What you should know about boilers and performance

Specifying a boiler is straightforward if you know what to look for in a boiler

V. Ganapathy, ABCO Industries, Abilene, Texas Most industrial plants use oil- and gasfired steam generators. Whenever a plant needs a steam generator or boiler, it hires a consultant or an A/E firm to develop specifications, evaluate bids from vendors, and purchase the boiler. Often, plant engineers and operators that must live with the boiler for several decades are never consulted. First cost considerations prevail in many cases and the end user or the plant is left with a boiler that has either too many maintenance problems or high operating costs. Before this happens to you, consider a few important aspects of boiler performance and some recent trends in their design. You then can ask the right questions of consultants or A/E firms and be involved in the evaluation process before making a purchasing decision.

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Trends in boiler designs

Packaged steam generators are available in capacities to 250,000 lb/h of steam at pressures to 1,500 psi and steam temperatures to 1,000 degr F Emissions of NO_x are typically less than 30 ppmv for natural gas and less than 100 ppmv for CO. Low-NO_X burners with fuel/air staging and flue gas recirculation achieve these results. A few places such as California require emissions of NO_x and CO below 9 ppmv and selective catalytic reduction systems achieve those levels. The high flame temperatures of fuels of high hydrogen content yield higher NO_x emissions.

The temptation A/E firms and consultants face is selecting or accepting standard models or pre-engineered designs to capitalize on their low initial cost. However, these designs are not suitable for every situation. These designs must make serious compromises in performance-efficiency, fuel costs, boiler gas pressure drop, fan operating costs assuming that desired emission levels can be met.

The design of packaged steam generators has seen several improvements. For example, water-cooled furnaces have advantages over refractory lined casings so prevalent decades ago. Radiant or semi-radiant superheaters were the norm in early designs. These exhibit operating problems such as tube over-

Table 1: Effect of excess air, FGR on flue gas

item	case 1	case 2	case 3	case 4	case 5	case 6
duty,MM	100.2	100.2	100.2	118.8	118.8	118.8
Exit gas, degr F	320	320	500	320	320	700
excess air, percent	10	15	15	10	15	15
FGR, percent	0	15	15	0	15	15
gas flow, lb/h	100385	120730	127100	119,000	143,150	160,000
fuel input, MM	119.3	119.6	125.9	141.4	141.8	158.6
Gas pr drop, in wc	10	15	16	14	20	27
Fan power, kW	68	104	114	98	150	209
efficiency, percent HHV	84.00	83.80	79.57	84.00	83.80	74.90

Cases 1 through 3: 100,000 lb/h, 150 psig saturated steam, 230 degr F feed water, 3 percent blowdown. Cases 4 through 6: 100,000 lb/h, 600 psig, 750 degr F steam, 230 degr F feedwater, 3 percent blowdown. This table does not consider that with larger flue gas quantity flowing through a given boiler, the exit gas temperature is higher. Approximately 40 degr F increase in exit gas temperature decreases boiler efficiency by 1 percent. This is equivalent to $30,000 based on fuel cost of 3 $/MM BTU.

Table 2: Comparison of surface areas

item	boiler 1	boiler 2
Heat release rate (BTU/ft³ h° F)	90,500	68,700
Heat release rate (BTU/ft² h° F)	148,900	116,500
furnace length (ft)	22	29
furnace width (ft)	6	6
furnace height (ft)	10	10
furnace exit gas (degr F)	2,364	2,255
boiler exit gas (degr F)	683	611
economizer exit (degr F)	315	315
furnace proj area (BTU/ft² h° F) (duty)	802 (36.6)	1,026 (40.4)
boiler surface (BTU/ft² h° F) (duty)	3,972 (53.7)	4,760 (52.1)
economizer surface (BTU/ft² h° F) (duty)	8,384 (10.5)	8,550 (8.3)
Geometry	evap/econ	evap/econ
tubes/row	11/15	10/15
no. deep	66/14	87/10
length (ft)	9.5/11	9.5/10
eco fins/in, ht, thick, serr	3x0.75x0.05x0.157	5x0.75x0.05x0.157
transverse pitch (in)	4.0/4.0	4.375/4.0
overall ht trans coeff	18.0/7.35	17.0/6.25

Parameters: 100,000 lb/h, 300 psig sat'd steam, 230° F feedwater, 2 percent blowdown, natural gas fuel, 10 percent excess air, boiler duty = 100.8 MM BTU/h, efficiency (HHV) = 84.3 percent, furnace back pressure = 7.0 in wc.

heating and frequent tube failures. The trend is to use shielded convectioe superheaters with interstage desuperheating to achieve longer life and lower tube wall temperatures.

Avoid air heaters as heat recovery equipment because of their impact on combustion temperatures and NO_x levels. Instead, opt for economizers. Also, the pressure drops for gas/air are higher with air heaters. That leads to higher fan operating costs. Back-end corrosion is more of a concern in air heaters compared to economizers. Manipulating tube pitch, length, and size or using extended surfaces in the convection section significantly reduces gas pressure drop through boiler while optimizing energy transfer.

To summarize, look at custom-designed boilers when evaluating options for packaged steam generators. Look for reduced maintenance concerns, lower operating costs, and meeting the emission levels. Don't focus exclusively on first cost.

Why standard designs and models are unsuitable

A 100,0001b/h *model* delivers a nominal 100,000 lb/h steam. In the early days, several boiler firms developed standard models or designs for various capacities. Unfortunately, one reason these standards are still being used today is that they save a lot of engineering effort and drafting time for the boiler firms. It is also convenient for the consultants as they can select a model with known overall dimensions, weights, and other measures to let them proceed with layout and engineering.

However, what the consultant does not consider is the fact that boiler duty, fuel heat input, air flow, and flue gas quantity, and efficiency vary with steam parameters. Excess air and flue gas recirculation rates vary by fuel and the emission levels of NO_x and CO to be attained. These, in turn, affect the total flue gas quantity flowing through the boiler. Also, a superheater and economizer affect the duty.

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Furnace geometry is a function of emission levels. The burner supplier must evaluate flame shape using modeling techniques and the furnace dimensions.

Lacking a proper evaluation, a standard boiler furnace is likely to have flame impingement problems. Often, 10 to 20 percent excess air and 10 to 20 percent flue gas recirculation rates meet emission levels of less than 0.05 lb NOx per million BTU input.

Decades ago when concerns over emissions were minimal, excess air was typically 5 to 10 percent with natural gas and flue gas recirculation was unknown. The objective then was to maximize efficiency alone.

As shown in Table 1, the flue gas quantity flowing through the boiler varies significantly depending upon duty and efficiency, even at constant boiler capacity. This results in high gas pressure drop and fan power consumption. The table assumes that the standard boiler is not modified to reduce gas pressure drop. It assumes constant tube size, pitch, and dimensions. With a given boiler size, the exit gas temperature increases with increased flue gas quantity. This leads to lower efficiency and more fuel consumption and, in turn, higher flue gas flow. Thus, the boiler performance is completely different from what the standard boiler was supposed to do.

For example, in Case 5 of Table 1, the additional fan power consumption is 70 kW over Case 1. With electricity cost at 5

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cents/kWh, the annual incremental cost is $28,000. Hence, simply by overlooking the gas pressure drop, the consultant does a disservice to the plant or end-user. These calculations do not consider the effect of lower efficiency. With a lower efficiency resulting from higher exit gas temperature, the fuel input increases along with the flue gas quantity and gas pressure drop. The design of a custom designed boiler considers the duty and the excess air, and flue gas recirculation rates on a case-by-case basis. A good evaluation considers the operating costs for fuel and electricity.

Also the furnace dimensions of standard units may not suitable for the fuels available and current emission levels. Flame shape is a function of excess air and flue gas recirculation rates. The furnace width, height and length may need to be increased to avoid flame impingement. As a result, a standard model may have a much higher furnace exit gas temperature that leads to radiant superheater tube failures, high boiler exit gas temperatures, and lower efficiency. With a standard or prepackaged design, the customer gets a poorly compromised option though the price and delivery terms may be attractive. The additional cost of a custom-designed boiler may have a payback of under a year.

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Water-cooled furnaces

One of the recent improvements in packaged boiler design is the water-cooled furnace that offers several advantages over refractory lined furnaces. The furnace front, rear as well as side walls and floor are of membrane wall construction. This results in a leak-proof enclosure for the products of combustion. It eliminates gas leakage and corrosion of casing as seen in boilers with refractory lined front/rear walls.

The water-cooled design eliminates problems associated with refractory maintenance. Plant engineers and personnel are familiar with the time it takes to replace boiler refractory and the amount of fuel wasted in heat-up procedure.

Fast boiler startup and heating rates are not a concern with water-cooled designs. The entire furnace expands and contracts uniformly as a unit. This eliminates relative expansion problems that occur at the interfaces between watercooled walls and refractory casings. Fast heat up rates are important in cogeneration projects in which the packaged steam generator must deliver steam to the customer within minutes of shut-down of the gas turbines and HRSGS. Fast startup rates also conserve substantial fuel over the long-term.

For a given volume, the water-cooled unit has lower furnace area heat release rates and heat fluxes because the front and rear water-cooled walls provide additional effective surface area. Also, some boiler suppliers still use refractory on the furnace floor that decreases the effectiveness of the cooling surfaces.

The cooling of the flame and the reradiation from the refractory walls impacts NO_x formation. In the case of completely water-cooled furnaces, the cooler envelope for the flame reduces the NO_x levels. In the case of boilers with a refractory-lined front wall, the reradiation from the refractory increases the combustion temperature, thus adding to the NO_x formation. A significant amount of NOx forms near the flame front and a cool envelope in the form of watercooled front wall helps.

Some boiler vendors even use refractory on the floor, a practice taken from decades ago when engineers were not familiar with heat fluxes and boiler circulation. They had to resort to this practice to prevent floor tubes from overheating. However there are hundreds of boilers without floor refractory in operation. The increased area available for cooling the flue gases reduces the furnace exit gas temperature. In several boiler designs, floor refractory added to the problems of failures of radiant superheater tubes located at the furnace exit. Floor refractory also adds to the flue gas recirculation levels and increases the furnace heat release rate and heat flux and increases furnace exit gas temperature.

The welded membrane partition wall between the furnace and convection section also avoids bypassing of the hot flue gases from the furnace to the convection section. Earlier designs used tangent tube construction for this partition. That promoted the formation of CO as it provided inadequate residence time for the combustion products. Increases in CO content not only decrease boiler efficiency but also add to emission levels.

Radiant and convective superheaters: a comparison

Radiant superheaters were the norm in the earlier designs of packaged boilers. They are located at the furnace exit directly facing the flame or at the turn to the convection section. Custom-designed boilers locate the superheater beyond a screen section and the size of the screen section can be varied depending upon the degree of superheat.

Predicting the convective superheater performance is easier and more accurate.

The radiant superheater is located at the furnace exit. Variations in excess air, flue gas recirculation rates, and flame patterns make the exit gas temperature difficult to predict. It could vary by 100 to 200° F from predicted values. The boiler supplier could be under-estimating the tube wall temperature by 50 to a few hundred degrees thus endangering the life of the tubes. At 2,300 to 2,500° F the radiant energy is intense and significant. The region is also subject to significant turbulence and non-uniformity in gas temperature profiles due to the turn involved. Predicting the tube wall tem-

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perature is difficult. The only advantage is that the superheater is lower in cost because it is smaller. It requires less surface area because of a higher log-mean temperature difference.

The convective superheater, on the other hand, is located at a zone of low gas temperature. The superheater is shielded by several screen rows that ensure not only the cooling of the flue gas but also aid in better mixing and uniformity in gas temperature profiles. Predicting the convective superheater performance is easier and more accurate. The screen section can be designed such that the gas temperature at the superheater inlet could vary from 1,000 to 1,900° F depending on steam temperature. The advantage is longer life derived from lower and predictable tube wall temperatures

. Several boilers operate at part loads for significant periods of time. The radiant superheater operates at higher radiant fluxes at lower loads compared to convective designs. Also, at partial loads, the steam flow distribution through superheater tubes as well as the gas flow across it will not be uniform. It is difficult to ensure uniform flow through the tubes because of the low steam-side pressure drops involved. If, say, at 100 percent load the superheater pressure drop was 50 psi, then at 25 percent load it is hardly 3 psi. Low pressure drop causes flow maldistribution, keeping some tubes from minimum steam flow required for cooling and thus overheating them. When the radiant flux in the radiant superheater is more, the cooling effect is reduced-a double negative. In convective designs, the gas temperatures are lower at lower loads, the heat fluxes are lower and lower steam flows will not cause increases in tube wall temperatures compared to radiant designs

It is possible to have interstage desuperheating with convective designs, while most radiant designs have a single stage, that can result in higher steam temperatures and tube wall temperatures at lower loads. Interstage desuperheating ensures that the steam temperatures do not exceed the desired final steam

Surface area can be misleading Now that computers and spread sheet programs are easily available, a common problem among even experienced boiler engineers is comparing different designs based on surface areas. I strongly recommend against this practice. Surface area (S) is given by the equation $Q/(U \times \Delta T)$ where Q is the energy absorbed by the surface (Btu/h), U is the overall heat transfer coefficient (BTU/ft' h° F), and ΔT is the log-mean temperature difference (° F). Unless you are familiar with computing heat transfer coefficients, do not compare on the basis of surface area. Also ΔT could vary depending on the gas temperature in the zone where the surface is located.

Use of finned tubes also distorts the picture significantly. With finned tubes, the surface areas can be 100 to 200 percent higher while transferring the same duty. This is due to poor choice of fin configuration. Tubes with high fin densities have lower heat transfer coefficients and *vice versa*. In a packaged steam generator it is possible to transfer duty among radiant section, convection, and economizer in different ways. This results in different surface areas as shown in Table 2. Note that the boiler duty, efficiency, and gas pressure drop are the same for both options. The economizer uses a higher fin density in boiler 2 thus requiring more surface area while transferring lesser duty. Unless you know how to compute U and can develop the gas/steam temperature profiles, comparing S values is meaningless. If gas pressure drops were different, the variations in surface areas would have been more compelling.