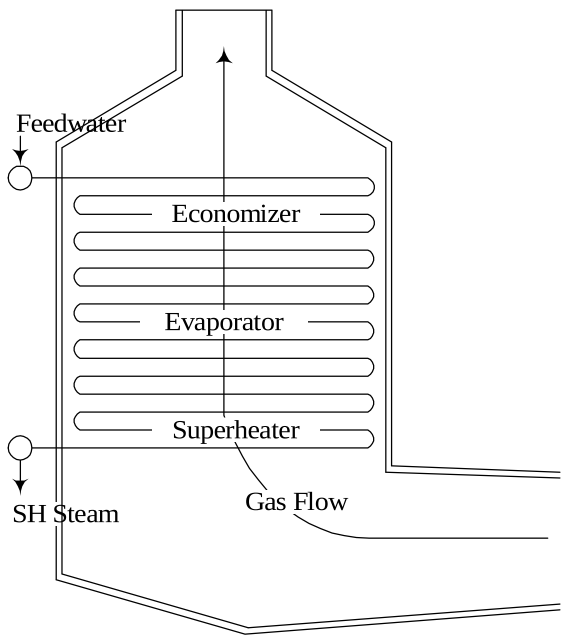
3.3 Once-Through Steam Generator – OTSG

In a once-through steam generator (OTSG) the gas turbine exhaust flows past vertical and/or horizontal tubes. The unit is basically a single continuous serpentine tube in which all the functions of economizer, evaporation and superheating are carried out, without discrete drums.



In the tube bundle, the phase change zone from liquid to gas is free to move up or down throughout the bundle, depending on gas conditions (flow and temperature) and the operational load.

OTSGs eliminate the need for the steam drums, level controls, blowdown and recirculation systems. Startup times can be greatly due to the absence of thick walled pressure vessels and the steam drum water inventory, which would otherwise require heating.

The OTSG has all the benefits of the forced circulation HRSG, but without circulation pumps, and with decreased start up times. Because there is no blowdown from this type of HRSG, improved feedwater treatment systems, and condensate polishers may be required.

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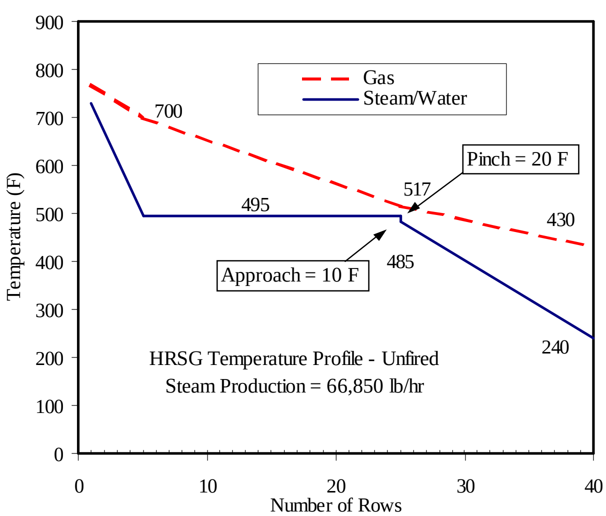
5.0 SINGLE vs. MULTI-PRESSURE HRSGs

5.1 Single Pressure HRSGs

Up to this point only single-pressure level HRSGs have been discussed.

Viable steam outlet pressures can range from a low of 60 ~ 100 psig to a high end of 2000 psig. Outlet steam temperatures can range from saturated, up to within ~50 deg F of the GT exhaust temperature (which ranges from 850 to 1200 deg F depending on the unit), although temperature must be limited to approximately 1050 deg F for material considerations.

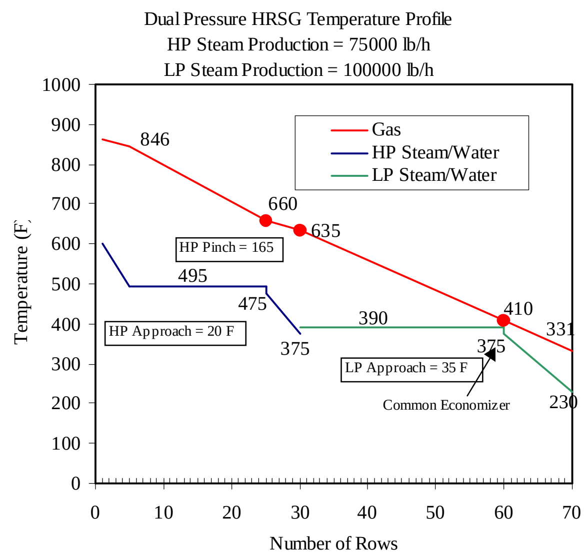
A typical temperature profile for a superheated, single-pressure level, natural or forced-circulation HRSG shows the final outlet temperature, pinch point, saturation and approach temperatures, and superheater, evaporator and economizer concepts that have been previously discussed.



In this case, a high pressure HRSG has been shown, to illustrate that there is a great deal of additional energy available after the economizer – which is potentially wasted.

5.2 Multi-Pressure HRSG

To recover this additional energy, the unit can be designed with multiple pressure levels – the assumption is made that the additional steam has a customer such as a process user, deaeration, feedwater preheating, gas turbine steam injection and/or a multi-inlet pressure (admission) steam turbine.



The following configurations of HRSGs are possible, arranged in order of increasing cost and complexity:

- Single Pressure
- Dual Pressure
- Dual Pressure with Reheat
- Triple Pressure
- Triple Pressure with Reheat

For each pressure level used, the relative location of the economizer, evaporator and superheater in the gas path are maintained. However, sections of each different pressure levels may be located in between some of the common pressure level sections so that a nearly parallel relationship between the temperature gradients for the gas side and steam/water side is achieved. This is best illustrated in the above temperature profile.

6.0 UNFIRED HRSGs vs. FIRED HRSGs

6.1 Unfired HRSGs

When the available GT exhaust energy, the consequential HRSG steam production, and the steam requirements are well balanced, an unfired HRSG can be selected.

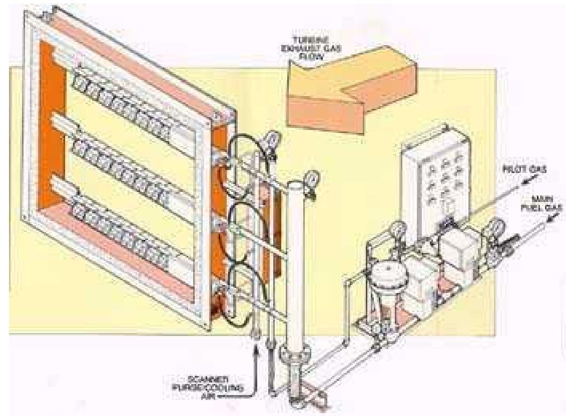
The performance (steam output) of the unfired HRSGs will be driven by the GT's operating conditions, and if for some reason additional steam is required, it would have to be provided by an external source, e.g. auxiliary boilers, existing boilers, etc., or by duct firing.

6.2 Fired HRSGs

The exhaust gases from a typical GT include from 14% ~ 16% oxygen by volume, which makes it possible to locate a supplemental burner downstream of the gas turbine exhaust – frequently called a duct burner.

These duct burners act to raise the gas temperature approaching the superheater or evaporator (as applicable) of the HRSG. Since steam production is a function of temperature differential, steam production will increase. The incremental steam is produced very efficiently (compared to a conventional boiler) since the gas turbine effectively preheats the combustion air, saving the additional fuel required to heat that air.

A gas-fired duct burner consists of several burner rows mounted inside a steel frame. Each row comprises a gas distribution pipe with pre-mounted flame stabilizing shields of refractory steel. The duct burner is designed to minimize gas side pressure drop, usually around 0.5" H20. A uniform temperature and flow profile in the duct upstream of the duct burner is crucial to ensure a uniform temperature downstream and emissions within predicted limits. HRSG manufacturers flow model all steam generators incorporating duct burners to try and prevent any problems downstream of the duct burner.

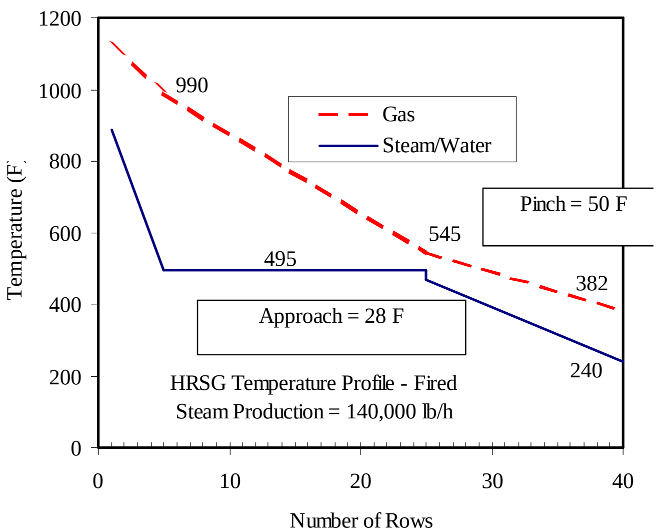


COEN Company, Inc.

Although duct firing can easily double the steam production of an unfired HRSG, there are also design implications such as:

- Higher cost superheater tube and fin material.
- Increased superheater, evaporator and economizer surface area requirements.
- Potential for economizer steaming, i.e. too much economizer surface area for unfired operation.
- Longer HRSG inlet duct to allow for complete combustion of the supplemental fuel.
- Increased heat insulation requirements on HRSG ducting walls.
- Burner management control system for duct burner.

The following single-pressure level HRSG temperature profile illustrates the affect of duct burner firing from 770 deg F GT exhaust temperature, to 1130 deg F HRSG inlet.



In addition to supplementary fired HRSGs, there are two other possible variations:

a) A **fully fired HRSG** is a unit having the same amount of oxygen in its stack gases as an ambient, air fired power boiler. The HRSG is essentially a power boiler with the GT exhaust as its air supply. Steam production can range up to six or seven times the unfired HRSG steam production rate.

Fuel requirements for the fully fired HRSG will usually be between 7.5% and 8% less than those of an ambient fired boiler providing the same incremental steam capacity. Although fully fired HRSG's provide large amounts of steam, few applications are found in industry.

b) In some critical process steam applications, **fresh air fired HRSGs** may be applied. Forced draft or induced draft fans, dampers and ducting are installed to allow the introduction of fresh ambient air in case the gas turbine stops.

7.0 POST-COMBUSTION EMISSION CONTROLS

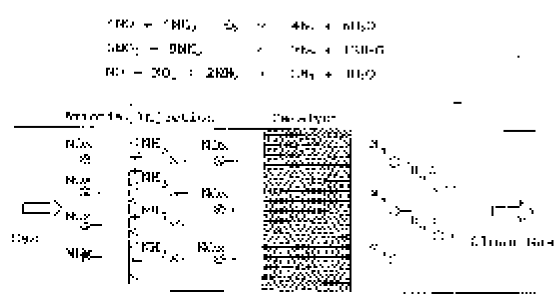
The drive for low NOx and CO production in the prime combustion device, the gas turbine, was covered in the previous chapter.

In certain jurisdictions and non-attainment areas, additional post-combustion emission mitigation measures are mandated beyond the 8~9 ppm_{VD} to 42 ppm_{VD} NOx being achieved by gas-fired DLN, steam or water-injected gas turbines.

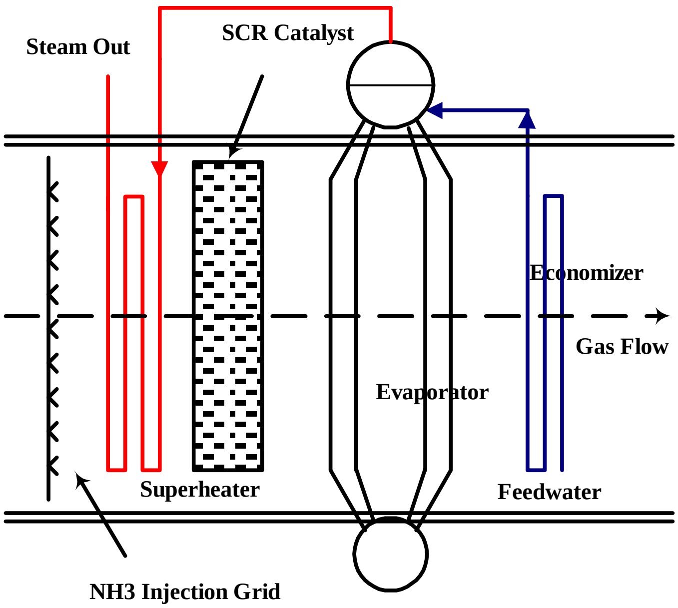
7.1 Selective Catalytic Reduction Systems

The most common post-combustion process applied to HRSGs is Selective Catalytic Reduction or SCR. Most new combined-cycle plants where stringent emissions limits exist (i.e. 5 ppm or less), are equipped with both DLN combustors on the gas turbine, and an HRSG incorporating an SCR system.

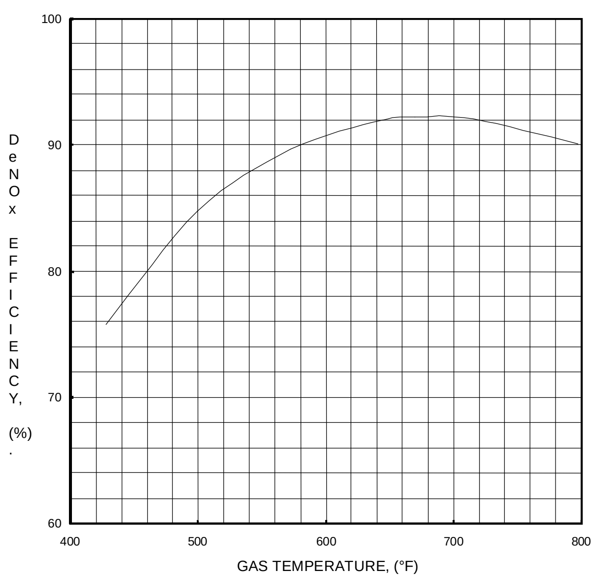
The SCR NO_x removal system (also referred to as $DeNO_x$) is a dry process in which ammonia (NH_3) is used as a reducing agent, and the NO_x contained in the flue gas is decomposed into harmless N_2 and H_2O. Ammonia (NH_3) is injected into the flue gas upstream of the SCR catalyst, through a special injection grid to assure even distribution and mixing within the flue gas. The flue gas then passes through the catalyst layer.



A **conventional SCR** module is located in the HRSG between the superheater and evaporator sections.



This zone is selected such that the DeNOx efficiency will be maximized. Maximum efficiency is reached at gas temperatures between 600 and 800 deg F gas temperature. Typical catalyst materials are vanadium, platinum and titanium.



Typical DeNOx Efficiency VS. Gas Temperature

Some **low-temperature SCR** systems that operate between 300 and 400 deg F have been developed and have been in operation for 3~5 years. They can be particularly useful for retrofits, where they could be located downstream of an existing HRSG (assuming real estate is available and existing stacks can be relocated, etc.).

High temperature SCR technology has also been developed that operates in the 800 to 1100 deg F range. These are possible retrofits to existing simple-cycle installations, mounted directly at the GT exhaust.

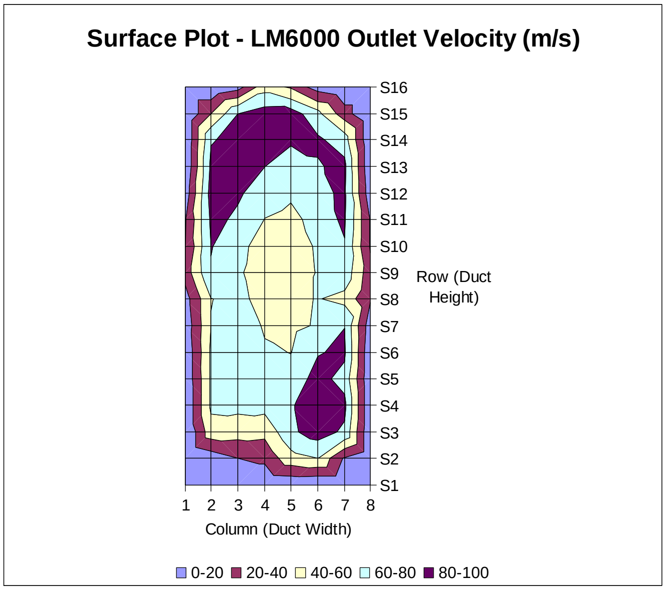
With the modern DLN gas turbine machines and SCR technology, a percentage of the injected ammonia can pass through the SCR catalyst bed unreacted (ammonia slip), since there are less and less NOx molecules to find. Ammonia slip causes as much environmental concern as NOx and CO emissions.

The use of sulfur-bearing gaseous and/or oil fuels in the gas turbine or duct-burner, can also create environmental and HRSG durability problems. Inhalable secondary particulates of environmental concern ($PM_{2.5}$ and PM_{10}) can be formed in the HRSG. And corrosion salts can be formed that attack the low temperature sections of the HRSG, leading to premature failure, if not regularly washed.

SCR catalysts lose activity over time, and must be replaced periodically, typically every 3 to 5 years.

8.0 FLOW MODELING

The gas flow distribution leaving the gas turbine is typically non-uniform. The figure below shows a typical gas flow distribution at the outlet of an LM6000 diffuser.



For proper performance this gas velocity distribution must be corrected. A uniform gas velocity profile at various locations in the HRSG is critical to meeting guaranteed performances. These locations are upstream of the duct burner, upstream of the tube bundle, upstream of SCR or CO catalyst and at the stack measurement locations. For these reasons, accurate prediction of gas velocity profile and correction of the gas velocity profile is critical. Until recently the engineering tool of choice for analysis of the flow distribution has been scale modeling.

Physical modeling has been used for a number of years. The models are typically 1/8th scale and constructed from clear acrylic to allow visualization. To measure the flow characteristics, ambient air is passed through the scale model at the specified flow rate. Velocities are measured with a pitot tube or a hot wire anemometer. Static pressures are measured using water or electronic manometers. Flow visualizations can also be made by passing smoke through the model.

A typical model is shown in the figure below.

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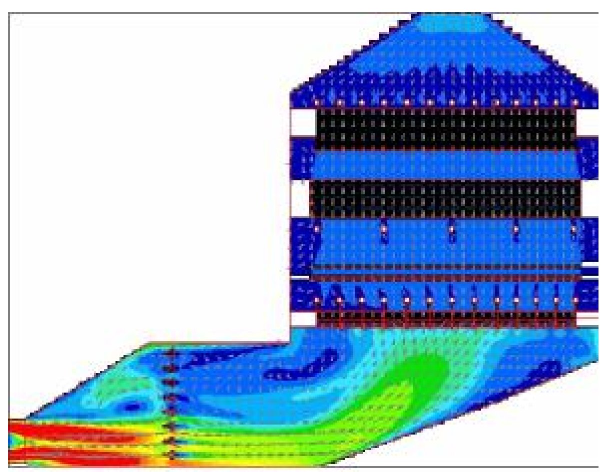
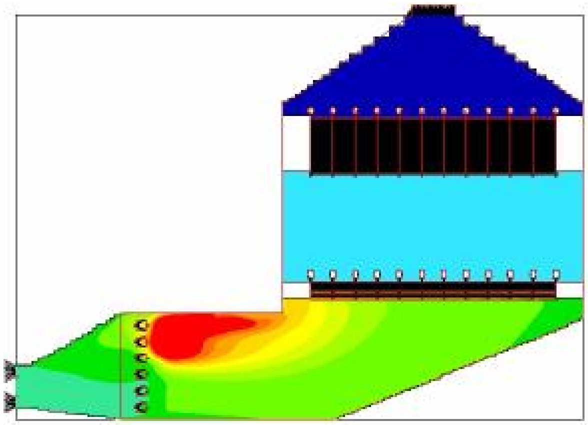
CFD (computational fluid dynamics) is beginning to be used successfully for the same application. CFD is a numerical tool to analyze flows. The software solves the relevant conservation equations (mass, momentum and energy) to which suitable boundary conditions (constraints) are applied to. The level of detail that can be modeled is a function of the number of elements that can be readily accommodated by the computer. A typical model is shown in the figure below.



Airflow Sciences Corporation/Innovative Steam Technologies

Advantages exist in predicting gas temperatures as well as flow distribution in CFD. Typical models showing uncorrected and corrected gas temperature distributions are shown below.



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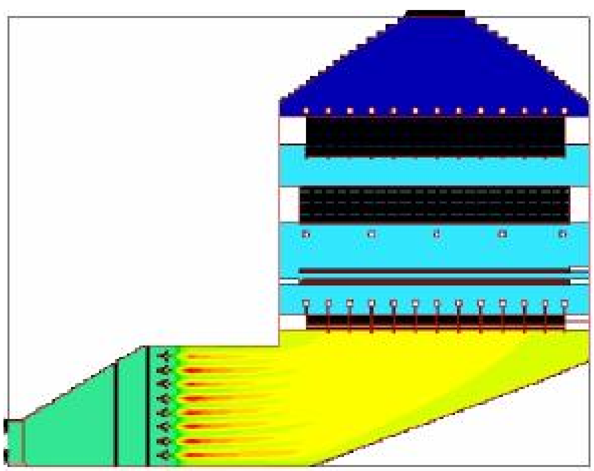

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To correct flow maldistribution, turning vanes and variable porosity plates are commonly used. The figure below shows a variable porosity plate upstream of a duct burner.

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Typical gas side pressure drop for a variable porosity plate ranges from 0.5 inches water column to 3 inches water column.