Understand boiler performance characteristics

Use these suggestions when buying, designing or optimizing steam generators

V Ganapathy, ABCO Industries, Abilene,

An understanding of the major differences in performance characteristics of steam generators is essential to better use and integrate them into plant steam systems. Process and cogeneration plants widely use gas- or oil-fired packaged steam generators (Fig. 1) and gas-turbine-exhaust, heat-recovery steam generators (HRSGs) (Fig. 2) to meet steam demands. The most important differences are efficiency versus load characteristics, gas/steam temperature profiles and partial load behavior. Also, steaming in the economizer is a concern at low steam flows for HRSGs, but not for packaged boilers.

Packaged boilers. Completely shop-assembled packaged boilers (Fig. 1) are used to generate steam up to 200,000 lb/h, 1,000 psig and 850°F. Slight deviations in these parameters are feasible on a case-by-case basis and depend on permitted boiler shipping dimensions. Typically, these steam generators fire natural gas and distillate oils with burners located in the furnace's front wall. A superheater and economizer may be used if superheated steam is required and a higher efficiency level is sought.

Two major configurations are available for packaged boilers: the D-type and O-type. In the D-type (Fig. 3a), combustion products of flue gases leaving the furnace make a 180 degree turn and flow over the convection tubes that may contain a superheater. Gases leaving the convection section then transfer energy to an economizer, which preheats the feed water. Generally, air heaters are not used in packaged boilers due to cost considerations, larger gas/air pressure drops and increased NOx formation due to higher flame temperatures.

In the 0-type boiler (Fig. 3b), the burner is mounted on the front wall. Combustion products travel to the furnace's end, make a 180 degree turn and flow towards the front via the two convection banks. These transfer energy to the convection tubes. In another option (Fig. 3c), the

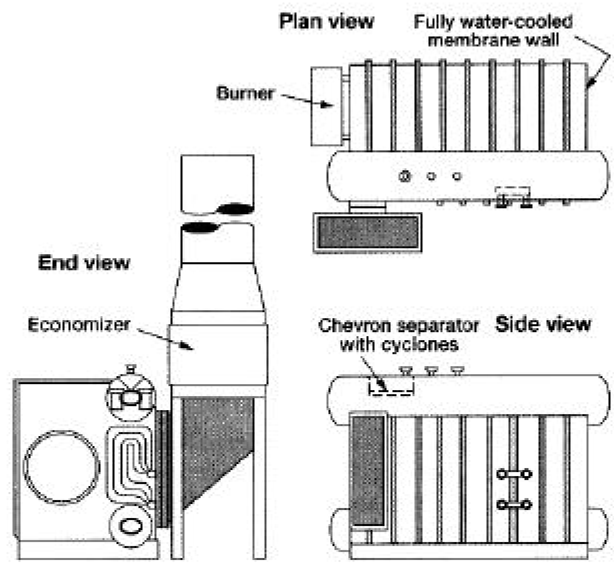

Fig. 1. Packaged steam generator.

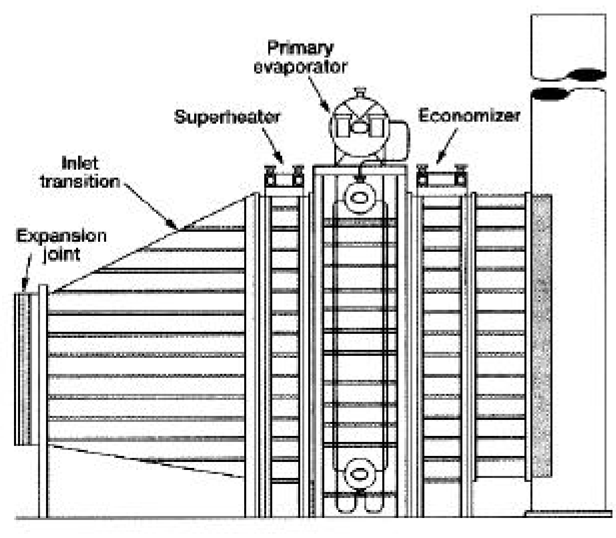

Fig. 2. Gas-turbine exhaust HRSG.

gases travel straight without making the turn. In this case, the boiler will be longer because its length

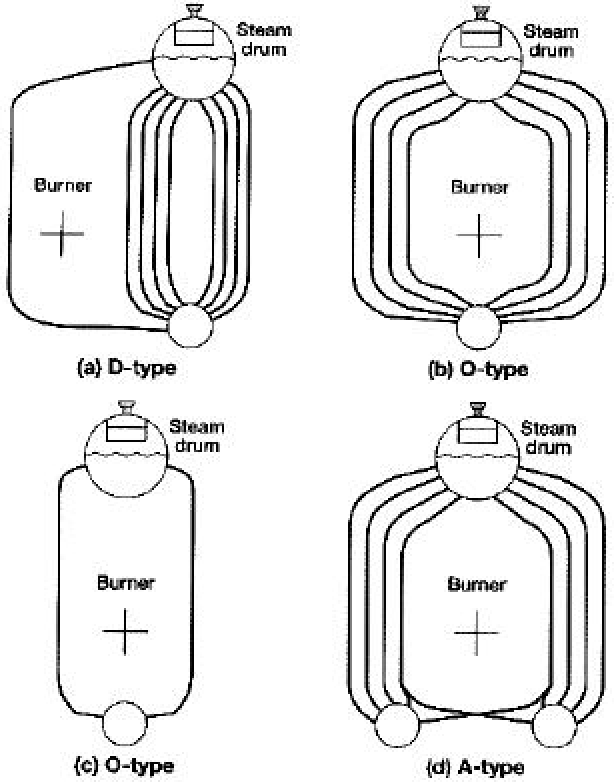

Fig. 3. Boiler tube configurations.

formation. But this method has less impact on conversion of fuel- the convection pass and furnace. The bottom drum in the 0-type may be replaced by two smaller drums resulting in an A-type configuration (Fig. 3d).

Generally, packaged boilers operate with a pressurized furnace design. A forced-draft fan sends combustion air through the burner. It then sends resulting flue gases all the way to the stack. Furnace pressures as high as 30 to 40 in $_{H}$20 are common. Natural circulation principles are used to circulate a steam-water mixture through the riser tubes in all of these units.

How emissions impact design of packaged boilers. Generally, NO_X levels of 30 to 80 ppm and CO levels of 150 to 300 ppmv can be attained by using gas recirculation, staged fuel or air combustion, low-NO_x burners, steam injection and excess-air control. Some regions require less than 9 ppmv NO_x and over an 85% reduction in CO. This can be attained only with a selective catalytic reduction system (SCR). These are very expensive, on the order of 20% to 35% of boiler cost.

Boiler design is impacted by emissions. Gas recirculation increases gas pressure drop through the boiler and also affects gas/steam temperature profiles. Typically, 5% to 15% gas recirculation is used. High excess air, around 15%, may also be required to control NOx and CO. If gas recirculation is used, a separate recirculation fan can transport cool flue gases from the boiler's rear to the flame region. Alternatively, a forced-draft fan may induce flue gases. Addition of cool flue gases at the burner region reduces flame temperature and, thus, limits NO_x bound nitrogen to NOx, as with liquid fuels.

Furnace dimensions should be discussed with the burner supplier so that modeling of flame characteristics can be done for emissions and burnout. The partition wall that separates the furnace and convection section must prevent leakage of flue gases because gas pressure can be 10 to 30 in $_{H}$20 higher in the furnace. Leakage can result in higher CO emissions due to incomplete combustion.

Completely water-cooled furnaces. A completely water-cooled membrane wall design that has the front and rear walls cooled in addition to the sides (Fig. 1) offers the maximum cooling surface for a given volume. This results in lower heat release rates and, therefore, a lower heat flux. The cool front-wall design also helps to minimize NO_x formation. This is because most NOx forms in a zone close to the start of the flame where a cooler front wall helps. A refractory-lined front wall or floor radiates energy back to the flame which increases NO_x formation. A few decades ago, refractory-lined floors and front/rear walls were common. But a completely water-cooled design results in lower heat release rates, lower emissions and fewer refractory maintenance problems. So plant engineers and consultants generally prefer a boiler with little or no refractory.

Superheater design. Superheaters in packaged boilers are preferably the convective, drainable type. They are located at an appropriate place in the convection section depending on required steam temperature and load range over which the steam temperature should be maintained. If the superheat requirement is small, around 20°F to 50°F, the superheater may be located between the evaporator and economizer. An interstage desuperheater can control the steam temperature if its actual value exceeds the desired value.

Packaged boiler performance characteristics. Major boiler performance characteristics of interest to the plant engineer are:

- Efficiency
- Steam/gas temperature profiles
- Emissions
- Efficiency

Boiler efficiency depends mainly on excess air and exit gas temperature. Fig. 4 shows major boiler heat losses and the effect from exit gas temperature and excess air on efficiency. Either the lower heating value (LHV) or higher heating value (HHV) should be used when specifying boiler efficiency. The relation between the two is: efficiency (LHV basis) X LHV =efficiency (HHV basis) X HHV (1)

The variation of several parameters with load or duty for a typical gas-fired packaged boiler is in Fig. 4. The gas flow decreases at lower loads, and with the same surface area, a larger decrease in gas temperature occurs. A 40°F decrease in stack gas temperature is equivalent to about a 1% improvement in efficiency. However, efficiency does not vary significantly with load as radiation losses increase in proportion to load. If the radiation loss is 0.5% at 100% Load, it would be 2% at 25% load, thus compensating for a lower exit gas temperature. Also, a higher excess air level

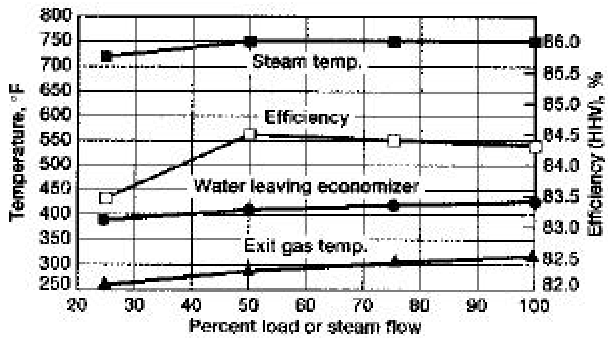

Fig. 4. Packaged boiler performance.

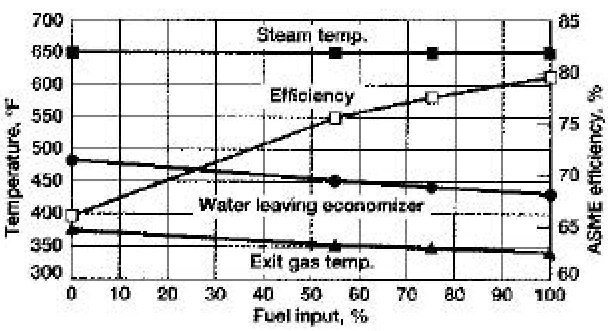

Fig. 5. HRSG performance.

may be required at lower loads for proper combustion, thus decreasing efficiency. At a load between 25% and 100%, efficiency peaks (Fig. 4) due to exit gas loss and radiation loss.

Gas/steam temperature profiles. The gas temperature throughout the boiler decreases as load decreases, starting from the furnace outlet. As a result, the convective superheater also absorbs less energy at lower loads, resulting in a lower steam temperature. If a constant steam temperature is desired from 60% to 100% load, the design approach is to ensure the desired steam temperature at 60% load. At higher loads, steam temperature is higher and can be controlled using interstage spray.

Feed water temperature leaving the economizer decreases at lower loads. The approach point (difference between saturation steam temperature and water temperature leaving economizer) increases with load. This is because the ratio of gas flow to steam flow is maintained near unity in packaged boilers. With a given surface area in the economizer and a lower inlet gas temperature, the energy transferred is lower. Conversely, the approach point decreases at lower loads in gas turbine HRSGs, leading to steaming conditions in the economizer. This is due to a higher gas flow to steam flow ratio in gas turbine units, where gas mass flow does not decrease with load as in packaged boilers. Hence, the economizer transfers a large amount of energy, though the steam flow is low, resulting in lower approach points at lower loads.

Heat-recovery steam generators.

Large HRSGs are generally the convective type (Fig. 2). But they can resemble large utility boilers with radiant furnaces if the firing temperature is above 1,600°F to 1,700°F. The duct burner is located ahead of the HRSG, which consists of a superheater, evaporator and economizer. Additional modules may be required in multi-pressure units. If a constant steam temperature is required at all loads, the design philosophy is to make sure that the steam temperature is achieved at unfired conditions. In the fired condition, although steam generation is larger, steam temperature is also higher due to a higher inlet gas temperature. Desuperheating may be restored to control the steam temperature. Simulation methods can be used to predict HRSG performance at different conditions.[3]

Table 1. Gas-turbine exhaust conditions vs. ambient temperature

Amb. temp, °F	Gas flow, lb/h	Gas temp, °F
10	588,600	
60	545,600	
100	474,300	

Table 2. HRSG performance (unfired) vs ambient temperature

Ambient temp, °F	10	60
Gas flow, lb/h	588,600	545,600
Gas temp to superheater, °F	900	979
Gas temp to evaporator, °F	853	920
Gas temp to economizer, °F	516	518
Gas temp leaving economizer °F	388	374
Steam flow, lb/h	74,000	80,700
Steam temp, °F	632	647
Feed water temp, °F	250	250
Leaving economizer, °F	492	482
Approach point, °F	7	17

Note: steam pressure = 650 psig; 3% blow down. Exhaust analysis, vol %: = 10.2, N_2 = 73.6, 0_2 =12.9 HRSG consists of superheater, evaporator and ec

Gas turbine HRSGs, unlike packaged steam generators, have fewer options for controlling emissions because exhaust gases are generated at the turbine. Modifications in gas-turbine combustors and steam/water injection have resulted in a low-NO, exhaust, around 40 ppmv. Gas turbine HRSGs refer to NO_x and CO at 15% oxygen dry volume whereas packaged steam generators use 3% oxygen as the basis. [1,2] If a NO_x level down to 9 ppmv is desired, an SCR is presently the only option. But combustors are now being developed by some large gas-turbine manufacturers to achieve less than 10 ppmv NO_x. SCRs may be located at suitable gas temperature zones to maximize emission reductions by separating the evaporator or superheater modules.

Basic differences between HRGs and packaged boilers.

Effect of ambient temperature. In packaged boilers, the required combustion air is the same for a given fuel at any ambient temperature if excess air is maintained. Hence, flue-gas mass flow at a given load does not vary with ambient conditions. It is important to select a forced-draft fan to handle the desired combustion air mass flow at the lowest density case, which results in the largest volume of air. Control methods, such as inlet vane modulation, adjust the combustion air flow to maintain desired excess air or air/fuel ratio.

Conversely, a gas turbine is a volume machine. The exhaust gas flow and temperature characteristics vary with ambient conditions in single-shaft machines (Table 1). This has some effect on HRSG performance, particularly on approach point, exit gas temperature and steam generation. Table 2 shows the performance of a HRSG for different ambient conditions based on data from Table 1. Note that the exit gas temperature is higher and approach point is smaller at low ambient conditions.

Efficiency vs. load. Fig. 5 shows the characteristics of a gas turbine HRSG vs. load (steam generation) at a given ambient temperature. At the lowest load, exit gas temperature is the highest and as the supplementary firing increases, more steam is generated at a higher efficiency. The ASME efficiency is defined in power test code 4.4 for HRSGs.[4]

The reason for the difference between HRSGs and packaged boilers is: Gas turbine exhaust typically contains 15 vol% oxygen and the mass flow through the HRSG varies only slightly with load. At higher steam demand conditions, this excess oxygen is used without adding air by raising the exhaust gas temperature to generate more steam. In effect, the excess air is reduced at higher loads. Also, due to the smaller ratio of gas/steam flows at higher loads, the exit gas temperature decreases with increased load. All these factors, coupled with lower radiation losses, result in significant improvement in efficiency with load.

Steaming in economizer. This is a concern at lower loads in HRSGs because the gas to steam ratio is very high and increases at lower loads. It is nearly unity in packaged boilers at all loads. Hence, a large increase in water temperature occurs in the economizer at lower loads in HRSGs, thus reducing the approach point.

Steam temperature. If the superheater is designed for a particular temperature in the unfired mode, it will increase at higher loads due to higher firing temperatures. This trend applies to HRSGs and packaged boilers. Generally, convective superheater designs are used in larte HRSGs (Fig. 2).

The author

V. Ganapathy is a heat transfer specialist with ABCO Industries Inc., Abilene, Texas. He is engaged in the engineering of heat recovery boilers for process, incineration and cogeneration applications and packaged water tube steam generators. He also develops software for engineering of heat recovery systems and components. He holds a B Tech degree in mechanical engineering from Indian Institute of Technology, Madras, India, and an MSc(eng) in boiler technology from Madras University. Mr. Ganapathy is the author of over 175 articles on boilers, heat transfer and steam plant systems and has written five books: Applied Heat Transfer, Stream Plant Calculations Manual, Nomograms for Steam Generation and Utilization, Basic Programs for Steam Plant Engineers (book and diskette), and Waste Heat Boiler Deskbook, copies of which are available from him. He also has contributed several chapters to the Encyclopedia of Chemical Processing and Design, Vols. 25 and 26, Marcel Dekker, New York.

Emissions. As mentioned above, the only option for emission control in HRSGs is using an SCR, while in packaged boilers several options are available.

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Composition that boiler feedwater should have depending on boiler working pressure.Â Characteristics of boiler feed water. Water absorbs more heat for a given temperature rise than any other common inorganic substance. It expands 1600 times as it evaporates to form steam at atmospheric pressure. If the boiler is oversized, the fuel bills will be excessive. If the boiler is undersized, it may not generate enough heat in winter. The ideal size for a boiler is one that just copes adequately on the coldest day of the year. Most boilers are oversized by at least 30%. This is due to the way systems used to be calculated with a card calculator.Â In many packaged boiler installations, the combustion air fan is designed and provided by the boiler manufacturer and is integral with the boiler housing. In installations where a stand-alone fan is provided, low-pressure centrifugal blowers are commonly used. An important characteristic of the blower is the ability to maintain a relatively constant air pressure over a wide range of airflows. Talk Page. Flue. To understand heat exchanger thermodynamics, a good starting point is to learn about the three ways in which heat can be transferred â€“ conduction, convection, and radiation. In the sections below, a review of each of these heat transfer modes is presented. Conduction.Â Based on the design characteristics indicated above, there are several different variants of heat exchangers available. Some of the more common variants employed throughout industry include: Shell and tube heat exchangers.Â Boilers, condensers, and evaporators are heat exchangers which employ a two-phase heat transfer mechanism. As mentioned previously, in two-phase heat exchangers one or more fluids undergo a phase change during the heat transfer process, either changing from a liquid to a gas or a gas to a liquid.