COMMERCIAL APPLICATION OF WASTE-FUEL FIRED HYBRID FLUIDIZED BED BOILERS

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INTRODUCTION

In the early 1980's, developments in California created opportunities for aggressive developers. The California Public Utilities Commission (CPUC) ordered the states utilities to sign power contracts with anyone willing to pay a nominal fee. A range of contract types were ordered. Amongst them was the Standard Offer No. 4 (SO4) type contract which calculated payments on avoided costs that utilities would have incurred had they installed new capacity. The SO4 contract resulted in very attractive payments for both capacity and energy. Before the CPUC rescinded the SO4 contract, nearly 12000 MW were signed up for by developers. Many of these contracts were for small power plants less than 50 MW in size. By staying below 50 MW, review of permits and need by the California Energy Commission was not required. And in most cases, plants burning solid fuels sized less than 30 MW could avoid US EPA review under the Prevention of Significant Deterioration (PSD) regulations.

Combustion Power entered this market with a hybrid circulating fluidized bed boiler. The system uses the positive attributes of a bubbling/turbulent bed combined with a bed-solids circulating loop to develop system performance and emissions profiles which possess substantially enhanced performance characteristics. First commercial operation of the technology was December 1986. At present, a total of 12 units are operating or under construction for a combined steam generation capacity of about 2,500,000 lb/hr (300 MWe). These FI CIRC™ boilers are designed to burn coal and/or a variety of waste fuels having sulfur levels of up to 5.0% and nitrogen up to 3.0%. SO_2 is controlled in typical fluidized bed combustor fashion by introducing limestone into the bed. NOx control, where required such as in California, is attained using a Combustion Power proprietary ammonia injection technique which was developed specifically for the California applications.

DESIGN CONCEPT

The hybrid approach was created by the need in California during the early 1980's to design a solid fuel fired boiler that could meet the very stringent emissions standards in that state. The emissions standards for NOx and SO_2 were typically 0.05 lb/mmBTU for both pollutants. These levels are 5% and 8% respectively of today's Federal EPA New Source Performance STandards for SO_2 and NOx.

Combustion Power has acquired significant fluid bed R&D and operational experience since 1970. This experience, combined with the experience of others, convinced us that the best technical approach for a "California" fluid bed boiler was a hybrid combination which could meet the following design criteria:

- Meet or exceed the most stringent SO_2, NOx and CO emissions standards.
- Have reliable scale-up from pilot plant data.
- Be largely shop-fabricated for low cost field fabrication.

- Designed for ease of maintenance and minimal erosion potential.

Figure 1 is a chart that is often used to classify the three major classes of fluid bed technologies by degree of fluidization. The chart is a plot of superficial gas velocity versus bed expansion with a comparison made between mean gas velocity (gas passing unhindered through the solids bed) and mean solids velocity. As the differential (slip velocity) decreases between these two velocities, the degree of bed expansion (i.e., solids carryover) increases to the point where the solid particle passes unhindered through the process.

Over the range of this expansion there is Type A, classical bubbling bed; Types B and C, circulating fluid beds; and Type D, transport reactors. As depicted, there are four types of beds in these three categories, with two being circulating beds.

At low velocities the Type "A" bed has a defined fluidized-solids/freeboard interface that is readily visible. A very high proportion of product solids is discharged from the bed via a gravity overflow or underflow technique. This is the well known bubbling bed concept.

Higher gas velocity creates a higher rate of particle elutriation (carryover). Also the fluidized-solids/freeboard interface becomes less defined. This is a Type "B" bed, often called a turbulent layer bed which is the bed closest to a FI CIRC™ combustor. This bed typically elutriates over 50% of its incoming solids to the recirculation cyclone for enhanced particle reprocessing. In a fluid bed boiler this reprocessing means improved carbon burnout and lime sulfation.

The Type "C" circulating bed differs in that much higher gas velocities are used. Extensive product recycling creates a condition known as particle "clustering". These clusters have much higher transport velocities which explains the greater slip velocities at increasing solids throughput.

Both Type "B" and "C" beds are considered true circulating fluid beds due to their greater solids elutriation and subsequent extensive recycling via cyclones when compared to Type "A". It is important to remember, however, that both "B" and "C" still retain a dense lower bed relative to the lower density upper zone. In some respects this dense lower bed is similar to a bubbling bed but with much greater gas-solids heat and mass transfer.

A key difference between the FI CIRC™ design and Type "C" beds is the utilization of multiple small-diameter, high-efficiency cyclones to recycle a larger cut of fine particles contained in the elutriated solids. Type "C" beds typically utilize only one or two large diameter cyclones, which do not have as small a fine particle Dp_{50} as a smaller diameter cyclone. Typical Dp_{50} for these larger cyclones is over 75 microns, whereas the FI CIRC™ cyclone Dp_{50} is 15 microns.

Since a significant portion of unsulfated calcium oxide and carbon particles are found in the larger particle cuts, the FI CIRC™ cyclones will recycle the majority of those particles that need to be recycled. The net result is that FI CIRC™ attains the same or better degree of fuel carbon burnout (98 to 99.5+) and lower Ca/S ratios (1.6 to 1.8 at 90% SO_2 suppression) at much lower solids recirculation rates than the Type "C" bed.

The cyclones are critical in FI CIRC™, as with any circulating bed design, since they greatly affect carbon burnout and lime utilization. But with FI CIRC™ they serve the extra function of constantly "doping" the lower bed with a large portion of small particles. It is this "doping" that creates the fine bed particle size average of 300 to 600 microns. With this fine bed average particle size a significant portion of the bed is elutriated, even at velocities of 3-6 ft. per second.

This "doping" also creates a dense bed having a fluidized bulk density of 40 to 60 lbs/ft^3. It is well know that decreasing solids fluidized bulk density decreases the bed side heat transfer coefficient. Increased fluidized bulk density increases the heat transfer coefficient. At these high densities, the bed side heat transfer film coefficient is typically over 100 Btu/hr-ft^{2}F.

FI CIRC™, with its higher heat transfer rate and denser combustion bed using in-bed tube bundles, controls steaming rate by pneumatic removal of bed solids into an external bed material silo. By dropping bed level and exposing tube surface, the steaming rate drops. A one-inch drop in bed level has a noticeable effect in steaming rate.

Because small bed level changes result in noticeable steam rate change, it is possible to maintain boiler MCR (Manufacturer's Continuous Rating) SO_2, CO and HC emissions levels as low as 60% MCR. All of these pollutants require residence time (bed depth) in an oxidizing mode to be thoroughly abated. Since bed level does not greatly change, FI CIRC™ can therefore maintain excellent emissions levels at low MCR ratings.

In summary, the FI CIRC™ fine particle recycling technique gives this design the flexibility to:

- Obtain very turbulent dense bed heat and mass transfer equivalent to higher velocity circulating bed designs without the high velocities or increased solids recirculation ratio and consequent erosion potential:

- Capture the fine particles and introduce them into the lower dense bed, thereby enhancing carbon burnout and greatly improving sulfur capture while also reducing lime consumption.

- Introduce a very high and stable bed side heat transfer coefficient which allows for accurate steaming rate control over a wide MCR range without sacrificing fuel efficiency or emissions control. The design overall heat transfer coefficient (Uo) is greater than 65 BTU/hr-ft^2-F and is constant within 60-to-100% of MCR.

- Permit combustion of low ashing fuels such as petroleum coke and wood waste without the need for either supplemental or costly bed makeup.

- Create a fine particle bed which at lower velocities is much less likely to erode critical in-bed metal components and refractory.

Figure 2 is a cross-sectional view of a typical FI CIRC™ fluid bed boiler and depicts many of the key design features. These features are:

- A standardized modular design, whereby each design "module" consists of:

    - one cyclone and dipleg
    - five fuel guns
    - four in-bed tube bundles
    - 112 ft^2 of tuyere area.

  Each "module" is capable of generating 25 KPPH to 40 KPPH of steam, depending on fuel and emissions standards. Each boiler, regardless of size, utilizes these "building block" modules to reduce scale-up variances. The FI CIRC™ pilot plant has a 4 ft^2 bed area so the maximum process scale-up factor for any size boiler is 112 ft^2 $\div$ 4 ft^2 or 28:1.

- Under bed above-stoichiometric air introduction to ensure uniform fluidization and complete combustion burnout in the lower zone where boiler water evaporation and sulfur removal control are critical. An oxidizing lower bed eliminates reducing gas initiated metal corrosion and ensures complete sulfur capture.

- Patented flat plate directional flow tuyeres which continuously move unfluidized particles to the gravity bed drain. This ensures optimal air introduction, fuel/air mixing and elimination of gas "jetting" with subsequent solids impingement on metal surfaces.

- Pneumatic fuel guns which positively and accurately introduce fine sized solids fuels under-bed, thereby enhancing fuel/air contact.

- Air swept spreaders or gravity drop pipes, which evenly distribute coarse particle fuels above-bed.

- Flanged, removable in-bed heat exchanger tube bundles which are located in the upper region of the dense bed to ensure uniform oxidation and minimize erosion. The upper bed placement also allows for quick and easy startup and fine steam rate control "on-the-run". They are also designed to be removed, turned over, and rotated, thereby extending wear life.

- A high freeboard region allows for coarse particle disengagement, thereby reducing refractory erosion in the cyclones. The freeboard also provides for final burnout and temperature stabilization which is required for good NOx removal without proprietary ammonia injection system.

- Multiple, small diameter, high efficiency cyclones which recycle fine particles (Dp_{50} = 15 microns) of unburned fuel and undersulfated lime particles into the lower dense bed via gravity diplegs.

- Forced circulation water flow through the tube bundles to ensure nucleate boiling in the evaporators. The net result is a low height profile, bottom supported fluid bed boiler.

FUEL PROPERTIES

Since 1977, Combustion Power has converted waste or low grade fuels to useable energy using fluidized bed combustors. Previous to then, the company was primarily doing research and development in the area of waste-to-energy conversion. Earliest work was with conversion of municipal solid waste processed to refuse derived fuel (RDF). A 100 TPD pilot plant was operated during the 1970's with continued work in a smaller unit through 1985. The pilot plant work consisted of pressurized fluidized bed combustion, atmospheric fluidized bed boiler development, and oxygen blown gasification. Typical RDF properties were as shown on Table I. Numerous other waste and low-grade fuels were burned in various Combustion Power Company pilot scale fluidized bed combustors, including high sodium North Dakota lignite, Texas lignite, pulp and paper industry sludges, wood wastes, waste oils, aircraft paint stripping wastes, etc.

These experiences with waste fuel combustion influenced design of the FI CIRC™ boiler. Low fluidizing velocities (high residence times) and high rates of solids recirculation are two examples of this. Currently operating or in construction boilers are being fired with or designed for, ponded coal fines, delayed petroleum coke, fluid petroleum coke, pat, mixed industrial wastes, log yard debris, pulp and paper sludge, municipal sludge, and rubber tires. Typical properties of some of these fuels are shown on Table II.

EMISSIONS CONTROL

Aside from particulates, there are four major gaseous species which are of most concern today: SO_2, NOx, HC and CO.

The FI CIRC™ system utilizes the principle of temperature, time and turbulence to effect extensive and cost efficient reduction of all these pollutants. SO_2 is controlled by the addition of calcium carbonate (limestone), bed temperature control, excess air, and dense bed height. CO and HC are controlled by operating temperature, excess air, and dense bed height. NOx is controlled by the addition of ammonia with gas temperature control.

All of these pollutants have temperature control in common and it is within the FI CIRC™ combustion region that the optimum range of temperatures is found. The optimum temperature range to remove each pollutant is as follows:

NOx with NH_3 reductant:	1500 - 1750°F
SO_2 with limestone:	1500 - 1750°F
CO with excess air:	above 1600°F
HC with excess air:	above 1550°F

Therefore the best temperature operating range is 1500 to 1600°F in the combustor bed and 1550 to 1650°F in the freeboard. The uniform temperatures long residence times at the proper temperatures and good solids-gas mixing are the key reasons why fluid bed combustors outperform older solid fuel combustion techniques, such as stokers and pulverized coal systems.

SO_2 is controlled by the chemical absorption of SO_2 with active calcium oxide primarily in the fluidized dense combustion bed. Some removal also occurs in the freeboard region. There are several simultaneous chemical reactions which occur to effect SO_2 removal.

$CxHyOzNiSj + O_2$	--->	$CO_2 + H_2O + N_2$
Fuel Combustion	--->	$CO + NOx + SO_2/SO_3 + HC$ + ash and char

The SO_2 portion is absorbed by calcium oxide after the calcium oxide is first formed by calcination of limestone:

$Ca\ CO_3$	--->	$CaO + CO_2$
$CaO + SO_2 + 1/2\ O_2$	--->	$CaSO_4$

The conversion to $CaSO_4$ does not occur unless oxygen is present. Also it is critical that the dense bed temperature remain below 1700°F to minimize calcium consumption. With FI CIRC™, the important Ca/S ratio is optimized via several techniques.

- Dense bed temperature control below 1700°F using in-bed heat exchange tube bundles.
- A dense bed high enough and operating at a low enough gas velocity to ensure excellent gas/solids contact time.
- Excess oxygen in the combustion zone to "drive" the sulfation reaction.
- Extensive fine particle recycling to ensure that elutriated and unreacted CaO is given another opportunity to sulfate.

The above techniques yield not only very low SO_2 emissions levels, as high as 98% suppression, but do so at very economical Ca/S ratios. Figure 3 depicts the relationship in a FI CIRC system between Ca/S ratio and SO_2 suppression.

In fluidized bed combustors operating at temperatures of 1700F or below, NOx is generated by the combustion of fuel-bound nitrogen. This NOx is destroyed by ammonia injected into the freeboard region at the proper residence time and temperature according to the following reactions:

$$4\ NH_3 + 4\ NO + O_2 \longrightarrow 4\ N_2 + 6\ H_2O$$
$$4\ NH_3 + 2\ NO + 2\ O_2 \longrightarrow 3\ N_2 + 6\ H_2O$$

Excessive ammonia introduction will create "ammonia slip" which is free ammonia leaving the stack as well as increasing CO production. This later relationship is as depicted on Figure 4. NOx control, as practiced by Combustion Power, is proprietary. This is due to the careful control required to ensure that NOx is indeed destroyed without undesired side effects, such as CO production and ammonia slip.

Both CO and hydrocarbon emissions are controlled by temperature and excess air:

$$HC + O_2 \longrightarrow CO_2 + H_2O$$
$$CO + 1/2\ O_2 \longrightarrow CO_2$$

As with SO_2 control, these pollutants are controlled in the FI CIRC™ boilers by:

- Dense bed temperature control using in-bed heat exchange tube bundles.
- A dense bed high enough and operating at a low enough gas velocity to enhance gas/ gas reaction times.
- Excess oxygen in the combustion zone to essentially complete the oxidation reactions.
- Careful ammonia injection control to minimize CO production.

This extensive emissions control technology has resulted in California FI CIRC™ plants being permitted at very low SO_2, NOx and CO levels. Of the 33 fluid bed boiler plants in California, 1/3 are FI CIRC™ systems.

Table III shows permitted and actual emissions from six petroleum coke fired plants in southern and northern California.

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TABLE I: REFUSED DERIVED FUEL CHARACTERISTICS
(composition on a dry basis*)

	Proximate Analysis (ASTM D 3172) wt % (mean)	(σ)		Ultimate Analysis (ASTM D 3176) wt % (mean)	(σ)
Ash	18.4%	(2.54%)	Ash	18.36%	(2.54%)
Volatile	71.5%	(2.27%)	C	41.66	(1.25%)
Fixed Carbon	10.1%	(2.86%)	H	5.41	(0.23%)
			N	.74	(0.17%)
			Cl	.37	(0.10%)
Heating Value	7272 Btu/lb	(283 Btu/lb)	S	.27	(0.09%)
			O	33.20	(2.12%)

*Based on 11 samples taken over 6 mo. period with average moisture content of 26%

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TABLE II: TYPICAL WASTE FUEL PROPERTIES

Property	Ponded Coal Fines	Delayed Pet Coke	Fluid Pet Coke	Peat	Mixed Ind. Wastes	Wood Wastes	Municipal Sludge	Rubber Tires
Moisture, wt%	15.0	3.1	0.2-0.8	37.6	35	50	70	0.5
Volatiles, wt%	NA*	9.0	4.7-6.4	35.9	35	45	NA	62.3
Ash & Inerts, wt%	25.5	0.2	0.2-0.3	1.9	8	1.5	NA	5.7
Ultimate Anal, wt%								
C	45.2	86.0	90-92	NA	NA	25.5	58.3	83.2
H	3.3	3.6	1.8-2.2	NA	NA	2.9	8.5	7.1
O	9.7	0.5	0.4-1.2	NA	NA	19.8	22.9	2.5
N	0.6	1.4	2.3-3.0	NA	2	0.1	8.8	0.3
S	0.6	5.2	2.7-3.5	0.3	NA	0.2	1.6	1.2
Cl	0.1	0.04	0.4-1.2	NA	NA	NA	NA	NA
Higher Heating Value, Btu/lb	8,150	14,770	14,550	6,481	6,423	4,500	3,600	16,329

*NA = Not Available

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TABLE III: FI CIRC™ EMISSIONS BURNING PETROLEUM

Plant	Fuel	SO_2[(1)]	NOx[(1)]	CO[(1)]	Total Part[(2)]
Torrance, CA	Delayed pet coke	21/13	19/8	190/13	7.8/1.7
Contra Costa County, CA (5 plants)	Fluid pet coke	54/20	50/25	117/25	3.0/1.8

(1) Values in table are given as Permit/Actual in ppm, dry, standard conditions, corrected to 3% O_2. Data taken from emissions compliance test conducted to obtain operating permit.

(2) Total particulate values are given as Permit/Actual in lb/hr.

TYPES OF FLUIDIZED BEDS

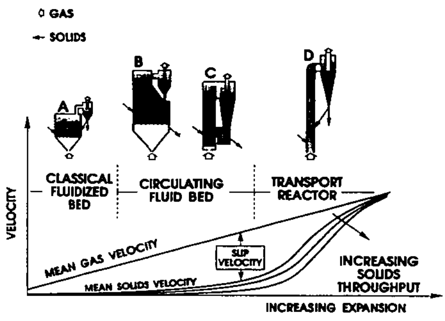

Figure 1

FICIRC™ FLUIDIZED BED BOILER SEGMENT

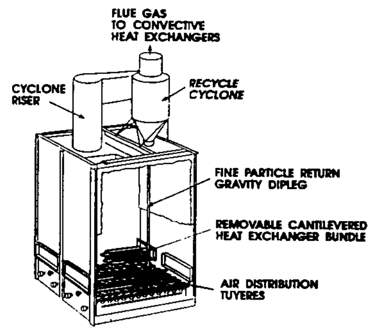

Figure 2

SO_2 CONTROL BY CALCIUM ADDITION

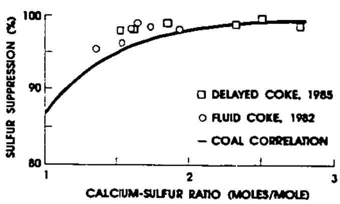

Figure 3

TYPICAL CARBON MONOXIDE PRODUCTION UPON AMMONIA INJECTION

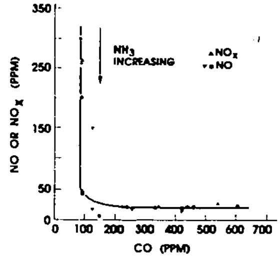

Figure 4