CFB Boiler and CFB Scrubber Technology for Large Scale Power Generation with Turkish Lignite – Soma 2x255MWe Project
ABSTRACT

Currently, Turkey is amongst the world’s fastest growing economies, and the country’s energy demand has been rapidly growing. Due to over 10 GT of proven domestic lignite reserves (IEA), lignite is considered a feasible alternative for large-scale electricity production compared to imported coal.

Recently, circulating fluidized bed (CFB) technology has emerged among the leading combustion technologies for utility-scale solid-fuel-fired power plants, especially in combustion of lignites. Benefits of the technology include high efficiency and availability and exceptional fuel flexibility with low emissions. Today, nearly 440 Amec Foster Wheeler CFB boilers have been sold with both subcritical and supercritical steam values. To reach required emission limits economically, additional emission control technologies, such as the circulating fluidized bed scrubbing (CFBS) technology has been applied together with CFB combustion technology to optimize the sulphur capture from flue gases. This is a viable pathway for addressing multi-pollutant control in a cost effective manner.

During the past 40 years Amec Foster Wheeler has supplied nearly 300 CFB boilers designed for coal including lignite with total thermal capacity of 71 GWt. All the boilers utilize the same circulating fluidization principle; however, depending on the quality of fuel, the boilers may differ in design and operation. The size of CFBs designed for lignite as primary fuel can vary in a broad range of steam capacity, from industrial to large-scale utility boilers, up to scale 600 to 800 MWt.

In this paper, economic benefits of combusting domestic lignite compared to imported coal are highlighted. Furthermore, a recent CFB project, Soma (2x255MWe), firing Turkish lignite as the main fuel, Harbin Electric International Co. Ltd. (HEI) being as an EPSC(Engineering, Procurement, Supervision & Commissioning) contractor, is presented. This is currently the biggest CFB boiler on Turkish lignite. Also the design and process of related flue gas cleaning concept featuring best available CFB (Circulating Fluid Bed) scrubbing technology (BAT) are discussed. There are two identical flue gas cleaning lines (one for each boiler), which consist of CFB scrubbers including bag-house with solids recirculation.

Keywords: Utility CFB technology, CFB scrubbing technology, Lignite firing
1 INTRODUCTION

Use of low rank coals and lignites for power production are growing, not only in Turkey, but also in India, China, Indonesia, Australia, South Africa, and Mozambique driven by the very low cost of these fuels relative to premium coals. Turkey is amongst the world’s fastest growing economies, and the country’s energy demand has been rapidly growing. Due to over 10 GT of proven domestic lignite reserves (IEA), lignite is considered a feasible alternative for large-scale electricity production compared to imported coal.

Since fuel cost makes up about 85%-90% of the total operating cost of a large power plant, the economic benefits of using low quality fuels are significant. Until recently, low quality coals and lignites have mainly been used in domestic markets and have not been part of the international coal market. This is because their economic benefit quickly erodes by their higher transportation cost due to their lower energy content. But today, we are seeing more low quality coals and even lignites coming into the global coal market driven by steep price discounts against a tight market for premium coals.

This is good news for power generators utilizing CFB technology. Due to the CFB’s fuel flexibility, plant owners could access the full range of discount coals, buying fuels for maximum economic benefit while avoiding the high priced premium coals. Circulating fluidized bed (CFB) has emerged among the leading combustion technologies for utility-scale, solid-fuel-fired power plants, especially when multi-fuel capabilities are required or fuel is of low quality. Established benefits of high efficiency, reliability and fuel flexibility, with low emissions and installation costs, have been demonstrated on nearly 440 Amec Foster Wheeler’s CFB boilers including both, subcritical and once-through supercritical boilers. The largest operating boiler is the TAURON’s owned Lagisza power plant in Poland, 460 MW e, which celebrates already five years of successful commercial operation. CFB technology is currently available in large-scale sizes up to scale 600-800 MWe for a wide range of solid fuels.

The size of CFB’s designed for lignite/coal as primary fuel can vary in a broad range of steam capacity, from industrial to large-scale utility boilers. Additionally, many of the boilers designed for coal feature the well-known fuel flexibility capability adding fuels such as biomass and various types of waste which are co-fired simultaneously.

This paper will present recent utility-size CFB boiler project designed to fire lignite as the main fuel: Soma, 2 x 255 MW_e.
Amec Foster Wheeler has been awarded a contract by Harbin Electric International Co. Ltd. (HEI) for the design and supply of two circulating fluidized-bed (CFB) boiler islands and flue gas scrubbers for HIDRO-GEN Energy Import, Export, Distribution and Trading Inc., a subsidiary of Kolin Group of Companies. HEI is acting as EPC contractor for HIDRO-GEN’s power project to be built close to lignite mines, near the town of Soma, west part of Turkey, 135 km north from Izmir (Figure 1).

Full notice to proceed on this project was received in January 2014. Commercial operation of the new steam generators is scheduled for the beginning of 2017 (Table 1).

<table>
<thead>
<tr>
<th>Table 1. Project execution schedule</th>
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<tbody>
<tr>
<td>Contract Award</td>
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<tr>
<td>Start of Erection</td>
</tr>
<tr>
<td>Commercial Operation</td>
</tr>
</tbody>
</table>

Amec Foster Wheeler’s scope includes design and supply two 255 MW_{e} (gross megawatt electric) steam generators and auxiliary equipment for the boiler islands, flue gas cleaning systems with CFB scrubbers, and technical advisory services during erection and commissioning. The CFB boilers will be designed to burn local lignite, due to the significant economic benefit of using this fuel for power generation. Currently, this is also the largest CFB project awarded in Turkey.
2.1 Soma CFB boilers

Soma CFB boilers are designed to utilize local lignite reserves located near Soma town, with design heating value of 6.77 MJ/kg (Table 2). Fuel characteristics have been considered in boiler design, for example in the bottom ash removal system (chapter 2.5). Boilers are natural circulation type of drum boilers (Figure 2) with reheat (see steam parameters in Tables 3-4). The CFB boiler design incorporates solids separators built from steam cooled panels integrated with the combustion chamber. The final superheating stages are INTREX™ heat exchangers located in special enclosures at the bottom of the furnace (adjacent to the main combustion chamber).

![Soma CFB boilers](image)

Figure 2. Soma CFB boilers

<table>
<thead>
<tr>
<th>DESIGN FUEL DATA</th>
<th>Lignite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulphur</td>
<td>0.95% d.s.</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.53% d.s.</td>
</tr>
<tr>
<td>Moisture</td>
<td>23.3% a.r</td>
</tr>
<tr>
<td>Ash</td>
<td>42.9% d.s.</td>
</tr>
<tr>
<td>LHV</td>
<td>6.77 MJ/kg</td>
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Table 3. Soma boiler steam data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SH flow</td>
<td>198.5kg/s</td>
</tr>
<tr>
<td>SH pressure</td>
<td>173 bar(a)</td>
</tr>
<tr>
<td>SH temperature</td>
<td>565 °C</td>
</tr>
<tr>
<td>RH flow</td>
<td>173kg/s</td>
</tr>
<tr>
<td>RH pressure</td>
<td>53 bar(a)</td>
</tr>
<tr>
<td>RH temperature</td>
<td>565 °C</td>
</tr>
<tr>
<td>Feed water temperature</td>
<td>262 °C</td>
</tr>
</tbody>
</table>

Table 4. Design performance

<table>
<thead>
<tr>
<th>Emissions</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>- NO&lt;sub&gt;x&lt;/sub&gt;</td>
<td>&lt;200 mg/Nm&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>- SO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>&lt;200 mg/Nm&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>- CO</td>
<td>&lt;200 mg/Nm&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Particulate Matter</td>
<td>&lt;30 mg/Nm&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

*) Emissions are expressed in dry flue gases @ 6%O<sub>2</sub>

2.2 Combustion process

The principle of the CFB combustion system can be characterized with the relationship between differential pressure and superficial gas velocity in a bed of particles. In a fixed bed, the differential pressure is approximately linearly proportional to the gas velocity. As the gas velocity increases beyond the minimum fluidization velocity, the bed starts to expand and become fluidized but the distinct bed level remains visible. The differential pressure stays almost constant until the bed material begins to elutriate (rise and separate) at the entrainment velocity of a bubbling bed. The turbulence of the particles continues increasing between the minimum and the entrainment velocity.

Beyond the entrainment velocity, the particles are carried out with gas flow more or less as condensed particle clouds. Part of the entrained solids remains in the furnace and fall down on the furnace walls (internal circulation). The other remains with the gas stream and will be carried into the separator (external circulation). The solids are separated from the gas in a centrifugal and gravity field of the separator and returned to the lower part of the furnace through return channels. A continuous process is maintained with circulating the particles from the furnace into the separator and return channels. At entrainment velocity the transition from a bubbling bed to a circulating bed will take place. Beyond this velocity, the logarithmic differential pressure is a function of velocity and solid circulating rate.
During start-up, the CFB combustion system operates in the region between a bubbling fluidized bed and a circulating fluidized bed as long as the normal bed temperatures are obtained. When increasing the output more fuel is fed into the furnace. Simultaneously primary airflow is increased above minimum and the entrainment velocity is reached. The combustion system operates as a circulating fluidized bed. High turbulence, solids mixing, and non-visible bed level characterizes this operation mode. The entrained bed material, with an average size in the range of 100 to 300 microns is separated in solids separator and returned to the bed via wall seals and INTREX chambers.

2.3 Advantages of the CFB process

The major advantages of the CFB combustion system can be summarized as follows:

Fuel flexibility
The combustion system can be designed to fire a wide range of fuels including high ash and moisture coals, biomass, and low volatile petroleum cokes.

Low sulphur emissions
Sulfur is captured with limestone in the combustion chamber.

The limestone reactions with the sulfur take place in two steps:

a. Calcination of limestone
   \[ \text{CaCO}_3 + \text{heat} \rightarrow \text{CaO} + \text{CO}_2 \]

b. Reaction with sulphur
   \[ \text{CaO} + \frac{1}{2} \text{O}_2 + \text{SO}_2 \rightarrow \text{CaSO}_4 + \text{heat} \]

The product, \( \text{CaSO}_4 \), is an inert substance known as gypsum.

The sulphur capture requires some excess amount of limestone present. The amount of excess limestone is dependent on a number of factors such as the amount of sulphur in the fuel, the temperature in the combustion system, and the physical and chemical characteristics of the limestone. The ideal reaction temperature range is 840-900 °C.

High combustion efficiency
Excellent vertical and lateral mixing of solids, fuel and oxygen together with long solids residence in the combustion chamber ensure maximum carbon burnout.

Low NOx emissions
Low combustion temperature and staged combustion result in low NO\textsubscript{x} emissions without downstream treatment. Urea injection further reduces flue gas NO\textsubscript{x} below the emission limit.

**Elimination of slag formation**
Low combustion temperature eliminates slag formation and reduces the volatilization of alkali salts. This reduces boiler corrosion and convective surface fouling.

**High turndown**
The high superficial velocity in the combustion chamber provides large load change capability.

### 2.4 Fuel feeding system
Local lignite from the Soma area is filled in the boiler silos by the client’s conveying system. Each boiler has five daily silos located in the front wall of the CFB boilers. Gravimetric type conveyors feed fuel to the front wall and rear wall of the furnace.

### 2.5 Bottom ash removal
In the combustion of high ash Turkish lignite containing 35-50 % ash (a.r.) results in relatively high bottom ash flow. The Soma CFB boilers are equipped with six (6) drum coolers each. Drum coolers drop bottom ash to redundant drag chain conveyors and further via elevators to the intermediate bottom ash silo. Capacity of the drum coolers is dimensioned so that one out of six coolers can be out of service with the maximum bottom ash flow rate. See figure 3 below illustrating the bottom ash removal system.

![Figure 3. Bottom ash removal system](image-url)
2.6 Limestone feeding

The Soma CFB boilers are equipped with in-furnace sulphur removal systems consisting of pneumatic conveying lines and altogether twelve feeding points located in the lower furnace. Limestone is evenly distributed to the furnace front and rear walls.

3 SOMA CFB FLUE GAS CLEANING

3.1 CFB scrubber

The multi-pollutant circulated fluidised bed scrubber (CFBS) is a flexible and economical technology capable of removing a wide array of pollutants from flue gases of nearly any combustion or industrial process. As shown in Figure 4, boiler flue gas enters at the bottom of the CFB scrubber’s up-flow absorber vessel. The gas mixes with hydrated lime and water injected into the absorber, as well as recirculated solids from the downstream fabric filter. The turbulator wall surface of the absorber causes high turbulent mixing of the flue gas, solids, and water to achieve high capture efficiency of the vapour phase acid gases and metals contained within the flue gas.

In June 2011, a 440-MWe rated coal power plant at Basin Electric’s Dry Fork station went online in Gillette, Wyoming. Due to its 4,430-foot site elevation, the Dry Fork plant has a gas volumetric flow rate equivalent to a 520 MWe plant at sea level. Behind its pulverized coal boiler sits the largest CFB scrubber operating in the world today. In addition, three CFB boilers delivered in the USA have been equipped with CFBS technology. Limestone injection in CFB furnace is used as the main sulphur sorbent and stack SO₂ emission is controlled to the permit level by hydrated lime in the CFBS. Unreacted CaO in boiler fly ash is partially utilized for SO₂ capture in CFBS which reduces the hydrated lime consumption.

An advantage of CFBS is the capability of injecting sorbent and controlling absorber temperature by water spraying separately. In spray drier technology (SDA) sorbent is injected in slurry form which limits the sorbent feeding to what is allowed by the absorber temperature control (water) and maximum solids content slurry (sorbent). This feature of CFBS allows feeding of a high inert containing conditioned fly ash in much higher quantities in order to increase the CaO input to scrubber. The absorber exit temperature can be controlled independently by water sprays above the dew point.

In order to reach required emission values (Table 4) in an economical way, the circulating fluidized bed scrubbing (CFBS) technology has been applied in the Soma power plant. This is a viable pathway for addressing multi-pollutant control in a cost effective manner. There are two identical flue gas cleaning lines, which consist of CFB scrubber including baghouse with solids recirculation (Figure 4).
Figure 4. CFB scrubber

CFB Absorber

Multiple flue gas venturies, shown in Figure 5, provide the required fluidising gas dispersion and adequate suspension of the solids across the full diameter of the absorber vessel. The multi-venturi design allows a wide capacity range while minimizing scale-up risk. Water injection nozzles provide an atomised spray cloud of water droplets enhancing heat and mass transfer rates over the large surface area of solids churning within the confines of the vessel walls. Residence time for gases entering the tall and narrow reflux CFB absorber can be as high as five seconds providing excellent capture efficiency for multiple gas pollutants, while maintaining a small absorber footprint. The CFB absorber maintenance is minimal as the vessel is self-cleaning. Water spray nozzles can be replaced, if necessary, while the unit is on-line. The absorber is fabricated from carbon steel, avoiding expensive liners or alloy metals.
Fabric Filter
A multi-compartment baghouse is located downstream of the absorber vessel for high efficiency capture and recirculation of the solid particles. Most of the ash and FDG products separated by the fabric filter bags are recirculated back to the absorber by means of non-mechanical air slide conveyors. Bed inventory in the absorber is maintained at set point by controlling the ash flow rate of air slides. The excess ash from the baghouse hoppers is discharged to the ash storage silo.

3.2 Lime Dry Hydrator (LDH)

Hydrated lime [Ca(OH)$_2$] used in the CFB scrubbing process can be purchased directly from suppliers. However, for high sulphur fuel applications requiring larger quantities of reagent, or in locations where hydrated lime suppliers are not available, owners can purchase less costly quicklime (CaO) and hydrate it on site. A lime dry hydration system can be located near the CFB absorber vessel. As shown in Figure 6, lime and low pressure steam are injected into the hydration reactor for conversion of calcium oxide to calcium hydroxide. Hydrated lime product from the hydrator is separated from the hydrator exhaust in a downstream cyclone and then collected in an ash hopper. From the product hopper, the hydrated lime can be sent directly to the CFB absorber or to a hydrated lime storage silo.
The dry lime hydration system does not require a dedicated fabric filter to handle the cyclone overflow as this stream is sent directly to the CFB scrubber. The hydration system requires less maintenance with no rotating equipment except for a fluidizing air fan, feeders for dosing lime into hydrator and discharging the hydrated product from hydrator.

In a CFB boiler, limestone injection is used to capture SO$_2$ from flue gas during the combustion in furnace. Required overdosing of limestone leaves part of the calcium unreacted in ash streams. During recent years, CFB scrubber technology has been developed towards the utilization of this unreacted CaO in the CFB boiler ash in the CFB scrubber. This way, it is possible to minimize the sulphur sorbent cost at the power plant. Due to the reduced sorbent usage also FGD products as produced and, hence, ash disposal cost is lower. Part of the CaO can be utilized in the scrubber when CaO in ash hydrates in the absorber due to water spraying there. Water spraying is applied in order to control the absorber temperature closer to the dew point and to increase the relative humidity of flue gas for enhanced sulphur capture. Fly ash can be conditioned also separately in an external hydrator. Thereafter, the activated ash is injected into the scrubber. This concept requires either pre-separation of fly ash upstream of the scrubber for hydration or recirculating fly ash from the particulate filter via the hydrator.

The CFB scrubbers at the Soma power plant are equipped with two lime dry hydrators for conditioning the fly ash which is partially separated from CFB boiler flue gas in an electrostatic precipitator (ESP) located upstream the scrubber. The main design parameters are shown in Table 5. From the hydrator the ash is fed directly to the CFB scrubber. By utilizing the fly ash in the integrated hydrator / CFB scrubber process, the required SO$_2$ control is fully achieved by injecting cheaper limestone in the furnace.
Limestone consumption is minimized by optimising the SO\textsubscript{2} capture between the CFB furnace and FGD system. The flue gas cleaning system of the Soma plant is illustrated in Figure 7.

<table>
<thead>
<tr>
<th>Table 5. Soma CFB scrubber data</th>
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<tbody>
<tr>
<td>Flue gas flow/train</td>
</tr>
<tr>
<td>Flue gas inlet temperature</td>
</tr>
<tr>
<td>Ash hydration capacity/hydrator</td>
</tr>
<tr>
<td>SO\textsubscript{2} emission (stack)</td>
</tr>
<tr>
<td>Hydrated lime</td>
</tr>
</tbody>
</table>

**Main components:**
1. Pre-separation ESP
2. Lime Dry Hydrator
3. Absorber vessel
4. Fabric filter
5. Hydrated lime silo

**Figure 7. Flue gas cleaning system at the Soma CFB power plant**

Construction costs can be reduced as the major FGD system components can be pre-assembled on the ground and lifted into place during system erection. The technology provides high pollutant removal efficiencies up to 99 % for SO\textsubscript{2}, SO\textsubscript{3}, HCl and HF. Further the absorber/fabric filter arrangement is highly adaptable for sorbent injection for removal of heavy metals including mercury. The main advantages of this technology combined with CFB boiler is reduced operating cost due to lower limestone consumption.
The global coal market is moving away from its traditionally rigid single specification coal market toward a more flexible price-for-coal-quality market. The convergence of the coal market shift with the CFB’s entry into utility power application is expected to accelerate the adoption of CFB technology in the large utility power sector. Due to the large economic benefit, the use of domestic lignite for utility power generation is growing in Turkey, which has abundant supplies of very economical low quality lignite. It is also expected that CFB technology will be utilized more in this market. Soma CFB boiler islands and flue gas scrubbers represent a valid reference case, presented in this paper.

CFB technology has undergone extensive development since the 1970s and Circulating Fluidized Bed (CFB) technology has now established its position at utility scale as a viable and efficient boiler technology for combustion of low quality fuels. The size of CFB’s can be up to 600-800 MW_e.

With the operational success of the CFB scrubber at the Basin Dry Fork station in Gillette, Wyoming, single train CFB scrubbers for large scale power plants have been proven at the 500 MW_e power plant scale. Single train designs up to 700 MW_e are available and can be offered with low scale up risk due to the technologies modular CFB absorber venturi and compartmental baghouse design concept. The technology has been applied widely in power plants, steel mills, refineries, waste-to-energy plants, combined heat and power plants, and plants in many other industries. It has been demonstrated over a range of flue gas flow rates from small industrial boilers to large coal power plants with capacities over 500 MW_e. Preceding the Soma plant, fly ash from CFB boilers has been utilized successfully for reducing the consumption of commercial hydrated lime in CFB scrubber at three Amec Foster Wheeler supplied CFB boilers in the United States.