FLUIDIZED BED COMBUSTION AS AN INDUSTRIAL BOILER STRATEGY: PROS AND CONS

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INTRODUCTION

Riley Stoker Corporation, Worcester, Massachusetts, and Fluidised Combustion Contractors Limited (FCCL), Crawley, Sussex, U. K. are collaborating in the designing and guaranteeing of fluidized bed boilers in the range of 50,000 to 500,000 lb/hr. steam flow. Riley has been involved with AFBC design starting with the Columbus Ohio Psychiatric Hospital (COPH) early in 1979 and has recently concluded the detailed design of of 200 MW utility boiler, in conjunction with FCCL and Babcock Contractors, Inc., Pittsburgh, PA, for the Tennessee Valley Authority's demonstration plant project. We are currently reviewing the data reduction and aquisition scheme for TVA's 20 MW test facility located in Paducah, Kentucky, which is scheduled for initial operation in April 1982. We are also actively bidding on AFBC boiler proposals for the world wide market.

The basis for the designs developed by Riley is the successful operation of a 40,000 pph boiler in Renfrew, Scotland. This 400 psi/550°F boiler was converted to fluidized bed firing from a dumping stoker in 1974 and has operated successfully for several thousand hours.

The Renfrew boiler is fired by an underbed direct firing system in which coal from the stockpile is crushed and fed directly without any intermediate storage. The bed contains saturated water cooled tubing to keep the bed temperature at 1560°F. The system has burned high sulfur coals with limestone and has burned coals with ash contents as high as sixty percent and high sulfur oils. The operation of the Renfrew boiler, in conjunction with test work at National Coal Board test facilities, has provided the basis for the designs offered by Riley-FCCL.

FUNDAMENTALS OF AFBC

What, exactly, is fluidized bed combustion, and what makes it a promising technology? An explanation of some of the processes on-going in a fluidized bed combustor is necessary.

FLUIDIZATION

A bed of particles is said to be fluidized by a gas when the gas velocity is sufficient to support the bed's weight. At low gas velocities, the gas permeates through the bed without disturbing the particles significantly.

At high velocities, the force exerted on the particles by the upward passage of the gas becomes greater so that, eventually, the gas stream supports the total weight of the bed. This causes the particles to separate and the bed to expand, marking the onset of fluidization. The gas velocity at this stage is termed the minimum or incipient fluidizing velocity.

At gas velocities greater than the minimum fluidizing velocity, bubbles form and rise up through the bed. It is normal to operate with a gas velocity several times greater than the minimum fluidizing velocity. The passage of bubbles through the bed causes violent turbulent mixing of bed particles, giving the bed the appearance of a boiling liquid. The analogy is, however, more than superficial; a fluid bed possesses several of the properties of a boiling liquid, including good heat and mass transfer properties and a hydrostatic head.

At this point, the bed pressure drop becomes independent of air flow, and equal to the weight of the supported material per unit area of bed. As velocity is further increased, smaller particles of bed material become entrained in the flue gases and a net loss of bed material may occur.

BED DESIGN

Fluidized bed material may be any inert material provided the proper size distribution is maintained consistent with the choice of fluidizing velocities. When burning coal, the bed is generally comprised of particles of coal ash or a sulfur acceptor (limestone or dolomite), and is fluidized by the combustion air. The concentration of carbon in the bed is typically less than one half percent. The fuel, usually coal, may be fed in a crushed form underbed or screened overbed. The bed temperature is maintained at the desired level by balancing the heat released by the combustion of the fuel against the heat contained in the exit gases leaving the bed and heat transfer surfaces immersed in the bed. The bed temperature is controlled within the range 1400-1650°F. This temperature range is maintained in a coal fired combustor principally because, for effective sulphur retention using limestone, the bed temperature has to be above about 1400°F to obtain an adequate rate of calcination. The sulfur retention efficiency falls away at high temperatures and may impose an upper limit on the bed temperature.

The added benefits of operating in this temperature regime is that formation of thermal NO_x is suppressed and that these temperatures are substantially below the fusion temperature of coal ash, eliminating the problem of slagging or fouling of furnace and convection surfaces, respectively.

The bed is maintained at the desired temperature by inserting cooling surfaces in the bed material. Heat transfer rates to the surfaces are on the order of 50 Btu/hr. ft.^{2} °F, which is roughly five times those rates normally experienced in the convection surfaces of the boiler, consequently, smaller surface areas can be used to transfer heat.

SULPHUR DIOXIDE EMISSION

While the fluidized bed combustor offers the user fuel flexibility and enhanced heat transfer to in-bed tubes, its principal appeal to industrial users is its ability to remove sulphur dioxide from the flue gas stream in the bed itself.

The organic and inorganic sulphur are released during combustion, and form sulphur dioxide and sulphur trioxide. Both types of oxide are air pollutants and are also important in the formation of corrosive compounds on metallic surfaces.

The reactions of limestone as a sulphur acceptor in a fluid bed are:

(I) Calcination
$CaCO_3 \quad CaO + CO_2$

(II) Sulphur retention
$CaO + SO_2 + \frac{1}{2}O_2 \quad CaSO_4$

The calcium/sulphur mole ratio refers to the acceptor feed rate, expressed as the number of times the theoretical (stoichiometric) feed rate required to retain all of the sulphur. As expected, the sulphur retention efficiency improves as the calcium/sulphur mole ratio increases. For atmospheric pressure combustion, a calcium/sulphur mole ratio of typically 2 to 4 is required for 85 percent retention depending on the operating conditions and the reactivity of the limestone.

The effectiveness of a limestone in removing sulphur dioxide from the bed is not strictly a function of its chemical analysis and must be characterized against a known benchmark in a laboratory test. Reinjection of material that has elutriated from the bed has been used to improve the overall combustion efficiency of the boiler, but an added benefit is that reinjection increases the residence time of unreacted limestone in the bed and hence has been shown to reduce the overall Ca:S molar ratio and hence limestone feed requirements.

PLANT CONFIGURATION

What does all this mean in terms of actual plant hardware? The following is a description of a fluidized bed system designed to produce 67,000 pph of saturated steam at 150 psig, (Figures 1 and 2). This AFBC boiler is designed to provide a 5.6:1 turndown of steam production and, consequently, was designed with four fluid beds to provide that capability. The basis for the boiler design is the Shop Assembled Modular (SAM) industrial boiler offered by Riley. The boiler consists of two shop assembled and rail shipped furnace modules with a single rail shippable boiler bank module. This particular boiler was designated for operation at an elevation of 4900 feet above sea level and, thus, requires more plan area for an eight foot per second superficial velocity than normal. Consequently, the unit was designed by selecting two 40,000 pph SAM modules to provide the 67,000 pph MCR and 72,500 pph peak conditions.

The boiler is designed to burn a western sub-bituminous coal with a high heating value of 9210 Btu/lb., .68 percent sulphur and 23 percent moisture. Because of the high fuel moisture the boiler is equipped with an airheater for heat recovery so that coal drying may be accomplished.

The limestone system was designed to remove 70 percent of the sulphur at a calcium to sulphur molar ratio of 3:1. Because of the low sulphur content of the fuel, the limestone requirements are low, approximately 5 pounds of limestone per 100 lbs. of coal.

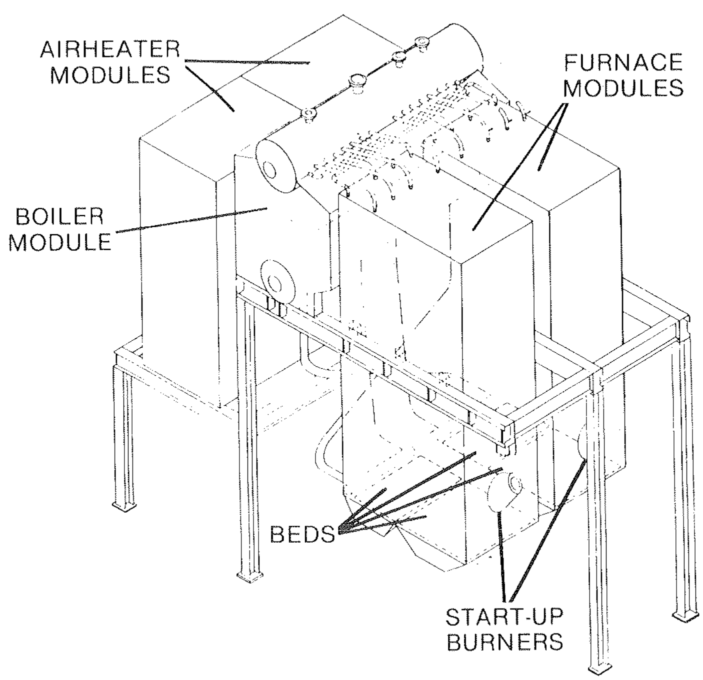

Figure 1 AFBC Shop Assembled Modular Boiler

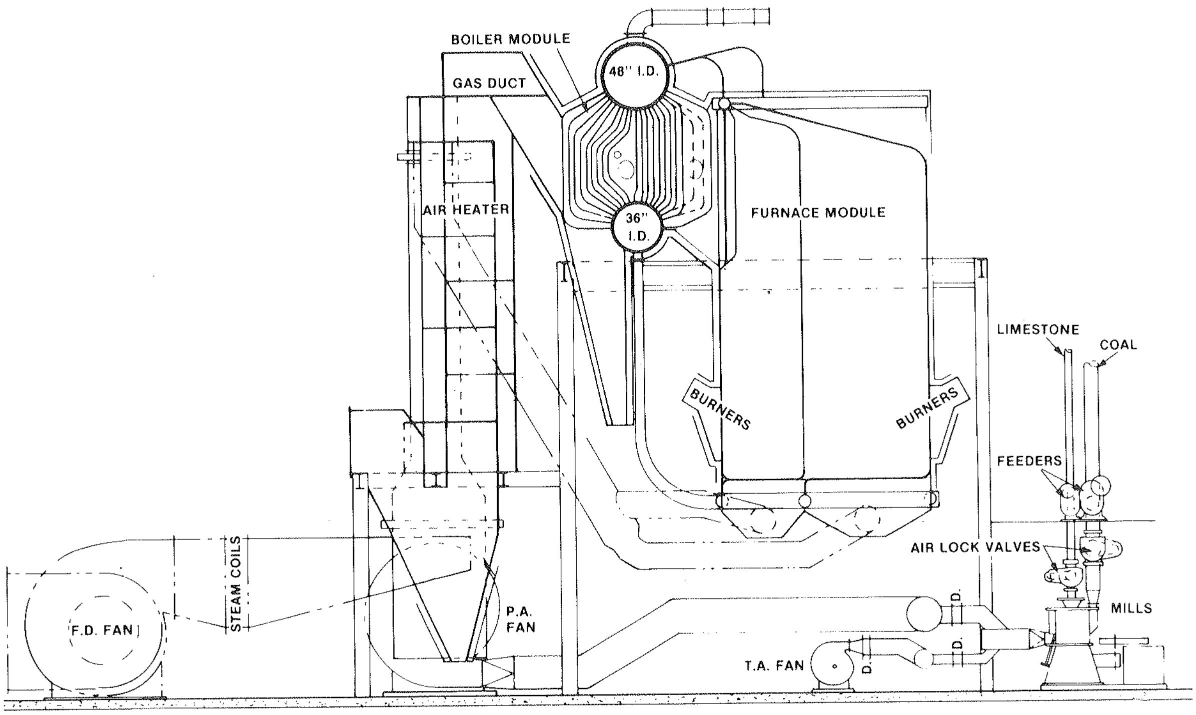

Figure 2 Boiler Cross Section

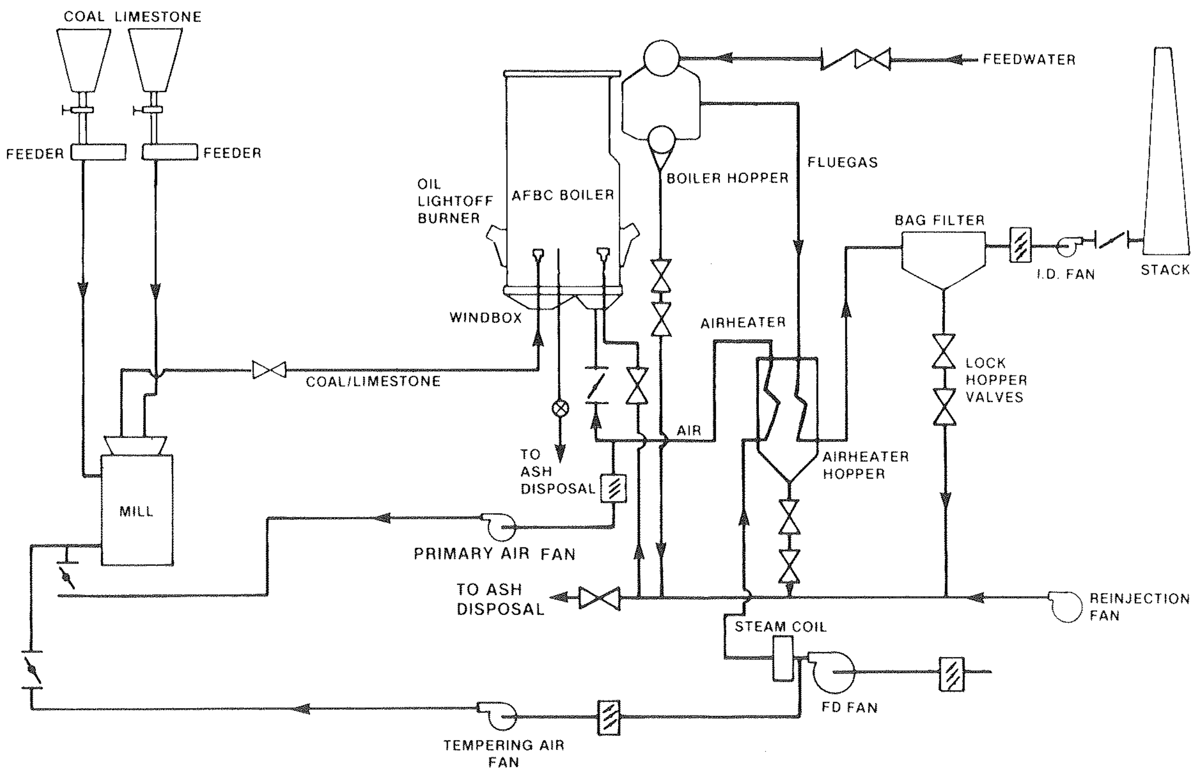

Figure 3 Schematic Diagram of AFBC System

The fuel and limestone feed systems are underbed pneumatic systems, Figure 3. Each bed has its own independent feed system. Coal is fed from the coal bunker isolated by an air lock valve through a volumetric feeder to a medium speed ball and race mill, where it is crushed to ¼ " x 0" size. Hot primary air is taken from the tubular airheater discharge to the suction side of a hot primary air fan. A tempering air fan takes suction from the discharge of the forced draft fan and the air stream is blended with the primary air stream to provide hot air to the mills. The coal is crushed, dried, and classified in the mills and is split into two or three streams in the turret section of the mill. Pre-crushed limestone (1/8″ x 0″) is admitted to the classifier from its own bunker-valve feeder system where it is flash dried and mixed with the coal stream. The coal limestone mixture is pneumatically transported to the fuel feed nozzles via 3″ lines where it is injected into the fluid bed. Fuel feed nozzles are generally spaced to provide one feedpoint to every 16 square feet of bed area. This design incorporates a total of ten feed points, with three in the large beds and two in the smaller beds. Control of the primary and tempering air dampers is based on maintaining approximately a 130—150°F classifier exit temperature to prevent plugging of the coal nozzles.

The bulk of the combustion air is secondary air which passes through the airheater and is admitted under the bed into a windbox at a temperature of 518°F. The air is distributed into the bed through a bed "plate" which has air nozzles based on a 4″ square pitch. The air holes in the nozzles are sized for a 10″ pressure drop to assure adequate distribution within the windbox. The "plate" is actually a water cooled membrane wall, which eliminates the problem of sealing a distributor plate to the boiler and allows the designer to use high air temperatures without having to design for differential expansion.

The wide fins in the distributor are insulated from the bed heat flux by a stagnant layer of bed material which is a direct result of the nozzle design. The nozzle is essentially a 1″ diameter stainless steel pipe with air holes drilled normal to the pipe axis at one end. The other end is welded to the distributor plate. This results in a zone of material not fluidized by the air flow and results in excellent insulating qualities for this stagnant layer.

The boiler itself is of natural circulation, welded wall construction. Approximately fifty percent of the net heat input is absorbed in the walls and in bed surface of the bed with the remaining percentage being absorbed in the furnace walls and boiler bank surface. Each furnace module contains two fluid beds and these beds are separated by a refractory wall supported by water cooled tube stringers. The refractory wall prevents splashing from an active bed on to an inactive bed, a configuration used for the low loads for which this boiler is designed. In addition, the refractory surface improves burnout of carbon particles in the furnace freeboard and thus improves carbon utilization.

Startup of the boiler is accomplished through the use of auxiliary oil burners. These burners, one per bed, are fired down upon the fluidized bed material until bed temperature has risen to a temperature sufficient to maintain coal ignition. Upon coal injection, the bed temperature will rise to its design set point as bed load is increased. The temperature at which bed material must be raised to provide ignition is a function of the coal properties. Verification of stable coal combustion can be made at about 1200°F.

Typical carbon loss from an underfed fluidized bed without flyash reinjection is approximately 5 percent. By reinjecting flyash caught in the boiler hopper, airheater hopper and baghouse, this carbon loss can be reduced to as little as one percent. An added benefit is the increased utilization of the sorbent, which is more important on units firing high sulfur coals.

Ash reinjection is accomplished by dense phase pneumatic transport of the material from the baghouse, airheater, and boiler hopper. This material is piped to the ash storage silo and reinjetion lines are fed directly from this system through an automatically controlled valve. There are two ash reinjection points per bed and reinjection is to one bed at a time only. This system allows for the high recycle rates that are required for one percent carbon loss goals. Reinjection nozzles are similar in design to coal nozzles and reinjection is underbed to provide for char residence time.

Ash removal from the bed is through water jacketed pipes to a lock valve from where the bed material is removed to the ash disposal silo. The amount of bed material removed via the bed drains is a function of the limestone feed rate and coal ash quantity as well as the attrition rate of the material in the bed. The water jacket ash cooling design is capable of handling the effluent from this particular design; other options include the use of water cooled screws to drop the bed material from 1600°F to a temperature where conventional systems can handle the ash.

The boiler control system is based on the fact that these boilers are comprised of four nearly identical subsystems, each with a mill-based feed system and an associated fluidized bed. Because of this configuration, a modular approach to the control system hardware has been used. The design incorporates a digital control system with four individual microcomputer-based units each dedicated to the startup, combustion control, and shutdown of a single fluid bed and fuel feed system. A cental control unit based on a similar microcomputer unit will then be used to call up each fluid bed as it is required. This unit will perform the calculations necessary to predict and then correct the temperature set points of the beds in service and will issue the set points to the individual bed controllers. A large part of the duties of communication with the plant operator will also be performed by the control unit.

Changing a combination of bed temperature and bed area is the basic method of load control. The fluid bed is designed to operate with all immersed tubes covered by the bed whenever it is fluidized so that output of heat to tubes is not affected by changes in bed height. Area change is made possible by segmenting the area into discrete beds. By cutting off air to any section, the bed is slumped, combustion ceases, and heat transfer falls to a very low value. Thus, heat transfer and combustion gas output are reduced in proportion to the area slumped.

150 psig operating pressure; 235 F feedwater;
Fuel - Coal: Moisture 23.66; V.M. 31.83; F.C. 38.82; Ash 5.69; 9,210 Btu per pound as fired.
C 53.02; O 12.72; S .68; N .95; H 3.51

	MCR
1. Pounds of steam per hour actual evap	67,500
2. Total K Btu output per hour	68,292
3. Temperature of air heater exit gases, F	337
4. Excess air in air heater exit gases	20
5. Temperature of water entering drum, F	235
6. Temperature of air entering FD fan	80
7. Temperature of air leaving heater, F	478
8. Boiler drum pressure, psig	151
9. Furnace draft iwg	.25
10. Draft loss through boiler	.26
11. Draft loss through air heater	.65
12. Draft loss through ducts	1.50
13. Draft loss through baghouse	8.0
14. Total Static Suction	10.66
15. Air pressure drop through firing equipment	51.3
16. Air pressure drop through ducts and dampers iwg	1.0
17. Air pressure drop through air heater	5.0
18. Air pressure drop through steam coil	.83
19. Total static pressure through FD fan	58.13
20. Pounds of fuel per hour	9,043
21. Pounds of air per hour for combustion	70,803
22. Pounds of gas entering air heater	78,909
23. Heat release in furnace Btu/cu. ft/hr	21,210
24. Heat release in furnace Btu/sq. ft/hr	33,087
25. Overall unit efficiency %	82.0
HEAT BALANCE%	
26. Loss due to dry flue gas	5.73
27. Loss due to hydrogen and fuel moisture	6.97
28. Loss due to moisture in air	.14
29. Loss due to radiation	.62
30. Loss due to unburned combustibles	2.84
31. Manufacturer's margin	1.00
32. Unaccounted loss	.50
33. Calcination loss	.38
34. Sulfation gain	−.33
35. Ash heat losses	.15
36. Total losses	18.00
37. Efficiencies of complete unit	82.00

Table I
Heat and Mass Balance for AFBC Unit

Temperature change is achieved by raising or lowering fuel feed rate. Since temperature is equally affected by changes in fluidizing air flow, it is possible to obtain a range of bed temperatures for any given coal feed rate. Normally, best performance from both the bed and the boiler is obtained at excess air levels around 20 percent.

The design of this boiler is representative of the systems offered by RSC/FCCL in the AFBC market place. The specifics of any system design are going to be a function of the coal and limestone ultimate analyses, as well as the reactivity of both of these constituents. A simplified heat and mass balance for this AFBC unit is found in Table I.

AFBC AS A RETROFIT

This design philosophy just described was applied to the retrofit in early 1979, of a 60,000 pph unit producing saturated steam at 150 psig at the Central Ohio Psychiatric Hospital, located in Columbus, Ohio. Babcock Contractors, Inc. of Pittsburgh was the general contractor, Riley Stoker Corporation on this particular project manufactured the pressure parts and Fluidized Combustion Contractors Ltd. was responsible for the process design and the control system design. The boiler house provides saturated steam at rates up to 100,000 pph for use in plant heating and other miscellaneous applications. The boiler was originally built in 1952 by Erie City Iron Works, with a width of 13′6″, depth of 11′2″ and a height of 11′2″.

Figures 4 and 5 are cross section diagrams before and after the retrofit, respectively. There is a single fluidized bed, but it is divided at the distributor plate and there are three windboxes or air plenum sections. Coal and limestone are supplied to the feed systems by larry car from the existing coal handling system and a new limestone bunker. In front of the boiler, there are six small bunkers, three for coal and three for

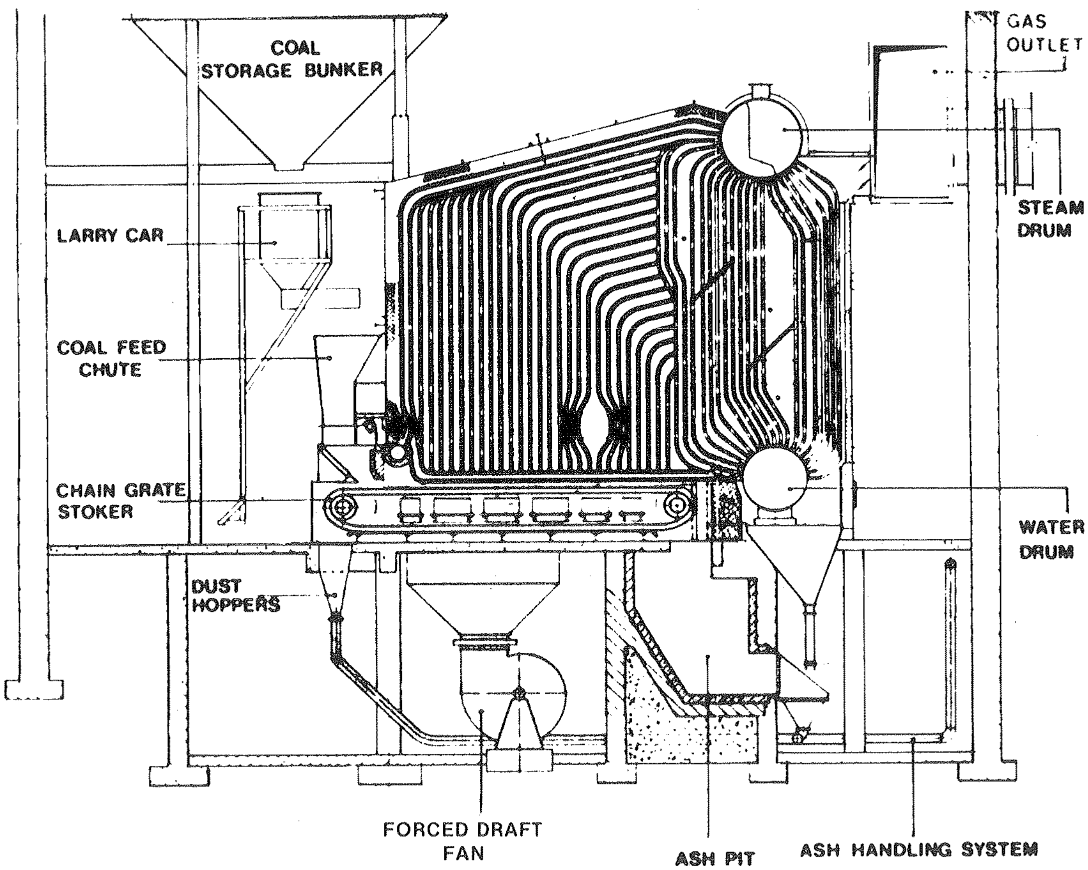

Figure 4 Central Ohio Psychiatric Hospital Before Conversion to Fluidized Bed Firing

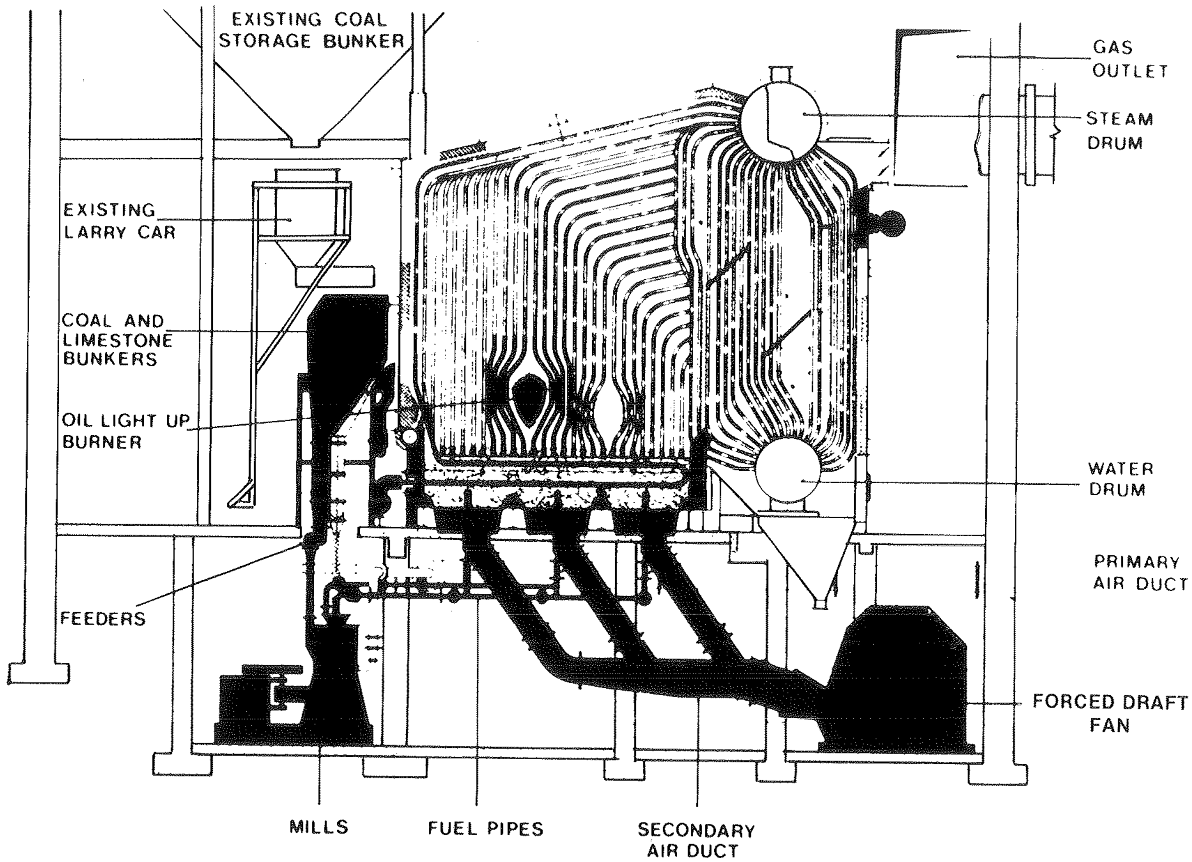

Figure 5 Central Ohio Psychiatric Hospital - Fluidized Bed Retrofit to No. 1 Boiler

limestone. From each of these bunkers, a screw feeder delivers coal or limestone at a controlled rate to one of three mills. These mills, one to supply each bed section, are B & W E mills, which is a ball-and-race type mill. The mill serves the function of both crushing the coal from 1½" down to ¼" x 0" and it also dries it. The limestone is introduced into the turret of the mill which serves as a zone to mix the coal and limestone and serves also as a splitting device. From each mill turret, there are three pneumatic feed lines to the bed section served by that mill.

Air from the forced draft fan is divided and a measured controlled amount is supplied to each of the three windboxes. The distributor plate is made of ¾" carbon steel plate with a series of standpipe air nozzles. These standpipes generate a static layer on top of the grid plate, providing insulation and protection against the heat of the bed.

The in-bed surface is made up of 24 tubes. It is a circulation assisted design. Three pumps (two operating, one spare) take suction from a manifold at the back of the boiler and supply water through a manifold to the in-bed tubes, from which it flows up front wall tubes to the drum. Light-off is accomplished by two over-bed oil burners, one on each side. On the back end of this boiler, not shown in this figure, are multicyclones, an air heater, a bag filter, and an I.D. fan that discharges to the stack.

Ash is removed from a single point in each of the three bed sections and passed through a rotary cooler. Ash is also removed from the boiler hopper, the cyclones, the air heater and the bag house, using an Allen-Sherman-Hoff system.

Installation was completed in October, 1980. Commissioning had progressed to the point where the boiler had been up to full load while firing the oil burners. Some coal had been introduced into the boiler with the bed fluidized. However, before more substantial testing was conducted, the State's funding of this program was depleted and the boiler was removed from service.

Negotiations are now under way for reactivating the project.

THE PROS AND CONS OF AFBC

This paper has attempted to explore some of the concepts of Atmospheric Fluidized Bed Combustion, and describe a boiler system designed for fluid bed firing. This paper also shows that this concept can be used to retrofit existing units and allow them to burn high sulfur coals. Ultimately, the industrial Atmospheric Fluidized Bed Boiler has to be competitive with either pulverized coal or the spreader stoker. Numbers of studies have been performed to try and determine how the AFBC boiler stacks up against the conventional boiler equipped with a wet scrubber. One study has determined captal cost for an AFBC to be 8 percent less than the cost of a comparable pulverized coal unit while the operating costs are approximately 3 percent higher when not considering new product contingencies.[1]

Another study, which performed a similar comparison but used spreader stokers as the "conventional" boiler, concluded that, within the accuracy of the analysis, the cost of two spreader stoker boilers with a flue gas scrubber was equal to two AFBC boiler plants. The life cycle analysis favors the AFBC units, but by a margin of about five percent.

These studies were based on specific boiler designs and specific coal and limestone analyses. The conclusion indicate that the AFBC boiler is competitive with conventional technologies within the accuracy of the studies and based on the conditions assumed by the authors.

What, basically, are the tradeoffs and comparisons in key areas of boiler design that the potential user should evaluate when considering AFBC? For the purpose of the comparison, the industrial boiler will be considered as a spreader stoker utilizing a traveling grate, burning coal.

FUEL TYPE

As previously stated, the AFBC boiler is insensitive to fouling and slagging characteristics, as well as ash content of a fuel. It can burn fuels of low calorific value. In this regard, the AFBC boiler is considerably more flexible than the spreader stoker in handling wide ranges of fuels, as coal volatile and ash content, slagging and fouling characteristics will have more of an impact on a stoker fired boiler's performance should fuel supply change after the initial design.

SULFUR CAPTURE

The in-bed capture of SO_2 in the AFBC, as well as the dry nature of the reaction product is the most obvious and acclaimed feature of the AFBC unit when compared to wet SO_2 scrubbers and the wet discharge that they produce.

The in-bed sulfur capture requires, typically, a Ca:S molar ratio of 3:1 or 200 perecent excess limestone to assure adequate CaO surface area to react with the SO_2. This compares to a Ca:S ratio somewhere between 1.01 and 1.11 for a wet scrubber system[2], or up to 11 percent excess limestone. In addition to the impact of the cost of limestone, the calcination reaction in the bed is endothermic, and results in a loss of boiler efficiency of approximately 1 percent for every additional mol ratio above the breakeven point of approximately 2.5 to 1. These numbers are, of course, a function of specific coal and limestone analyses and are based on a coal having 4 percent sulfur. It should be noted that current work indicates that recycle can bring the Ca:S ratio down close to 2.0.

POWER CONSUMPTION

The major disadvantage of the fluid bed system is the forced draft fan power consumption. Pressure drop through the bed distributor plate is 10 iwg to provide adequate distribution. The bed material requires roughly one inch of fan head for every inch of expanded bed height at 8 ft/sec. and 1560°F. Total fan pressure for the system including an airheater is approximately 60 iwg, compared to a normal stoker fired unit forced draft fan head of 10 iwg. The power consumption differential for a 100,000 pph 750°F, 750 psi unit would be 370 hp and 60 hp for the AFBC and the stoker unit respectively. Some tradeoff comes on the induced draft side, where a differential draft loss of eight inches results when comparing a scrubber versus no scrubber case. The differential power consumption for the induced draft fans for these two units would be 80 horsepower in favor of the AFBC.

BOILER DIMENSION

The plan area of a stoker boiler is normally adjusted to provide grate area heat releases at MCR of 750,000 Btu/hr ft^2 of stoker plan area. These rates provide the maximum turndown capability for the boiler while limiting the fly ash carryover to acceptable rates. The design criterion for the AFBC is generally a superficial velocity of 8 ft/sec which equates to values of 560,000 to 585,000 Btu/hr ft^2 for western sub-bituminous and low volatile bituminous coals respectively. Thus an AFBC boiler will require roughly 25 percent more plan area than a stoker boiler for equivalent heat input. Both concepts require essentially the same criterion for volatile combustion and particle disengagement and thus, volumetric heat releases are comparable in both the designs at about 23,000 Btu/h ft^3. Thus, While AFBC units have extremely high heat transfer rates to the in-bed surfaces, the overall reduction of boiler dimensions become influenced by other criterion and cost differentials between stoker fired and AFBC boilers cannot be related simply the heat transfer rates to generating surfaces.

CARBON LOSS

The boiler designs described in this paper have utilized the underbed feed system for coal injection into the fluid bed.

The major advantage of the underbed feed system is the reduction of once through carbon loss when compared to overbed feed system on the fluidized bed sytem. The underbed system once-through loss is approximately 5 percent while some overbed systems for fluid bed can give carbon losses as high as 10 percent. This carbon loss for the underbed system compares to a 5-8 percent loss ÷ for a spreader stoker at a grate heat release of 725,000 Btu/hr ft^2. These losses can be reduced by reinjection from the boiler bank hoppers, dust collector hoppers and even baghouse hoppers. High reinjection rates, however, increase the dust loading on the particulate collection equipment and require reduction of velocities in convection passes.

Very low carbon losses with either system can be attained provided the expense of the reinjection system is justifiable. It should be noted that reinjection in a fluid bed system requires reinjection underbed so the transport system must be capable of producing 50 iwg heads to overcome bed hydrostatic head.

CONTROL

The turndown of a spreader stoker is roughly 3:1 with a lower limit on grate heat release of about 300,000 Btu/hr ft^2. The AFBC designs described in this paper have a turndown of approximately 1.25:1 on a given fluid bed module. The Riley/FCCL design relies on temperature modulation of the beds between 1400 and 1650°F over a constant bed surface area. Other design concepts change loads by varying bed inventory and consequently, varying the surface area covered by bed material. Bed material must consequently be removed, cooled and stored.

Because of the limited turndown of an individual bed module, multiple modules are necessary to provide the desired turndown. The three-bed design at Columbus can provide nearly a 4:1 turndown ratio. Each module has its own feed and control system, so as turndown requirements become more severe, the equipment cost increases correspondingly.

SUMMARY AND CONCLUSIONS

The purpose of this paper is to describe some of the design features of the AFBC industrial boiler as it compares to conventional equipment.

The economic evaluation of an AFBC boiler versus conventional equipment will be extremely site specific, as this paper has attempted to indicate. Boiler turndown requirements, limestone availability and reactivity, fuel analysis and cost of power may impact the trade-offs between the two concepts.

The ultimate attraction that the AFBC offers, though, is the ability to produce power from coal with controllable NO_x and SO_x emissions. Should a fuel become unavailable, the AFBC unit has the flexibility to burn coals with extremely different ash fusion characteristics. Ranges in fuel sulfur can be accomodated by simply increasing sorbent feed rate to maintain the desired SO_x emission.

The waste product of the AFBC is a dry mixture of lime, $CaCO_3$, $CaSO_4$, and coal ash, and its disposal does not provide the environmental problems that wet scrubber effluent does.

This paper has explained some of the fundamentals of the AFBC boiler, identified areas where trade-offs may be necessary, and indicated the potential of this technology.

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