Evaluation and selection of circulating fluidized bed boilers

Fred T. Marcinek

Circulating fluidized bed (CFB) boilers differ significantly from conventional boilers. The conventional approach to boiler evaluation must be adapted to include the unique aspects of the CFB combustion process.

The use of circulating fluidized bed (CFB) boilers to generate steam on an industrial scale is increasing. The reasons for this growth include high combustion efficiency, fuel flexibility, and inherent emissions control capability, particularly with regards to control of nitrogen oxides (NOx) and sulfur oxides (SOx). However, CFB boiler technology is unique, with operating, performance, and construction features that differ significantly from those used in conventional pulverized coal (PC) and stoker-fired boiler technology.

Unique aspects of CFB boilers

Operating and performance features

The central concept of the CFB boiler is the circulating bed, which is made up of semientrained solids (fuel-ash-sorbent) throughout the furnace. Gas velocities in the furnace are on the order of 4.6–9.2 m/s (15–30 ft/s), and bed density varies relative to elevation in the furnace. Suspension and circulation of the bed requires significant fan capability, with under-bed air pressures on the order of 10–20 kPa (40–80 in. wg).

The turbulence created by suspension and circulation of the bed enhances combustion and, in cases where sulfur capture is required, maximizes sorbent utilization. The high turbulence and continuous recirculation produce a bed temperature that is fairly consistent throughout the furnace. Temperature is controlled by varying fuel and/or air flow into the furnace. By controlling the bed temperature, it is possible to:

- Obtain optimum sulfur removal [90% of the sulfur at temperatures between 1100°K and 1200°K (1500°F and 1700°F)]
- Minimize NOx generation
- Minimize if not eliminate ash slagging and fouling in the furnace and convection passes of the boiler.

The thermal inertia and firing characteristics of the circulating bed make it possible to burn a fairly broad spectrum of fuels in the same furnace. Combustion efficiencies up to 98%—comparable with that of PC firing—are possible in CFB boilers because of the high turbulence, the long particle residence time, and the continual recirculation of the bed back into the furnace, all of which enhance carbon utilization. These characteristics also maximize sorbent utilization for sulfur capture. Calcium-to-sulfur ratios on the order of 1.5 can be achieved with 90% sulfur removal when limestone is used as a sorbent.

Design features

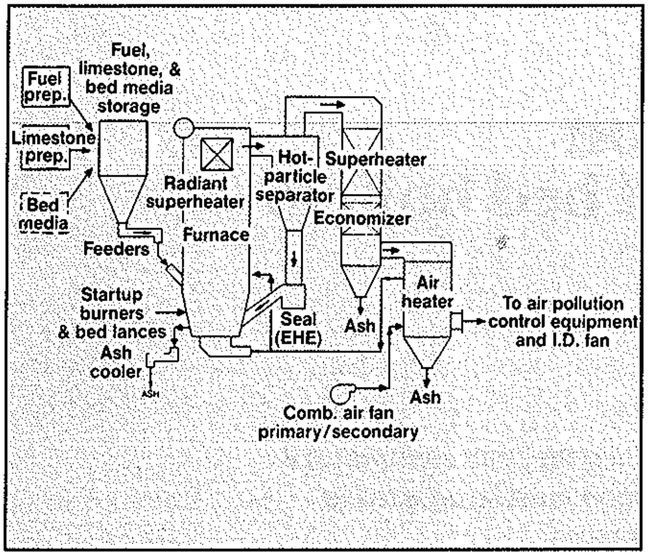
CFB boilers have a number of unique physical design features. Fuel and sorbent feed to the furnace is relatively simple. Fuel is often fed to the furnace through rotary air locks or air-swept feeders. Only two or three feed points are required for every 140,000 kg/h (300,000 lb/h) of steaming capacity. Gas- or oil-fired burners, bed lances, and/or duct burners are normally provided for startup and for operation at low load.

Perhaps the most essential and prominent features of CFB construction and operation are the hot-solids (particle) separation and solids-recycle devices. High-pressure fans, 15–20 kPa (60–80 in. wg), provide combustion air for bed fluidization and secondary air injection. The CFB boiler also may include an external heat exchanger (EHE), depending on the heating values and other qualities associated with the range of fuels to be burned.

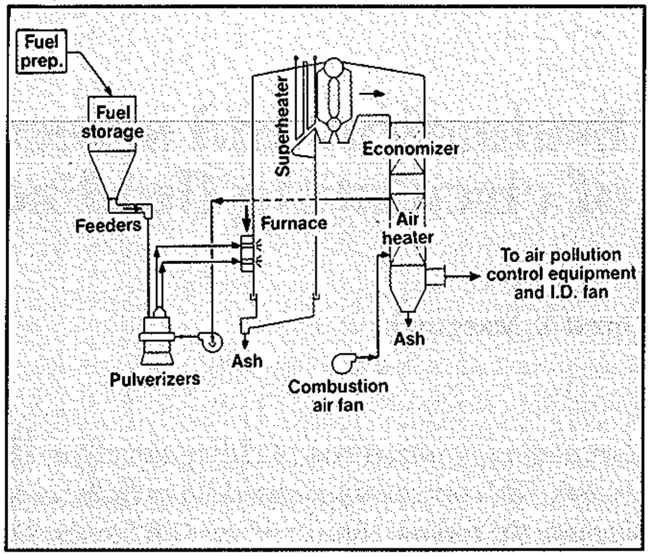
Refractory linings are provided at the lower, dense-bed portions of the furnace water walls and at high-velocity areas that would be subject to erosion, such as the furnace exit, the hot-particle separator, and the outlet duct to the back pass. There is no grate or ash pit as with conventional boilers. However, ash is removed from the bottom of the furnace to an ash cooler and often is conveyed to ash storage

Marcinek is a mechanical engineer with Charles B. Tibbits and Associates, 302 Norton Bldg., Seattle, Wash. 98104.

1. Typical configuration for CFB boiler



2. Typical configuration for PC boiler



by conventional means.

Figures 1, 2, and 3 illustrate typical configurations for CFB, PC, and stoker-fired boilers, respectively.

Suppliers

CFB boiler technology is still developing, and there are significant differences among the designs offered by various suppliers. The key areas where these differences occur include:

- Solids inventory
- Solids recirculation rate
- Hot-solids separation and reinjection
- Use of an EHE
- Gas velocity and density
- Fuel and limestone preparation
- Thermal loading
- Use and location of refractory
- Power requirements.

A mill contemplating the purchase of a CFB boiler must evaluate these differences within the CFB market as well as those features that distinguish CFB boilers from conventional technology.

CFB boiler evaluation

The procurement process for a CFB boiler is similar to that of a conventional boiler. Specifications for a boiler generally include consideration of the following criteria:

- Performance fuels
- Alternative fuels
- Unit capacity
- Main steam pressure and temperature
- Unit turndown
- Economizer inlet water temperature
- Exit gas temperature
- Flue-gas emissions requirements.

Boiler performance is generally evaluated on the basis of the following criteria:

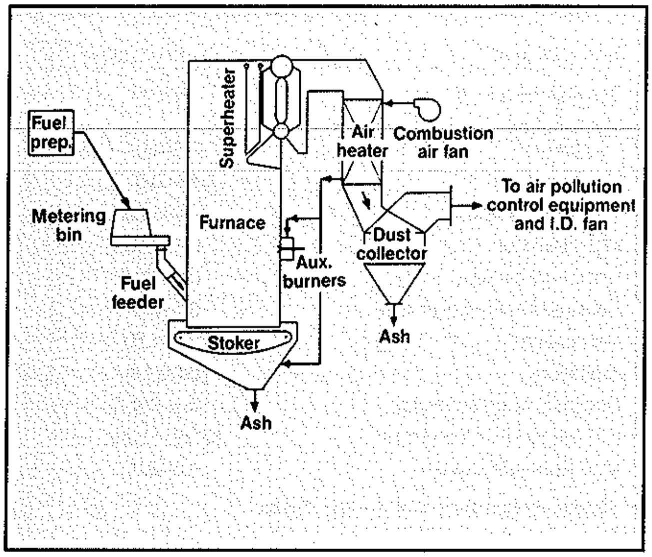
- Unit output
- Unit efficiency and performance guarantees
- Fuel burn rate
- Combustion-air requirements
- Flue-gas flow rates
- Emissions guarantees
- Temperature profiles
- Velocity profiles
- Draft losses
- Power requirements
- Furnace size
- Plant configuration
- Maintenance requirements
- Redundancy provisions
- Performance history.

These and other items should be included in any detailed boiler evaluation. However, a detailed review of all aspects of CFB boiler evaluation is beyond the scope of this article. The intent here is to examine design and performance characteristics that (a) require modification of conventional evaluation procedures or (b) are unique to CFB boiler technology and thus require establishment of a new basis for evaluation.

Specific design and performance parameters discussed in this article include:

- Boiler efficiency calculations
- Fuel and sorbent preparation
- Fuel flexibility considerations
- Boiler and auxiliary power requirements
- Turndown/cycling
- Solids flow/separation/recirculation.

3. Typical configuration for stoker-fired boiler



For the purposes of the discussion here, it is assumed that coal is the primary fuel used in the CFB and that limestone is the sorbent used for sulfur capture.

Boiler efficiency calculations

The ASME Power Test Code for Steam Generating Units (PTC 4.1) (*1*) is the accepted industry standard for determining the efficiency of conventionally fired boilers. An abbreviated form of Section 5 (Efficiency by Heat Loss Method) provides a convenient and effective means of comparing conventional boilers. However, the Power Test Code (PTC) does not take into account some of the heat gains and losses that are unique to CFB combustion. In addition, some of the heat losses addressed in the PTC should be adjusted to accommodate the physical and operational characteristics of CFB boilers.

Specific heat losses and gains that require special attention when evaluating CFB boiler efficiencies include calcination loss, sulfation gain, loss to moisture in limestone, unburned carbon loss, radiation and convection losses, boiler ash sensible heat loss, and combustion-air fan credits.

Calcination loss

When limestone is used as a bed material (sorbent) for sulfur removal, it must first be converted or calcined to form calcium oxide (or, in some cases, magnesium oxide) before it can react with the sulfur. This process is an endothermic reaction that requires the addition of heat.(*2*)

$$CaCO_3 + Hc \longrightarrow CaO + CO_2 \quad (1)$$

$$MgCO_3 + H_m \longrightarrow MgO + CO_2 \quad (2)$$

where

H_c = heat of calcium = 4.567 MJ/kg (1965 Btu/lb)

H_m = heat of magnesium = 4.097 MJ/kg (1763 Btu/lb)

The heat loss from calcination depends on two factors:

Limestone reactivity. Hard, crystalline limestone has low reactivity. Soft, powdery, amorphous limestone usually has high reactivity.

Limestone size. A bed made of large limestone particles has a smaller effective surface area than a bed made of small particles.

Both factors affect the calcium-to-sulfur ratio and, thus, calcination heat losses. Mills that are in the process of evaluating boilers from different suppliers should specify a value for the heat of reaction and stipulate the required limestone composition, reactivity, and size. This ensures that all suppliers follow the same design criteria.

Sulfation gain

The calcium oxide produced through calcination reacts with sulfur dioxide to form calcium sulfate. (Calcium sulfate is a solid and can thus be collected in conventional equipment used to control air pollution.) The formation of calcium sulfate is an exothermic reaction. (*2*)

$$CaO + SO_2 + 1/2\,O_2 \longrightarrow CaSO_4 + H_s \quad (3)$$

where

H_s = heat of sulfur = 15.146 MJ/kg (6517 Btu/lb)

The heat gained during sulfation is directly proportional to the amount of SO_2 captured. Once the user specifies the SO_2 removal requirement, the boiler vendor can calculate sulfation heat gains on the basis of fuel firing rate. Again, the mill should specify the heat of reaction and request all vendors to calculate heat gains on this basis.

Loss to moisture in limestone

The heat needed to vaporize the moisture in the limestone is another source of heat loss. This loss is usually based on the amount of limestone fed to the furnace, which is in turn based on the specified sulfur-removal requirement. Depending on the amount of moisture in the limestone, this loss can range from less than 0.05% up to 0.2% or more.

Unburned carbon loss

Combustion efficiency is determined by measuring the amount of unburned carbon in the boiler ash. While CFB suppliers state that efficiencies greater than 99% are possible, the actual unburned carbon loss often ranges from 0.3% to 2.0%. Losses at the high end of this range can be attributed to the CFB boiler's sensitivity to fuel size, which affects separation in the hot-particle collection device, especially at lower firing rates.

Radiation and convection losses

Radiation and convection losses for conventional boilers are usually estimated by using ABMA charts, which provide loss figures based on the size of the unit. (*3*) However, this approach may not provide a true estimate in the case of CFB boilers because of the substantial surface area of the hot-particle separator. Additional radiant losses are also incurred on boilers equipped with an EHE. The radiant loss can be up to 0.8–0.9%, which represents a fairly significant portion of the overall heat loss.

It may be useful to have CFB boiler suppliers identify the percentage of heat loss associated with each major boiler component. This would provide a meaningful basis of comparison and valuable insight into losses associated with such major items as the furnace, the hot-particle separator, the convection-pass enclosure, and the EHE.

Boiler ash sensible heat loss

The boiler ash sensible heat loss is the combined heat losses of the bottom ash (bed ash) and the fly ash leaving the boiler. Bed ash temperatures in a CFB boiler ranges from 1120°K to 1170°K (1550°F to 1650°F). Thus the amount of bed ash removed from the furnace can have a significant effect on boiler ash sensible heat loss. The quantity of bed ash flow is affected by the calcium-to-sulfur ratio. In general, the higher the calcium-to-sulfur ratio the more unspent calcium carbonate (unreacted lime) and calcium oxide must be removed as ash.

CFB boiler suppliers have significantly different operating philosophies regarding the quantity of bed ash flow. Proposed bed ash flows can range from zero to 60% of total ash flow. It is essential that the effect of this loss on boiler efficiency be quantified when evaluating boilers from different suppliers.

I. Heat losses and gains for calculating boiler efficiency*

Heat loss (gain)	*Typical range of values, %*
Sensible heat in dry gas	3.5-5.5
Moisture from burning hydrogen in fuel	3.5-4.0
Moisture in fuel	0.55-0.9
Moisture in sorbent	0.05-0.20
Moisture in air	0.1-0.14
Unburned carbon	0.3-2.0
Sensible heat in boiler ash	0.1-0.8
Calcination	1.0-1.70
(Sulfation)	(1.6)-(1.8)
Radiation and convection	0.3-0.9
(Combustion-air fan power)	(0.55)-(0.65)
Manufacturer's margin	1.0-2.0

*Overall unit efficiency = 100% - total losses.

Combustion-air fan credit

Significant fan power is required to provide the high combustion-air pressures of 10-20 kPa (40-80 in. wg) needed to fluidize and circulate the bed. These fans impart energy to the air, which increases its temperature before it enters the furnace. This can represent up to 0.6% heat gain to the boiler.

Fan power requirements vary widely among CFB boiler suppliers. Because fan energy can represent a significant heat gain to the boiler, it is prudent to include the combustion-air fan credit (heat gain) when comparing the efficiencies of different boilers.

Boiler efficiency summary

The heat losses and gains that should be considered when comparing the efficiencies of different CFB boilers are listed in **Table I**. Design criteria that would affect the vendor's boiler efficiency calculations should be specified in as much detail as possible by the purchaser in order to provide a common basis for comparison. These design criteria should include:

- Performance fuel, design fuel, and alternative fuel analyses
- Limestone analysis, reactivity and size distribution
- Calcination heat of reaction
- Sulfation heat of reaction
- SOx removal requirements.

Fuel and sorbent preparation

Fuel size requirements vary significantly among CFB boiler suppliers, depending on the design and operational requirements of the furnace and associated hot-particle separation equipment. The size requirements for coal fuel range from <6 mm (0.25 in.) to <50 mm (2 in.). Fuel size has a direct effect on fan power requirements and the bed density within the furnace.

Once the prospective buyer specifies the as-received fuel size, the as-fired fuel size requirements for the vendor's boiler determine the type and extent of preparation equipment that must be furnished. The additional capital and operating costs associated with screens and crushers should be included in the evaluation for those boilers that require a reduction in fuel size.

The size requirements for the sorbent particles also vary significantly amongst boiler vendors, ranging from <6 mm (0.25 in.) down to 100% < 1000 μm and 50% <150 μm. The size of delivered limestone is on the average of <6 mm (0.25 in.) to <3 mm (0.125 in.). Limestone size reduction from <6 mm (0.25 in.) to the 1000-μm range requires the installation of power-intensive size-reduction equipment such as pulverizers. As with coal preparation, the CFB boiler evaluation should include the additional capital and operating costs required to meet the boiler's "as-fired" limestone size requirements.

Fuel and sorbent size are integrally related to CFB boiler design and operation. The purchaser must understand the relationships between fuel and sorbent size and (a) combustion-air fan horsepower requirements (b) the calcium-to-sulfur ratio, and (c) the efficiency of the hot-particle separator.

The CFB boiler designer chooses fuel and sorbent sizes to optimize operation and performance under the specified design conditions. For example, smaller fuel sizes provide a more favorable rate of fuel burnout because of the increased surface exposure and higher turbulence in the bed. In addition, less fan power is needed to support the bed. On the other hand, size-reduction equipment may be required, carbon carryover through the hot-particle separator may increase, and the smaller fuel size may require a more elaborate system to feed fuel into the furnace.

A larger fuel size is easier to feed into the CFB, is captured more easily in the hot-particle separator, and can possibly be fired as received, with no size reduction required. However, greater fan power is required to suspend the bed, and the time required for particle burnout is greater.

Similarly, a smaller sorbent size enhances sulfur capture and calcium utilization (resulting in a lower calcium-to-sulfur ratio) by increasing the surface area

II. Chemical analysis of five common fuels (as-received)

	Chemical content, % (by weight)				
	Bituminous coal #1	*Bituminous coal #2*	*Petroleum coke*	*No. 2 fuel oil*	*Wood*
Carbon	70.40	60.00	81.86	86.35	32.77
Hydrogen	4.70	4.20	3.19	13.35	4.18
Sulfur	2.90	4.00	5.84	0.30	0.00
Oxygen	3.90	5.60	0.72	0.00	22.60
Nitrogen	1.30	1.20	0.72	0.00	0.05
Ash	10.80	15.00	0.37	0.00	0.40
Water	6.00	10.00	7.30	0.00	40.00
Heating value, MJ/kg (Btu/lb)	29.05 (12,500)	25.56 (11,000)	33.05 (14,222)	45.60 (19,620)	13.17 (5,666)

III. Effects of five common fuels on boiler design parameters[a]

	Bituminous coal #1	*Bituminous coal #2*	*Petroleum coke*	*No. 2 fuel oil*	*Wood*
Fuel burn rate, metric (short) tons/h	13.68 (15.08)	15.60 (17.20)	11.80 (13.01)	8.95 (9.87)	34.51 (38.05)
Sorbent feed rate, kg/h (pph)	2,340 (5,160)	3,690 (8,120)	4,070 (8,970)	...	...
Combustion air flow, kg/h (pph)	166,490 (366,720)	163,090 (359,220)	160,070 (352,570)	163,050 (359,130)	182,850 (402,750)
Flue gas flow, kg/h (pph)	181,060 (398,800)	178,750 (393,730)	174,210 (383,720)	174,180 (383,650)	219,670 (483,860)
Flue gas vol., actual m^3/m (ft^3/m)	3,460 (122,400)	3,430 (121,230)	3,310 (116,990)	3,380 (119,430)	4,400 (155,620)
Ash flow rate,[b] kg/h (pph)	3,740 (8,240)	5,870 (12,930)	3,930 (8,660)	...	240 (520)
Boiler efficiency, %	88.51	88.19	90.21	86.13	77.39

[a]The figures in this table are based on a boiler capable of producing 145,000 kg steam/h at 10.34 MPa and 780° K (320,000 lb/h at 1500 psig and 950°F).
[b]Including: ash, calcium sulfate, unreacted CaO, inerts from limestone, and unburned carbon.

available for contact by the sulfur. However, it may require the addition of size-reduction equipment.

To compare boilers on an equitable basis, the potential purchaser can (a) elect to estimate the additional capital costs associated with fuel and/or sorbent size reduction equipment or (b) require that such equipment be included within the boiler supplier's proposal. Depending on the purchaser's requirements, it may also be desirable to provide standby and/or redundancy in equipment to ensure availability of the fuel and sorbent preparation systems.

Fuel flexibility considerations

The CFB boiler is capable of firing a wide range of fuels. The size and design of CFB boilers and auxiliaries are determined to a large extent by the type of fuels that are fired. Thus the effects of firing different types of fuel should be considered during the initial development of boiler specifications. Design parameters that are directly dependent on fuel properties include fuel feed rate, combustion air flow, flue gas volume, boiler efficiency, and ash flow rate.

Table II is a chemical analysis of five commonly fired fuels. **Table III** shows the effects of these fuels on boiler design parameters. The most significant variation occurs upon switching from a high-grade coal to a low-carbon, high-moisture, low-heating-value fuel such as wood.

Fuel properties strongly influence boiler design parameters. If multiple fuel capability is required, the user must assess the effect of the primary fuel and any alternative fuels that will be fired. The boiler specification should include (a) a chemical analysis of each fuel to be fired and (b) the purchaser's preferences regarding the size of the boiler and its auxiliaries with respect to the anticipated variations in fuel properties.

The following list is a cursory overview of fuel-related factors that should be considered when determining the

IV. Power required to operate auxiliary CFB boiler equipment from five suppliers.

	Operating power, kW*h/h				
	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5
Primary air fan	425	517	381	500	1305
Secondary air fan	110	144	336	479	...
I.D. fan	332	318	375	1430	932
Boiler circ. pump	...	...	...	76	...
Boiler feed pump	97	90	95	77	54
Fuel prep.	8	8	22	8	8
Limestone prep.	22	8	26	49	26
Miscellaneous	107	114	258	618	117
Total	1101	1199	1493	3237	2442
Hourly cost ($0.02/kW*h), $	22.02	23.98	29.86	64.74	48.84
Annual cost (8600 h/yr), $	189,372	206,228	256,796	556,764	420,024

required capacity for a CFB boiler system.

- The capacity of the fuel-handling and -feed equipment should be based on the alternative fuel with the lowest Btu value.
- The capacity of the sorbent-handling equipment should be based on the alternative fuel with the highest sulfur content.
- Although slagging and fouling are greatly reduced in CFB boilers, sootblowers should be installed in the convective heat-transfer areas if fuels with such tendencies are to be fired.
- Ash-removal equipment for both the bed and fly ash should be capable of handling the worst fuel condition, respectively.
- Superheater size should be based on the best fuel, i.e., the one with the lowest flue-gas flow and thus the lowest heat-transfer rate. The size of the steam attemperators, on the other hand, should be based on the lowest grade of fuel to be fired. (These considerations may become less significant or even irrelevant when an EHE is used for superheat temperature control, since solids flow through the EHE can be varied independently of the furnace to control steam temperature.)
- Combustion-air fans and ducts should be capable of providing a sufficient amount of combustion air when firing the lowest-grade fuel.
- The flue gas system—including the induced-draft (I.D.) fan, ductwork, and pollution control device (bag house or electrostatic precipitator)—should be capable of handling gas flows and particulate loadings from the full range of potential fuels.

Boiler auxiliary power requirements

The operating power requirements and the cost of the boiler's auxiliary equipment are important considerations when comparing boiler proposals. These items are even more important when evaluating CFB boilers. Power requirements for some auxiliaries (e.g., combustion-air fans) are significantly higher than for conventional boilers. In addition, auxiliary power requirements vary significantly from one supplier to another because of the wide disparity in physical and operating parameters among CFB boiler suppliers. A tabulation of the operating power requirements for boiler auxiliaries should include the following equipment:

- Combustion-air fans (primary and secondary)
- I.D. fan
- Boiler circulation pumps
- Supply pressure to the boiler feed pump (to accommodate the drop in pressure between the economizer inlet and the superheater outlet)
- Fuel preparation equipment
- Limestone preparation equipment
- Miscellaneous blowers, fans, etc. for pressurizing, fluidizing, etc.

The power requirements for operating the auxiliaries should be tabulated in kilowatt-hours per hour. This can then be converted to an annual energy charge and incorporated in the summary of yearly operating and maintenance costs, as seen in **Table IV.** The table shows that the power requirements for operating the auxiliary equipment and the associated annual operating costs can differ significantly among CFB boiler suppliers.

Turndown/cycling

Turndown, rate of load change, and cycling requirements are essential considerations when matching any boiler to the process system dynamics. CFB boiler suppliers have provided guaranteed turndown ratios on the order of 3:1 and 4:1. When evaluating various suppliers, the purchaser will want to consider how cold startup time and low-load operation affect plant operations and examine the applicability and desirability of installing an EHE.

Cold startup time requirements of CFB boilers are determined by the allowable rate of thermal expansion for the boiler's pressure parts and refractory. CFB boilers equipped with thicker refractory linings in the hot-particle separators, ducts, and furnace will require the longer time periods from cold-start conditions to full-load operation. CFB boilers with water- or steam-cooled hot-particle separators generally have the shortest time from cold-start conditions. Suppliers should be asked to provide the time required for cold startup as well as information regarding hot shutdown time periods and associated restart time requirements.

In consideration of operation at low-load conditions, the purchaser will want to consider the impact on boiler efficiency and at what minimum load an auxiliary fuel must be fired to sustain combustion.

CFB boiler suppliers disagree about the utility of an EHE. However, an EHE can increase the stability of boiler operation during rapidly changing load swings of significant magnitude and/or wide variations in fuel quality.

Solids flow/separation/recirculation

The flow of the circulating solids, their separation from the gas stream, and their recirculation back into the bed are essential aspects of CFB boiler operation. Yet, this is an area where great differences exist among CFB boiler suppliers. These differences occur in both the design and operation of the equipment. When evaluating various CFB boiler designs, one must try to understand how each supplier has treated factors such as solids loading, particle size, gas velocity, thermal density, and erosion potential in the physical design and operation of the boiler.

Solids flow

Solids flow can be evaluated by asking each supplier to provide data regarding solids flow leaving the furnace, solids flow recycled to the combustor, solids inventory, gas-velocity profiles throughout the boiler, solids-loading profiles, and solids-size profiles throughout the height of the furnace. Armed with this information, the purchaser can evaluate the merits and drawbacks of each system and determine if there is an equitable balance between erosion potential (solids loading and velocity) and heat-transfer rate (thermal density).

The potential for erosion increases with higher solids loading and/or higher velocity. Higher velocities also increase turbulence and enhance combustion and sulfur capture. However, higher velocities decrease particle residence time. Increasing solids densities improves thermal heat-transfer rates and increases the thermal capacitance of the bed, thus making it less sensitive to sudden changes in fuel quality. However, increasing the solids density also increases both the potential for erosion increases and fan power requirements. Each of these factors should be quantified as a first step in determining their potential impacts on operation.

Solids separation and recirculation

The separation and return of hot solids to the bed (ash, unburned carbon, and unspent sorbent) is crucial to efficient and economical operation of a CFB boiler. Actual separation equipment varies significantly among suppliers. Some use large-diameter cyclones, while others use a proprietary separator design. Some vendors use two separators, while others use a single separator. Some designs utilize thick refractory linings for erosion protection and thermal insulation. Other designs provide steam or water-cooled walls for heat absorption and relatively thin refractory linings for erosion protection.

Evaluation of the hot-solids separator should consider particle size vs. separator efficiency, separator efficiency at various boiler loads, the effect of fuel changes on separator efficiency, erosion potentials and associated maintenance requirements, and thermal expansion between the furnace and separator as well as between the separator and convection bank.

The purchaser should pay close attention to how hot-particle separator efficiency is affected (a) at partial-load operation and (b) when significant fuel changes are made. If these conditions lead to inefficient operation of the hot-particle separator (higher grain loadings in the flue gas), then the purchaser must consider how this would impact downstream air pollution control equipment. The purchaser should also know whether the supplier is providing a mechanical collector downstream of the hot-particle separator in order to comply with grain-loading requirements at the bag house or precipitator inlet.

Hot-solids recirculation devices also vary significantly among CFB boiler suppliers. All are designed to seal the bottom of the hot-particle separator and provide a means of reintroducing solids back into the furnace. Solids-recirculation techniques include a single nonmechanical seal, use of multiple reinjection tubes, and passing the hot solids through an EHE before cycling the solids back into the furnace. However, one common feature of each of the designs is the utilization of fluidizing air to induce and control solids flow. The purchaser should review the operating principles of these recirculation devices, their construction, their susceptibility to erosion, redundancy provisions, and operational reliability.

Other considerations

A purchaser who is contemplating combustion of multiple fuels should request each boiler supplier to inform him of any additional requirements regarding bed inventory control and bed maintenance. For example, if a low-ash fuel is burnt, will the bed need to be supplemented with additional inert material? If so, what material? What are its size limitations and how much would be required? The cost of this material could then be factored into the evaluation.

Conclusion

The circulating fluidized bed (CFB) boiler utilizes a solid-fuel combustion technology that offers the combined benefits of fuel flexibility, simplicity of operation, and minimal emission rates of NOx, SOx, and particulate. A potential purchaser who wants to evaluate this modern combustion technique must determine how these benefits are affected by fuel properties, design features, and operating conditions.

While the combustion technology of CFB boilers differs from that of conventional boilers, the operation and performance characteristics of CFB boilers can be evaluated using conventional, time-proven engineering principles. The aspects of CFB boiler design and operation reviewed in this article can help a potential purchaser evaluate the various CFB boilers on the market. Development and application of this approach before preparation of the boiler specification and the subsequent request for a proposal is an important step towards enabling all parties to understand the requirements of the application.□

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