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TRENDS IN PACKAGED BOILER DESIGN

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INTRODUCTION

Designing large package boilers is more challenging than ever. Demand from the marketplace is increasing for special features including low emissions, quick startup requirements, hot standby operation, heavy cycling ability, high turndown and increased efficiency, to name a few. It is no longer feasible for a Plant Engineer to select a boiler out of a catalog that will meet his exact needs. The same holds true for boiler manufacturers, who must evaluate several heat transfer scenarios before arriving at a final design. The standard boiler models developed decades ago may not be suitable for today's needs. New boilers have to be engineered carefully, taking into consideration burner requirements such as excess air, flue gas recirculation (FGR) and burner flame shape, which impacts the furnace geometry. Boiler heating surface & tube spacing has to be optimized to obtain good thermal performance and low fan power consumption over a wide load range. Performance of ancillary equipment has to be evaluated to ensure proper integration. In short, custom design is the key to success in today's industrial watertube boiler market.

This article outlines two unique boiler systems recently engineered and supplied by Cleaver Brooks Engineered Boiler Systems group that are in successful operation in North America. The first is a 150,000 lb/hr, 650 psig, 750°F superheated Nebraska D-type standby boiler for a city utility power plant (Fig 1). The second is a 426,000 lb/hr, 550 psig saturated Nebraska boiler (Fig 4) for an Oil Major with an Elevated Steam Drum and an innovative closed-loop glycol heat recovery system to boost efficiency. Both systems are natural gas fired.

Fig 1: (Addendum) Custom designed 150,000 lb/hr Nebraska D Type superheated steam boiler engineered for future low emissions with finned tube convection bank (shown ready to ship via railcar).

BOILER DESIGN FOR FUTURE LOW NOX REQUIREMENTS AND STANDBY OPERATION

This 150,000 lb/hr Nebraska boiler system is unique in many ways. The boiler operates as a standby boiler in conjunction with the main Gas Turbines and HRSGs at a city utility, and is designed to operate as an integral part of the overall plant. Several custom-engineered features are summarized below:

- The system is "future 15 ppm ready". It is currently operating at 76 ppmv NOx, in accordance with current emissions regulations in the area. However, the city engineers wanted to plan ahead and purchase a system that can easily be converted to lower emissions in the future. The excess air and FGR rates were determined to be 15% and 5% respectively for meeting 76 ppmv. However, to meet the future 15 ppmv NOx limit, 20% excess air and 25% FGR are required. This has an significant impact on the overall boiler design due to the large variation in flue gas flows as seen in Table 1. Several options were modeled with bare and finned tubes in the convection bank. An optimum configuration was arrived at considering the gas pressure drop, economizer exit gas temperature and fan power consumption. Multiple rows of finned tubes of density 3 fins/in were used in the low-temperature zone of the convection bank to optimize the energy transfer. The "approach" point (temperature difference between saturation and water temperature leaving the economizer) will be affected by the large variations in flue gas flow through the boiler. The approach point is particularly important as the water leaving the economizer is used to condense steam for use as sweetwater for the interstage spray desuperheater (discussed in further detail below). Boiler bank tube spacing is wider than normal to accommodate the variations in flue gas flow through the boiler. This custom approach alleviates the city utility's concerns about future emissions regulations. Only the FD Fan and Burner spuds need to be replaced should regulations become more stringent.

- As an auxiliary boiler, the unit will be in standby condition most of the time, but must be able to achieve full load within 4-5 minutes upon a system trip of the main HRSGs. This requirement was achieved with some outside-of-the-box thinking. Cleaver-Brooks' proprietary Natcom burner includes a unique "Center Core" stabilizing gas injector (Fig 2) that is usually used to improve flame stability and turndown. For this application, the Center Core is also used as a second smaller burner during hot standby. Heat input is approximately 5% MCR. This maintains the boiler at pressure so it can be ramped to full load in a short period. A small dedicated fan is used during hot standby to avoid operating the main FD Fan, which saves considerable money over time. An added benefit of this design is that the air purge cycle normally specified by NFPA is not required since the burner is already running. Once the main fan is started up, the main gas lances are lit off and the unit can immediately begin ramping, which saves time. A lower drum steam heating coil is also provided to further assist in maintaining the boiler in hot standby conditions.

Fig 2: (Addendum) Close-up view of Cleaver-Brooks' Natcom burner showing unique Center Core stabilizing gas injector, which is used to achieve high turndown while maintaining the boiler in hot standby.

- The feedwater for the boiler is condensate from the steam turbine at about 90°F. The city engineers chose not to utilize a traditional Deaerator for this system, which preheats the condensate in a typical system. As such, this cold condensate must be preheated above the flue gas water dew point prior to entering the economizer to avoid corrosion. The city utility engineers wanted a large margin to ensure no condensation occurred. Therefore, 200°F was chosen as the inlet feed water temperature. A shell-and-tube heat exchanger was selected to preheat the condensate. Also considering the extended operation at low loads, a parallel water flow economizer was specified by the city engineers to further avoid corrosion.

- A dual-stage superheater system was provided. This design incorporates interstage spray attemperation to maintain a steady steam temperature over turndown. A modulating control valve varies the amount of spray injection based on a signal from a temperature transmitter located downstream in the main plant piping. The 2nd stage superheater ensures that the spray water is fully heated which avoids the potential for any water droplets eventually reaching the turbine blades.

- Since the customer did not want to inject the condensate directly into the steam for superheater temperature control, a sweetwater condensing system was utilized (Fig 3). This approach ensures high purity at the main steam outlet since it avoids adding the solids typically entrained in boiler feed water (or condensate in this case). A heat exchanger located between the economizer and the steam drum is used to condense steam into water, which is used for spray attemperation. Calculations had to be done at various loads to ensure the physical location of the exchanger provided adequate head for spray after accounting for the line and superheater steam side losses.

- The system is capable of operation from 10 to 100%. Due to this fact, the pressure drop in the superheater had to be reasonably high at full load to account for the large variation in flow. At lower loads, the steam side pressure drop can be small, resulting in non-uniformity of flow inside the tubes. This approach reduces the potential for premature tube failure. Also the location of the superheater in the convection bank was optimized considering the steam temperature variations with load.

- Welded tube-to-drum connections were used in the boiler bank and furnace instead of the typical rolled joints to minimize thermal stresses due to cycling operation and fast load changes.

- Cleaver-Brooks included their standard 5 year limited warranty on the proprietary Boiler & Burner components.

Table 1 shows the predicted performance of the boiler. Performance tests done during start-up closely matched the predicted values within instrument errors. Note the large difference in flue gas flows due to higher excess air and FGR rates.

TABLE 1: BOILER PERFORMANCE DATA (Addendum)

Load,%	100%	75%	50%	100%	75%	50%
NOx guarantee,ppmv	<76	<76	<76	<15	<15	<15
Steam flow,lb/h	150000	112500	75000	150000	112500	75000
SH pressure,psig	600	600	600	600	600	600
Steam temp,F	750	750	750	750	750	750
Feed water temperature,F	200	200	200	200	200	200
Econ gas outlet,F	382	352	323	412	381	349
Excess air,%	15	15	15	20	20	20
Flue gas rercirculation,%	5	5	5	25	25	25
Flue gas flow thro boiler,lb/h	206838	154280	102493	259486	193417	128364
Back pressure, in wc	13.31	7.16	3.02	21.3	11.7	5.1
Efficiency,% HHV	82.1	82.6	82.9	81.0	81.6	82.1

Standard natural gas is the fuel used. Note the variations in flue gas quantities for future conditions of lower NOx. The system was optimized for both emissions scenarios.

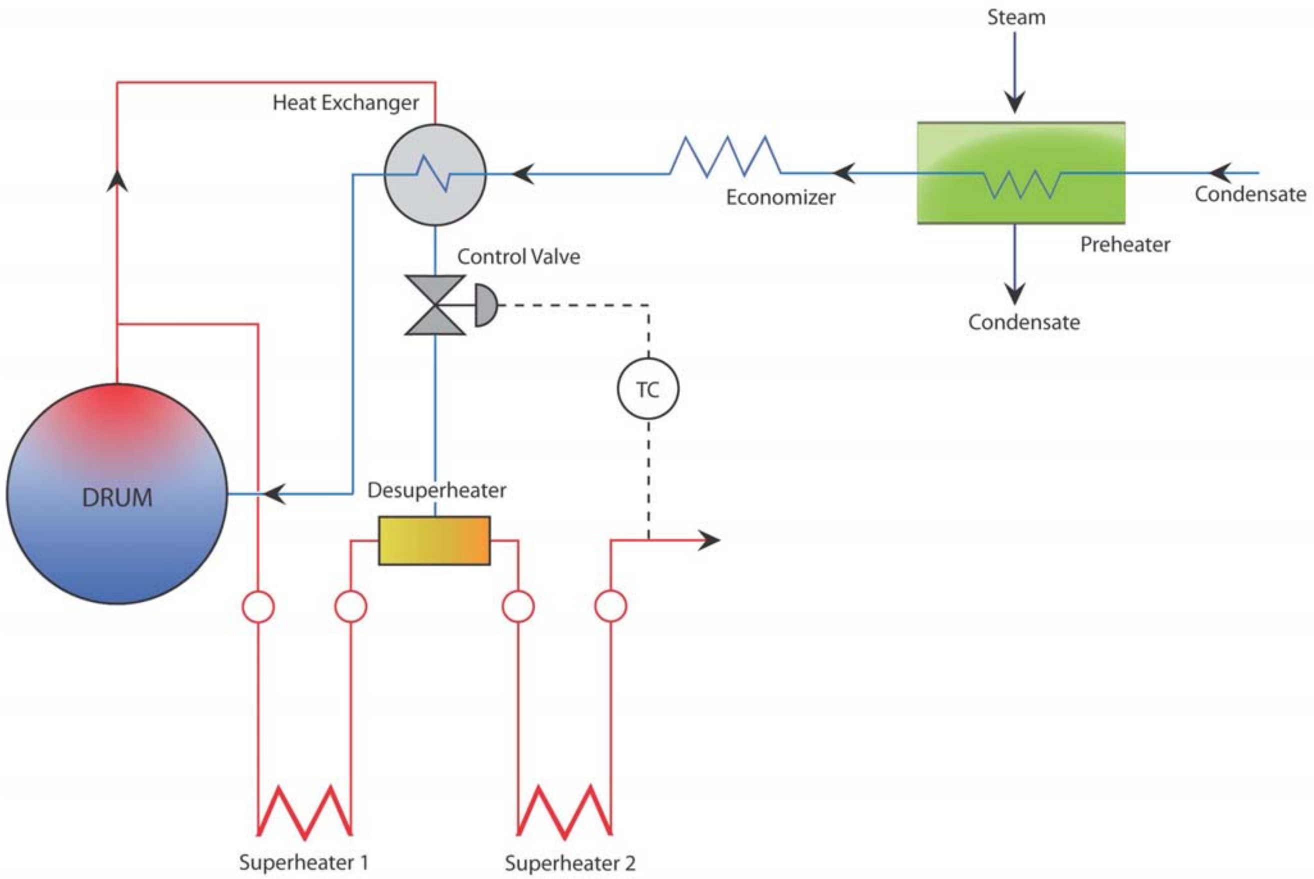

FIG 3: (Addendum) Schematic of sweetwater condensing system used for superheated steam temperature control over turndown.

LARGE PACKAGE BOILERS WITH HIGH EFFICIENCY

Designing package boilers greater than 250,000 lb/hr steam capacity is quite a challenge given the shipping limitations in the US & Canada. Typically, these larger boilers are field-erected designs built on-site by a costly army of workers. Working to address the large steam demands of the marketplace, Cleaver-Brooks developed a novel modularized design, utilizing concepts widely used in the design of their HRSG and waste heat boilers, namely an elevated steam drum (Fig 4, 5). Removing the drum from the boiler profile allows for larger furnaces and tube banks within the same shipping envelope, thus increasing capacity.

Fig 4: (Addendum) Elevated Drum package boilers, each rated for 426,000 lb/hr, shown during installation. A total of five(5) units were supplied on this project for a major oil producer.

The main boiler modules were fully shop-assembled, hydrotested, insulated, lagged and each shipped as one piece. The steam drums were hydrotested, insulated, lagged and shipped separately. Once at the jobsite, the steam drums were connected to the main boiler module by an external downcomer and riser system, the sizing of which was arrived at after a careful evaluation of the boiler circulation. The unheated downcomers ensure superior natural circulation, a common feature for HRSGs. The downcomer/riser piping is pre-fabricated and only twenty-eight (28) field pipe welds were required to complete the pressure vessel. Once the burners were mounted, each complete packaged boiler was ready to be piped up and put into service.

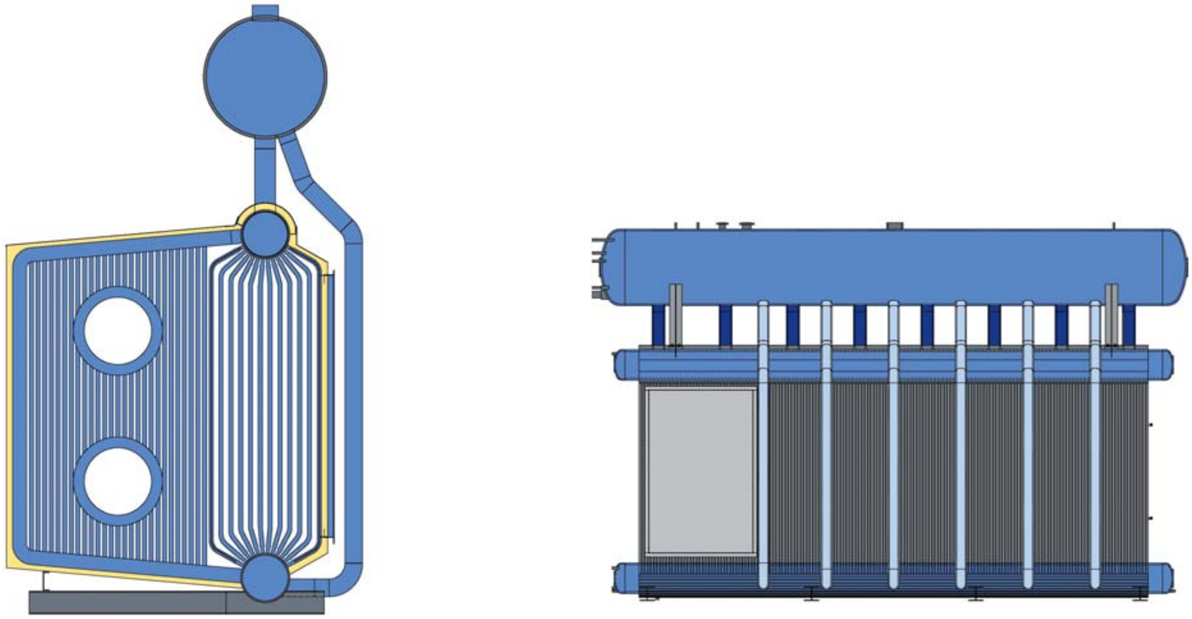

FIG 5: (Addendum) Front & side elevation views of Cleaver-Brooks Elevated Drum D-Type Boiler.

WATER-COOLED FURNACE DESIGN

A completely water-cooled membrane boiler design (Fig 6) is a standard feature of Cleaver-Brooks' Nebraska boilers. This proven design has been in operation worldwide for nearly two decades. Traditionally, burner front wall designs include refractory, which re-radiates energy back to the flame. This increases local combustion temperatures and generates additional NOx. Some older designs also had refractory around the burner throat and on the floor. Much of the NOx formation occurs at the front end of the furnace, hence a membrane front wall with a refractory-free burner throat helps reduce NOx. Additional advantages of completely water-cooled designs include:

- Lower heat flux for a given volume, about 9-12%, due to the higher effective area for a given furnace volume
- Lower area heat release rate
- Lower excess air or FGR rates may be used due to less intense combustion process compared to a refractory lined furnace
- Furnace is leak proof and hence no bypass of gases to second pass, which results in larger CO formation and inefficiency
- No refractory maintenance concerns – no refractory gas seals.
- Startup rates can be faster as concerns with refractory breaking or cracking are absent
- No casing leaks or corrosion concerns as the furnace is leak proof in a fully membrane wall unit
- Minimum thermal stresses between casing and tubes during startup or shut down as the entire enclosure is at a constant temperature equal to the saturation temperature of steam.

FIG: 6: (Addendum) 100% water-cooled membrane furnace design avoids costly refractory maintenance. Unit shown is a 426,000 lb/hr design during manufacture.

HIGH EFFICIENCY DESIGN

In order to improve the boiler efficiency, an innovative closed-loop glycol recirculation system was used (Fig 7). Heat is scavenged from the stack and pumped to a series of air preheaters to maximize efficiency. The typical exit gas temperature in a package boiler with economizer is 300°F. With the glycol system, the exit gas temperature could be lowered to less than 200°F, even with 230°F feed water, since the final heat sink is the glycol scavenger and not the economizer. With 200°F exit gas temperature, the boiler efficiency is at least 2-3% higher than usual, which results in substantial reduction in fuel costs for such a large packaged boiler. This approach is far superior to tubular air heaters or air-to-air exchangers used in older designs. The flue gas side pressure drop is also lower with these finned tube coils.

The jobsite was located in the Northern Canadian Oil Sands region, which experiences harsh winters. The 1st stage inlet air heater increases combustion air from a minimum -40°F to approx 50°F before entering the FD Fan. Fan reliability is improved and capital cost is reduced. The 2nd stage inlet air heater increases the air temp into the burner significantly, which reduces fuel consumption. Since this hot inlet air is downstream of the FD Fan, the power consumption is reduced compared to single-stage air heater system located upstream of the fan. A bypass system helps limit the air temperature into the fan during the summer. Table 2 shows the boiler design and geometry data.

Table 2: Elevated Drum Boiler Design Data (Addendum)

Steam generation at 120% load, lb/hr	426000
Steam pressure, psig	550
Feed water in, F	230
Boiler max duty, MM Btu/h	429
Burner duty, MM Btu/h-HHV	499
Boiler exit gas temperature, F	212
Efficiency-% HHV	86
Furnace length, ft	44
Furnace width, ft	10
Furnace height, ft	16
Furnace projected area,ft^2	2361
Furnace volume,ft^3	6400
Area heat release rate,Btu/ft^2h	177,000
Volumetric heat release rate,Btu/ft^3h	66,000
Average Heat flux,Btu/ft2h	47000
Convection surface,ft^2	11860
Economizer surface,ft^2	39900
Air heater 1,ft^2	7466
Air heater2 ft^2	22400
Scavenger,ft^2	30000

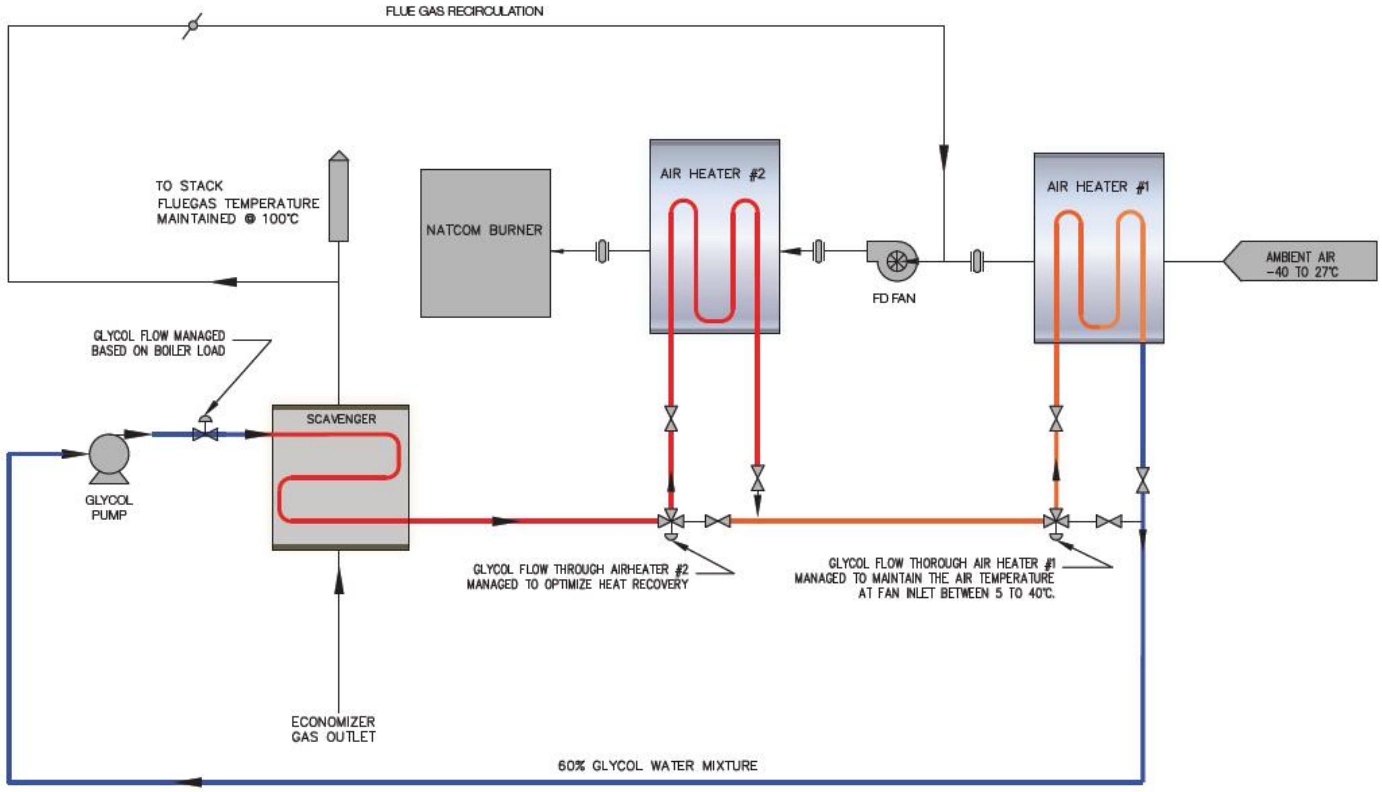

Fig 7: (Addendum) Glycol heat recovery and air heating system to improve boiler efficiency and also preheat combustion air during harsh winter months in Northern Canada.

CONCLUSION

The engineering experience gathered during the design, fabrication and commissioning of these large & highly efficient steam generators has re-assured the Cleaver-Brooks team that large package boilers can be custom-engineered and built cost-effectively while meeting a variety of unique customer needs.

Packaged industrial watertube boiler design is no longer a simple task. In fact, many consider it a science and an art. Several variables enter into the design process, which involves an understanding of each customer's unique requirements and how they can be achieved with the lowest installed and operating costs. The standard boiler vessel concept has been replaced by the benefits of custom design. Job-specific needs such as low emissions, quick start-up, standby operation, turndown and superheat have to be reviewed on a case-by-case basis. Furnace geometry & evaporator tube spacing should be modified in order to optimize the performance. Finned tubes may be considered to minimize the gas pressure drop and the footprint while also meeting the desired thermal performance. As always, all design decisions should be driven by the need to increase efficiency. By analyzing these criteria and more, maximum value can be realized for new boiler owners.

All Pictures courtesy of Cleaver Brooks Engineered Boiler Systems.