



1300°F 800 MWe USC CFB Boiler Design Study

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ABSTRACT Concern about air emissions and the effect on global warming is one of the key factors for developing and implementing new advanced energy production solutions today. One state-of-the-art solution is circulating fluidized bed (CFB) combustion technology combined with a high efficiency once-through steam cycle. Due to this extremely high efficiency, the proven CFB technology offers a good solution for CO₂ reduction. Its excellent fuel flexibility further reduces CO₂ emissions by co-firing coal with biomass. Development work is under way to offer CFB technology up to 800 MWe capacities with ultra-supercritical (USC) steam parameters. In 2009 a 460 MWe once-through supercritical (OTSC) CFB boiler designed and constructed by Foster Wheeler will start up. However, scaling up the technology further to 600-800 MWe with net efficiency of 45-50% is needed to meet the future requirements of utility operators. To support the move to these larger sizes, an 800 MWe CFB boiler conceptual design study was conducted and is reported on herein. The use of USC conditions (~1100°F steam) was studied and then the changes, that would enable the unit to generate 1300°F steam, were identified. The study has shown that by using INTREX™ heat exchangers in a unique internal-external solids circulation arrangement, Foster Wheeler's CFB boiler configuration can easily accommodate 1300°F steam and will not require a major increase in heat transfer surface areas.

Keywords: CFB, USC, INTREX

INTRODUCTION

Increased energy efficiency is needed to sustain robust economic growth, enhance national security, and protect environment and coal is expected to remain the leading fuel source for power generation for a long time. Efficiency and environmental performance are key issues when considering either repowering existing power plants or constructing new power plants. One of the main approaches to reduce emissions from power plants is to increase their efficiency. High efficiency means a lower fuel requirement, and results in lower ash discharge and gas emissions, including CO₂. The need for high efficiency is also important for CO₂ removal by oxy-combustion, because a reduction in fuel firing also means a lower O₂ requirement from its air separation unit, less CO₂ gas to be processed in downstream CO₂ compression and purification unit, and less storage volume for CO₂ sequestration.

With supercritical steam cycles providing high plant efficiencies, the interest is to pursue even more advanced steam conditions, such as 1300°F (700°C) to further increase efficiency and reduce emissions.

Circulating fluidized bed (CFB) combustion, with its well-known benefits of fuel flexibility, biomass co-firing capability, and low emissions, has established itself as a boiler technology suitable for utility-scale power generation. Interest in CFB combustion has been steadily increasing, 300 MWe plant sizes are in operation, and designs for larger boilers are being developed. As example, Foster Wheeler has designed and is constructing a 460 MWe SC CFB boiler for the Lagisza power station in Poland, a unit scheduled to start up in 2009 (Ref-5). Developing even larger size CFBs (600-800 MWe) with higher efficiencies is an ongoing challenge (Ref-1 to 4). A conceptual design study for an 800 MWe has been conducted to investigate the technical feasibility and economics of USC CFB boilers under U.S. Department of Energy (DOE) Cooperative Agreement No. DE-FC26-03NT41737. Foster Wheeler, together with a group of

interested companies in Europe has completed a similar study for an 800 MWe power plant with USC CFB (Ref-1). Foster Wheeler has also started a boiler design with emphasis of configuration effect on part load performance of a 660 MWe SC CFB boiler at 620°C.

Table 1 Study Steam Cycle Conditions

	Case 2	Case 3
Unit Nominal Capacity, MWe	800	800
Main Steam Pressure, psia	4351	5076
Main Steam Temperature, F	1112	1292
Reheat Inlet Temperature, F	1148	1328
Condenser Back Pressure, "Hg	2.0	2.0

The USC steam cycle conditions used in the DOE study are listed in Table-1. In this study USC CFB boiler conceptual designs were developed for nominal plant outputs of 400 and 800 MWe and then the changes to the latter that would generate 1300°F superheat and reheat steam, were identified. In Case-1 a nominal 400 MWe CFB boilers was conceptually designed for superheat and reheat steam temperatures of 1100°F, that are coming into use in the latest PC boilers. Case-2 investigated a move to a nominal 800 MWe size with a modest increase in superheat and reheat temperatures (1112°F and 1148°F respectively). In Case-3 the nominal 800 MWe CFB boiler was moved to more advanced steam conditions at 5061 psig and 1300°F steam temperatures for further gains in plant efficiency. The performance and cost of the 400 MWe Case-1 plant were presented in an earlier paper, whereas, the performance and design aspects of the 800 MWe CFB boilers are presented herein. With superheater/reheater tube metal temperatures typically running 100-200°F hotter than their steam, 1300°F steam will require a new generation of pressure part materials with high creep strength. These new materials are under development and test under other DOE contracts.

DESIGN AND SCALING UP

Preliminary studies show that the scaling-up to 800 MWe is possible for boiler components such as the furnace, solids separators, and fluidized bed heat exchangers (INTREX™). The actual scaling-up of the dimensions and size of plant components required is quite moderate due to Foster Wheeler’s modular approach shown in Figure 1.

The design of a CFB furnace involves a careful evaluation of fuel and sorbent characteristics followed by a selection of operating temperature, gas velocity, gas/solids residence times, and solids circulation rates. Furnace heights are typically below 165 feet to maximize the cost effectiveness of its heat transfer surfaces. Similar, the furnace depth (side wall to side wall distance) is typically limited to approximately 40 feet to insure distribution uniformly across the unit for fuel and secondary air injections. Primary air is admitted at the base of the unit and, to provide highly turbulent mixing of fuel, air, and sorbent, plus enhanced solids entrainment, Foster Wheeler narrows the furnace cross section at the base of the unit by slopping the side walls inward. With maximum allowable furnace heights and depths established, the main remaining variable in the scaling-up process is the width of the furnace. By using the Figure 1 modular approach, the boiler cross sectional flow area can be increased to accommodate increased firing rates and enable flue gas velocities to be kept at normal levels.

The number of fuel feeding and limestone injection points required by large units will be based on the cross section feed areas (pounds per hour per square feet of bed area) proven in smaller units. The same applies also for air distribution and start-up burners. Other auxiliary equipment, such as fans, conveyors, feeders, air heaters, baghouse filters, etc. are similar to those used in large power plants, which means that there will be no scaling-up issues in the auxiliary systems.

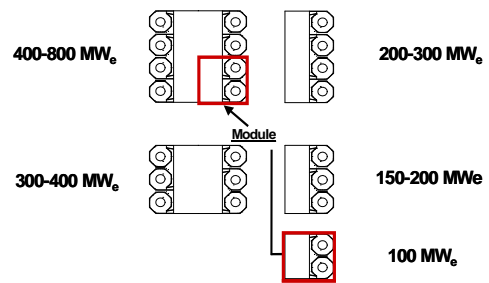


Fig. 1: Modular design of CFB boiler

Maintaining high collection efficiency in the CFB boiler's solids separators is a key to achieving high combustion efficiency, reduced limestone consumption, and high sulfur capture efficiency. Since the separation efficiency of these devices tends to decrease as physical sizes/diameters increase, large CFB boilers will use the separator sizes proven in smaller size units. Although a large CFB boiler will tend to require a larger number of separators, they will be of a proven size and design. By applying them in nominal 100 MWe furnace-separator module building blocks (Figure 1), scaling-up will not be an issue, especially since Foster Wheeler has already provided several CFB boilers with separators installed on opposing walls.

In addition to an increase in physical dimensions, the move to larger size, higher efficiency plants results in changes in boiler heat duty distributions; Table 3 shows the heat duty distributions of the Case 2 and Case 3 plants.

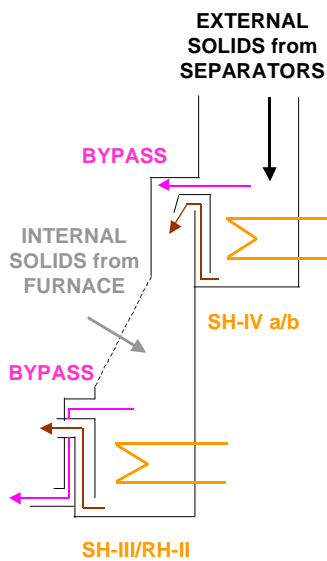


Fig. 2: Cascading INTREX™

Foster Wheeler's cascading INTREX™ design, as an example, shown in Figure 2 has been utilized to meet their needs. The INTREX™ fluidized bed heat exchangers are located under the solids separators. The solids collected by the separators pass through the INTREX™ cells (external solids circulation), after transferring heat to the immersed tube bundles, and return to the furnace via aerated lift legs. Slots can be provided in the lower furnace walls adjacent to the INTREX™ cells to allow bed hot solids from the lower furnace to fall into the INTREX™ cells (internal solids circulation), which increases LMTD and heat duty for USC steam finish superheating. These exchangers provide a dense “package” of highly efficient heat transfer surfaces and have been utilized on several Foster Wheeler CFB boilers.

After passing through the furnace solids separators, the nominal 1600°F flue gas of a large CFB boiler will be cooled in a heat recovery area (HRA) consisting of convective tube bundles and walls used for steam superheating, reheating, and feedwater preheating; the arrangement will be typical of large PC boilers.

Because CFB furnace heat fluxes are relatively low and uniform, its tubes probably do not require internal rifling and they can operate with water mass flow rates lower than those of a PC furnace and still be protected from dry-out (Figure 3). With the flow rate reduced, the tube friction loss is much smaller than the hydrostatic pressure effect. Although an increase in heat input still increases the friction loss, the increase is less than the reduction in hydrostatic pressure. With the tube total pressure loss now less than that of the average tube, the water flow rate to the tube will increase; this flow increase provides additional cooling that will help limit increases in tube metal temperatures. This is the desirable self-compensating characteristic wherein an excessively heated tube will experience an increase in flow that tends to limit over heating. Even though the furnace walls of a CFB will not require rifled tubing, evaporative tube surfaces that protrude into the furnace will be provided with normal rifling as, being heated from both sides, their heat fluxes are significantly higher than the one-side heated enclosure wall values. Compared with a SC PC boiler, a SC CFB boiler will operate with lower water mass flow rates that result in reduced pressure loss/pumping power.

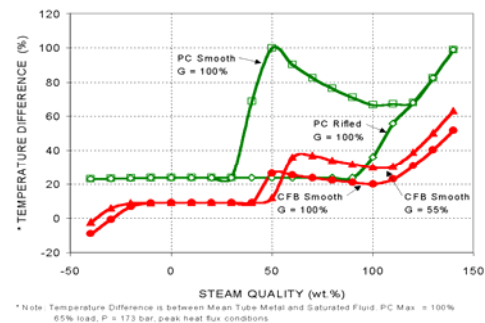


Fig. 3 Comparison of dry out

PLANT PERFORMANCE

Full load heat and material balances were prepared for the nominal 800 MWe plants. Both utilized a single reheat steam turbine and a single-pressure condenser operating at 2.0 inches Hg absolute, with feedwater heater trains consisting 3 HP and 5 LP units, and one deaerator. Table-2 summarizes the full load performance of the two plants. In order to clearly see the effects of higher steam temperatures, the CFB boilers have been designed to operate with essentially the same coal, limestone, air, and flue gas flow rates. The higher steam temperatures and pressures of the Case-3 plant result in both a higher plant efficiency and a higher power output. The Case-2 and Case-3 plants have net outputs of 740.5 MWe and 768.2 MWe with efficiencies of 41.3% and 43.3% (HHV) respectively. These efficiencies are 15-20% higher than a comparable 36% efficient sub-critical pressure CFB plant. As a result, the USC plants operate with less coal flow and higher outputs than sub-critical plants and their emissions are proportionately reduced.

The operating conditions of the USC CFB boilers are also shown in Table 2. Both boilers operate with nominal 1560°F bed/furnace temperatures and combust 2.5% sulfur Illinois No. 6 coal with 20% excess air. The CFB operates with staged air injection to control NO_x emissions, and limestone is injected into their furnaces at a Ca/S molar feed ratio of 2.4 to provide 96% sulfur capture. Table 3 lists the heat duties of the two boilers. The 1300°F Case-3 boiler, because of its higher feed water and combustion air inlet temperatures together with a ~4 % smaller steam flow, operates with a ~4% lower total duty; preheat, evaporation, and reheat duties are smaller, whereas, the total superheat duty is about 13 % higher.

Table 2 Operation Conditions

Case		2	3
Nominal USC Steam Temperatures		1,100F	1,300F
Plant Power Summary			
Gross Output, MWe		777.6	804.6
Auxiliary Load, Mwe*		37.2	36.4
Net Output, MWe		740.4	768.2
HHV Efficiency, %		41.3	43.3
Turbine Steam Conditions:			
Main Steam Flow Rate	Mlb/hr	4,514	4334
Main Steam Temperature	F	1,112	1292
Main Steam Pressure	psia	4,351	5076
Reheat Steam Flow Rate	Mlb/hr	3,867	3508
Reheat Steam Temperature	F	1,148	1328
Reheat Steam Pressure	psia	653	970
H&M Balance Parameters:			
Flow Rates:			
Combustion Air	Mlb/hr	5,446	5,389
Coal	Mlb/hr	524.5	518.8
Limestone	Mlb/hr	105.6	104.3
Total Ash	Mlb/hr	149.4	147.6
Stack Flue Gas	Mlb/hr	5,927	5,864
CO ₂ in Flue Gas	Mlb/hr	1,250	1,236
CO ₂ in Flue Gas	lb/MWeNet	1,688	1,607
Temperatures:			
Ambient	F	63	63
Combustion Air Entering CFB	F	535	625
CFB Furnace Exit	F	1,568	1,564
Flue Gas Entering Air Heater	F	625	800
Flue Gas Leaving Air Heater	F	267	268
Stack Flue Gas	F	286	287
CFB Bottom Ash	F	500	500
CFB Feedwater Inlet	F	553	629
Plant/CFB Excess Air	%	20	20
Steam Condenser Cooling Duty	MMBtu/hr	2,731	2,570
*Boiler Feed Pump Has Steam Turbine Drive			

Table 3 USC CFB Boiler Full Load Duties

Case		2	3
Nominal USC Steam Temperatures		1,100F	1,300F
Full Load Boiler Duties			
Preheat/Economizer	MMBtu/hr	461	330
Evaporation	MMBtu/hr	2032	1876
Superheat	MMBtu/hr	1710	1929
Reheat	MMBtu/hr	1214	1058
Total	MMBtu/hr	5417	5193

Table 4 lists the general features of the CFB boilers, all of which reflect conventional CFB design practices, and the 1300°F boiler is shown in side view in Figure 4. Including silos, fans, and air heater, both nominal 800 MWe units occupy an approximate 200 feet by 330 feet footprint and are top supported from structural steel approximately 250 feet above grade.

divided into 16 units; to eliminate equipment congestion along the sidewalls, they are provided in pairs in a stacked configuration, placed one above the other rather than side by side. Solids collected by the Compact Separators pass through the upper eight external circulating INTREX™ cells and, after cooling, cascade down into the lower eight INTREX™ cells for return to the furnace. The lower INTREX™ cells supplement their external solids circulation with internal solids circulation wherein nominal 1600°F solids flow directly into these cells from the furnace; this raises their hot side temperature and, with bed to steam log mean temperature differences (LMTD) increased, reduces their tube surface area requirements. Solids can also be bypassed around both upper and lower INTREX™ cells by controlling the aeration rate to their lift legs. As a result of the Figure 1 modular scale-up approach, the boilers reflect a conventional arrangement of proven components; although the approach of stacking of the INTREX™ heat exchangers is new, rather than side by side placement, there are no perceived development or scale-up issues.

Table 5 Comparison of Furnace Dimensions and INTREX™ Sizes

Operating Plant or Case	JEA 1-2	Turow 4-6	Case 2	Case 3
Nominal Gross Boiler Output, MWe	300	262	800	800
Steam Cycle Pressure	SubCrit	SubCrit	USC	USC
Furnace Dimensions, ft				
Depth	22.0	33.1	38.0	38.0
Width	85.3	72.2	129.7	129.7
Height	115.2	137.8	164.0	164.0
Solids Separators				
Total Number	3	4	8	8
Arrangement	In Line	Opposed	Opposed	Opposed
Number of INTREX Heat Exchangers	6	8	16	16

In a CFB boiler the air flow rate and, hence, fluidizing velocity varies with load/coal firing rate until a minimum, turn down design value is reached. Reduced flue gas velocities result in reduced solids circulation rates, reduced upper furnace temperatures, and reduced INTREX™ bed temperatures, especially in the lower level. To maintain both superheat and reheat temperatures with a cascading INTREX™ arrangement, the finishing superheater (SH-IVa/b) was placed in the upper INTREX™ level, and the intermediate superheater and finishing reheater were located in the lower level where internal circulation was used to augment their performance. By combining a stacked INTREX™ configuration with internal solids circulation and a parallel pass HRA, superheat and reheat temperatures can be maintained at full load values over the 45 to 100% load range.

As identified in Table 3 the move to 1300°F steam reduces the boiler's preheat, evaporation, and reheat duties but increases its superheat duty. The changes to the boiler to accommodate these new conditions are summarized as follows:

- a) To reduce evaporation duty: Furnace height was reduced by approximately 6.5 feet; Full height evaporator wing-walls were removed; Less conductive, thicker refractory is used in the lower furnace
- b) To reduce economizer duty: Upper economizer surface increased (+18%), lower reduced (-63%); Air heater surface increased (+5%); adjustment required to achieve stack temperature with reduced economizer duty (shifts more heat into high temperature furnace solids circulation loop)
- c) To increase superheat duty: In-furnace platen superheaters (10%) were added upstream of INTREX™ SH-III; A loop of tubing was added to upper INTREX™ SH-IV (now same number of tube elements in the upper and lower INTREX™ cells);

d) To meet reduced reheat duty: Convection reheater surface increased (+25%); addition required to compensate for reduced INTREX™ RH-III duty resulting from higher steam temperatures and increased INTREX™ RH-IV duty which lowers solids temperature to RH-III

With these changes, the evaporator inlet water is sufficiently sub-cooled over the load range, maximum evaporator outlet superheat is about 86 Btu/lb, and full reheat steam temperature is maintained down to approximately 45% load (1323°F at 40% load). These results show that a CFB boiler can achieve/operate with advanced USC steam conditions (5261 psig and 1300°F) in a conventional configuration provided materials, with sufficient strength, fire side corrosion resistance, and steam side oxidation resistance, are developed for these conditions.

SUMMARY

This study, as an example, has shown that CFB boilers can move to USC steam conditions in 800 MWe sizes; these units are expected to have performance and economics that are similar to those of comparably sized PC boilers while still offering greater fuel flexibility and ability of co-firing with biomass. In addition, their furnaces can be built from straight, self supporting, vertical tubes rather than complex spiral wall designs. Their lower pressure drop will enable them to operate with a self-compensating characteristic, that will limit tube overheating and failures. When advanced materials are developed with sufficient strength, outside corrosion resistance, and inside oxidation resistance, CFB boilers can accommodate steam temperatures as high as 1300°F while maintaining conventional, cost effective configurations.

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