Advanced utility CFB technology for challenging new solid biomass fuels
ABSTRACT

New boundaries for power plant operation are being set in the European energy production markets. Several factors, such as biomass subsidies, have increased the interest in large scale, commercially feasible biomass fired power plants. To further increase and ensure the profitability of these plants, investors and plant operators have widened their fuel portfolios to include low cost biomass, such as encroaching wood species and agro-pellets from Europe, South America, Africa and USA.

This trend has resulted in increased pressure to develop utility power plant technology that is capable of both flexible and highly efficient operation with higher steam parameters, while firing these challenging solid biomass fuels. European utility sized power plants now have new requirements and expectations for their operational capability: to fire new and challenging types of biomass in highly efficient large-scale power plants while maintaining high plant availability.

Circulating Fluidized Bed (CFB) combustion technology is increasingly becoming the market-leading technology used in the large-scale utility power sector firing a broad range of solid biomass fuels, due to its well-known benefits such as fuel flexibility, high efficiency, availability, and reliability. However, detailed knowledge of biomass specifications and full understanding of their variability of supply are paramount to design boilers with the highest efficiency and availability, and to operate them in the most economical way.

After introducing the market drivers and technical challenges of firing new types of solid biomass and residues in utility boilers, this paper presents the key technical features needed in CFB boilers firing challenging biomass, in order to overcome challenges associated with plant availability. The paper also reviews relevant boiler references in commercial operation: 110-MWth CFB of Kraftringen Energi AB, Örtofta, Lund, Sweden, designed to burn wood biomass, demolition wood and peat; 447-MWth CFB of GDF SUEZ, Polaniec, Poland, designed for wood chips and agro biomass; and 154-MWth CFB of ZE PAK, S.A., Konin, Poland, designed for wood and crop waste.

Keywords: CFB, Biomass, Renewable Energy, Boiler availability
INTRODUCTION

Amec Foster Wheeler started the development of circulating fluidized bed (CFB) combustion for the thermal conversion of solids fuels in the mid-1970s. During the first years of pilot testing, the technology was adapted to burn a wide range of fuels including biomass. The first units built had a small capacity, below 10 MWth, while the largest single unit sizes today are approx. 447 MWth with pure biomass and 1166 MWth with coal / biomass. Of the total 440 CFB boilers sold to date, approximately 120 are designed for firing biomass.

Along with the scale-up the power production efficiency has also increased, resulting in more efficient utilization of the biomass fuel. In order to continue this development, higher steam temperatures and pressures are being pursued. Simultaneously investors and plant operators have widened their fuel portfolios to include low cost biomass, such as encroaching wood species and agro-pellets from Europe, South America, Africa and USA.

The Advanced Bio CFB technology further improves the well-known benefits of CFB technology’s superior fuel flexibility, inherently low emissions, and high availability. Today, the Advanced Bio CFB technology offers efficient sub-critical boilers up to 600 MWe for 100 % biomass firing. This technology also offers supercritical steam parameters for biomass and coal co-firing applications up to 800 MWe. This is the result of continuous development work, building on experience and data from over 400 CFB reference boilers.

CHARACTERISTICS OF BIOMASS FUELS

Properties of New Non-Conventional Biomass Fuels

Biomass properties vary considerably depending on their biological origin, location, seasonality, farming and harvesting practices, and ultimately their preparation and processing (Figure 1). This leads to broad variations in chemical composition and physical properties across different biomass types and even within the same type. Their wide property differences is one of the key challenges of using biomass as a fuel for power and steam production.
Tables 1 and 2 show the heat value, proximate and ultimate analyses as well as the ash forming elements (determined mostly by the ICP-OES method) of some woody biomass and agro biomass fuels, respectively.

As shown in the tables, the variation in heat value of dry fuel is modest between different biomass types and the same goes for the main elements in the ultimate analysis. However, the physical properties such as bulk density and moisture content and thus the heating value on an as-received basis varies in a wide range, and these properties affect plant design in terms of fuel handling, feeding systems and overall boiler dimensioning. Generally, boilers sized to handle the modest amounts of flue gas from dry pellets may have difficulties managing the considerably larger volumes of flue gas from wet chips. Conversely, furnaces designed to handle the moderate heat from wet chips may suffer overheating from drier and more calorific biomass and residue.

The ash forming elements of biomass largely define the degree of challenges in combustion, and as shown in the tables, differences in these elements can be major, more than an order of magnitude. As an example, Table 2 includes two straw analyses, one in pellet form (from Europe) and the other in fluff form (from South America), with major differences in some elements but minor in others. Ash related problems may include furnace slagging, bed agglomeration, boiler fouling, localized erosion, and extended corrosion. Elevated levels of alkali metals especially potassium in biomass, as well as chlorine concentrate in the boiler ash cause fouling and corrosion within the boiler. Challenges introduced by conventional woody biomass are well understood and reliably predicted by in-house models. However, the broader variety of biomass fuels currently available in the market demand more complex fuel evaluations, as other elements such as phosphorous, calcium, or silica may play a key role in complex chemistry of fuel-ash transformation during combustion. Also, firing different biomass fuels in a mixture...
may involve beneficial or detrimental interactions between harmful elements, bed material and possible additives. Therefore, models and prediction tools capable to assess ash-related challenges in CFB combustion, such as agglomeration, fouling and corrosion, have been developed at Amec Foster Wheeler, and are continuously validated for a broad range of biomass fuels and mixtures, including cofiring with fossil fuels.

Table 1. Properties of Selected Woody Biomass Fuels.

<table>
<thead>
<tr>
<th></th>
<th>Wood Chips (Stem Wood)</th>
<th>Wood Pellets (Stem Wood)</th>
<th>Mesquite Pellets</th>
<th>Rubber Wood Chips</th>
<th>Shea Tree Pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td>HHV dry MJ/kg</td>
<td>20.0</td>
<td>19.7</td>
<td>19.9</td>
<td>19.3</td>
<td>19.3</td>
</tr>
<tr>
<td>LHV dry MJ/kg</td>
<td>18.7</td>
<td>18.4</td>
<td>18.7</td>
<td>18.1</td>
<td>18.2</td>
</tr>
<tr>
<td>LHV wetMJ/kg</td>
<td>7.43</td>
<td>16.8</td>
<td>17.3</td>
<td>15.8</td>
<td>15.6</td>
</tr>
<tr>
<td>Bulk density kg/m³</td>
<td>344</td>
<td>646</td>
<td>N/A</td>
<td>N/A</td>
<td>760</td>
</tr>
<tr>
<td>Proximate analysis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture, total %-%</td>
<td>53.3</td>
<td>7.9</td>
<td>6.5</td>
<td>11.3</td>
<td>12.6</td>
</tr>
<tr>
<td>Fixed carbon dry %-%</td>
<td>16.7</td>
<td>N/A</td>
<td>20.6</td>
<td>15.9</td>
<td>30.3</td>
</tr>
<tr>
<td>Volatiles dry %-%</td>
<td>81.4</td>
<td>N/A</td>
<td>77.1</td>
<td>82.8</td>
<td>63.8</td>
</tr>
<tr>
<td>Ash dry %-%</td>
<td>1.9</td>
<td>1.0</td>
<td>2.3</td>
<td>1.3</td>
<td>5.9</td>
</tr>
<tr>
<td>Fuel ratio FC/VM</td>
<td>--</td>
<td>0.27</td>
<td>0.19</td>
<td>0.47</td>
<td></td>
</tr>
<tr>
<td>Ultimate analysis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C dry %-%</td>
<td>48.6</td>
<td>50.8</td>
<td>50.3</td>
<td>48.7</td>
<td>50.4</td>
</tr>
<tr>
<td>H dry %-%</td>
<td>6.1</td>
<td>6.1</td>
<td>5.6</td>
<td>5.8</td>
<td>5.4</td>
</tr>
<tr>
<td>N dry %-%</td>
<td>&lt;0.3</td>
<td>&lt;0.2</td>
<td>0.48</td>
<td>0.29</td>
<td>2.96</td>
</tr>
<tr>
<td>S dry %-%</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
<td>0.03</td>
<td>0.04</td>
<td>0.28</td>
</tr>
<tr>
<td>Ash forming elements</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cl dry mg/kg</td>
<td>100</td>
<td>230</td>
<td>560</td>
<td>150</td>
<td>880</td>
</tr>
<tr>
<td>Ca, total dry mg/kg</td>
<td>2700</td>
<td>1800</td>
<td>11200</td>
<td>4100</td>
<td>2300</td>
</tr>
<tr>
<td>Mg, total dry mg/kg</td>
<td>310</td>
<td>400</td>
<td>210</td>
<td>1400</td>
<td>2200</td>
</tr>
<tr>
<td>Na, acid soluble¹     dry mg/kg</td>
<td>50</td>
<td>82</td>
<td>60</td>
<td>66</td>
<td>140</td>
</tr>
<tr>
<td>K, acid soluble¹      dry mg/kg</td>
<td>750</td>
<td>790</td>
<td>910</td>
<td>2000</td>
<td>20700</td>
</tr>
<tr>
<td>Na, total dry mg/kg</td>
<td>110</td>
<td>130</td>
<td>72</td>
<td>59</td>
<td>190</td>
</tr>
<tr>
<td>K, total dry mg/kg</td>
<td>950</td>
<td>980</td>
<td>1100</td>
<td>2200</td>
<td>23300</td>
</tr>
<tr>
<td>P, total dry mg/kg</td>
<td>130</td>
<td>110</td>
<td>130</td>
<td>230</td>
<td>2000</td>
</tr>
<tr>
<td>Si, total dry mg/kg</td>
<td>3300</td>
<td>1100</td>
<td>1200</td>
<td>360</td>
<td>5200</td>
</tr>
<tr>
<td>Al, total dry mg/kg</td>
<td>340</td>
<td>360</td>
<td>290</td>
<td>100</td>
<td>650</td>
</tr>
<tr>
<td>Fe, total dry mg/kg</td>
<td>530</td>
<td>340</td>
<td>220</td>
<td>100</td>
<td>920</td>
</tr>
</tbody>
</table>

Notes: ¹) Acetic acid soluble
Characterization of Biomass Fuels for CFB Combustion

As properties affecting combustion behavior of a fuel in CFBs vary substantially even within the same type of biomass, knowing the fuel type, source, and origin are insufficient for full fuel characterization. During the years, a detailed characterization method has been developed at Amec Foster Wheeler which enables full assessment of fuel properties, and includes:

- Standard physicochemical analyses such as proximate and ultimate analysis, heating value, bulk density, and particle size
- Concentration of ash-forming elements preferably performed with Inductively Coupled Plasma coupled with optical emission spectroscopy (ICP-AES) on fully digested biomass without prior ashing
- Selective leaching of ash-forming elements with two solutions of increasing pH which allows an estimate of chemical forms present in the fuel
- Characterization tests for pellets including durability
- Thermogravimetric determination of the burning profile
- In-house developed methods such as combustion test and sintering test.

For new biomass types the characterization test can be further complemented with pilot test in test rigs ranging from a bench-scale defluidization reactor, a small-scale (0.1 MW class) pilot CFB, and a large-scale (1 MW class) pilot CFB, as described in [1].
Results from the characterization tests are compared with data from an in-house database which contains nearly 1500 biomass samples, and used in models and tools. For example, Figure 2 shows the results of the in-house model, described in [2], that estimates agglomeration, fouling and corrosion for fuels show in Tables 1 and 2. Shea tree pellets, sunflower and straw are expected to be among most challenging non-conventional biomass shown here.

These hold the highest potential to create operational difficulties such as agglomeration of fluidized beds, as well as fouling and corrosion of convective heat surfaces. These problems can be traced back to elevated concentrations of alkali, phosphorous and chlorine, which are typically much higher in most agros than in wood. This unfavorable composition is the main reason why the utilization of novel biomass fuels has been limited in energy production so far.

Detailed knowledge of biomass specifications and full understanding of their variability of supply are paramount to design boilers with the highest efficiency and availability, and to operate them in the most economical way.

**LARGE SCALE CFB FOR BIOMASS COMBUSTION – ABC TECHNOLOGY**

Due to it's inherent fuel flexibility, CFB boiler technology is ideal for large scale power generation with a broad range of biomass fuels, either alone or co-fired with fossil fuels. Amec Foster Wheeler has progressively advanced and scaled-up CFB technology for biomass firing since the 1980s, starting from small multi-fuel boilers firing residue from Nordic wood in the pulp and paper industry. Advanced Bio CFB (ABC) technology is today’s state-of-the-art for biomass combustion. ABC is the result of corporate knowledge on biomass and experience from over 400 CFB commercial references combined with continuous research.
The ABC technology not only addresses the fuel issues related to biomass firing, but also adopts plant requirements and optimizes the investment factors. Plant requirements include the type of the boiler i.e. utility or industrial boiler, capacity, operational load range, steam data, emission limits and other requirements set by legislation. Investment factors include plant availability, fuel flexibility requirements, the investment costs and operation costs. Consequently, economical boiler designs have been developed to fire easy-to-burn biomass, while more robust solutions are implemented as the biomass quality degrades and becomes more challenging to burn reliably.

Key design features of the ABC technology are summarized in Figure 3. This concept has been utilized in the operating references described in the next chapter.

**Figure 3. Key Features of the ABC Technology.**

**RECENT CFB REFERENCES FOR BIOMASS COMBUSTION**

Starting in the 1970’s, Amec Foster Wheeler’s biomass references include approx. 210 CFB or BFB boilers. The most recent, operating biomass CFB boilers are as follows:

- **Kraftringen Energi AB, Örtofta, Lund, Sweden**
  - 110 MW<sub>th</sub>, 35 MW<sub>e</sub>, main steam 154 t/h, 540 °C, 113 bar, a
  - Design fuels wood biomass, demolition wood, peat

- **GDF SUEZ, Polaniec, Poland**
  - 447 MW<sub>th</sub>, main/reheat steam 569/486 t/h, 535/535 °C, 127/20 bar, a
  - Design fuels wood chips, agro biomass

- **ZE PAK, S.A., Konin, Poland**
  - 154 MW<sub>th</sub>, 215 t/h, main steam 540 °C, 97 bar, a
  - Design fuels wood, crop waste
Additionally, a 253-MW<sub>th</sub> CFB boiler is being supplied for GS E&C in Danjing, South Korea, and it will be commissioned in 2015. This boiler is designed to burn palm kernel shell (PKS) as the primary fuel and bituminous coal as a secondary fuel. It will produce 390 t/h of steam at 540 °C, 130 bar, a.

**The Latest — Kraftringen’s 110 MW<sub>th</sub> Biofuel Fired CHP Plant**

Kraftringen, a Swedish municipal electricity, district heating (DH), district cooling and gas company, decided to invest in a new biofuel CHP project in order to have a totally fossil free DH production by the year 2020. The new CHP plant went into commercial operation in March 2014, replacing old fossil-fired capacity. Besides virgin biomass, it was designed to burn up to 50 % demolition wood, which is known to be a challenging fuel due to high levels of impurities and a highly inhomogeneous nature. CFB combustion was selected for the project due to its fuel flexibility, track record with demolition wood and high efficiency that can be achieved e.g. by using fluidized bed heat exchangers for high-temperature steam generation. Amec Foster Wheeler (Finland) was selected as the supplier of the boiler island and the contract was awarded in February 2012. The boiler implies the salient features of the ABC technology such as step grid and an INTREX<sup>TM</sup> final superheater.

Amec Foster Wheeler’s scope of work included a CFB boiler island including designing and supplying the steam generator, auxiliary equipment and carrying out erection and commissioning of the boiler island. In November 2013 the boiler was taken into operation, producing electricity and heat and entered commercial operation in March 2014. Figure 4 shows the appearance of the new plant.
Figure 4. Kraftringen’s New 110 MWth Biomass CFB in Örtofta.

Figure 5 shows a schematic of the Lund CFB boiler. It is a state-of-the-art biomass firing unit designed for firing forest wood chips, demolition wood and peat as the main fuels; it is also capable of firing saw dust, bark, salix (willow) and stump chips. The boiler design consists of the furnace (8.8 m x 5.5 m x 28 m) and two water-cooled high-efficiency solids separators. The feedwater temperature is 210 °C, main steam flow 42.9 kg/s, pressure 113 bar, a and temperature 540 °C. Due to the demolition wood, the temperature shall be maintained above 850 °C for a minimum of 2 s in the furnace. SH I - II tube bundles are of hanging type, located in the essentially horizontal cross-over duct leading from solids separators to the back pass, while SH III - IV are located in the INTREX chambers. Material of the hottest superheaters is X8CrNi19-11 (TP347HFG). Economizer and tubular air preheater are located in the back pass.
The planned annual production is 550 GWh of heat to the surrounding municipalities and 220 GWh of electricity. The boiler efficiency is 91.4 %, and with a flue gas condenser the CHP efficiency is nearly 100 %. Of the fuel consumption of 310000 tons, 55 % consists of forestry residues, 30 % of recycled wood and 15 % of peat [3]. The fuel feeding systems consists of two feeding lines, each including a day silo with reclaimer, chain conveyors, robbing screws (with speed control) and feeding chutes to solids return flow. Both feeding lines can feed all of the four feeding points. Co-firing of peat reduces corrosion risks related to the biomass and recycled wood firing, which is carried out without specific additives.

The cumulative availability for Amec Foster Wheeler boiler scope from the start of commercial operation to early March, 2015 has been over 99 %. The average fuel mix has been as follows: forestry residues 52 %, recycled wood 22 %, bark 10 %, peat 9 % and saw dust 7 %.

**The Largest — Polaniec 447-MW<sub>b</sub> CFB in Poland**

Using agricultural biomass in addition to virgin biomass at large scale biomass firing power plants has raised some interest. In April 2010, GDF Suez Energia Polska S.A. awarded Amec Foster Wheeler with a contract for a CFB biomass firing boiler for the Polaniec Power plant. The combustion technology design is based on the Advanced Bio CFB (ABC) technology (Fig. 2), and a reheat steam cycle is used to further improve the steam cycle efficiency. The Polaniec boiler is a 205 MW<sub>e, gross</sub>/447 MW<sub>b</sub>, 158/135 kg/s, 535/535 ºC and 127/20 bar, a utility boiler that operates on a broad range of biomass fuels, achieves the highest efficiency and availability currently possible, and operates in accordance with Polish regulations. The Polish regulations set the proportion of agro biomass used for firing to a minimum of 20 % for plants in operation by the end of 2012. Agro biomass fuels have high alkali and chlorine contents, requiring appropriate design and operation to avoid agglomeration, fouling and
corrosion issues in the boiler. The plant reached its commercial operation date a full six weeks ahead of the contractual schedule on Nov 15, 2012, and has been in commercial operation since then.

![Figure 6. Polaniec CFB Boiler based on the Advanced Bio CFB Technology.](image)

In order to control the boiler’s emissions, the boiler design utilizes the well-known benefits of CFB combustion, such as the low and uniform temperature profile in the furnace and the staged combustion. In addition to these combustion process related measures, the boiler design includes an ammonia injection system and catalyst (SNCR+SCR) to control the nitrogen oxide emission, as well as an electrostatic precipitator (ESP) to control particulate emission. With the inclusion of these measures in its design, the Polaniec CFB boiler can meet all of the relevant emission limits (150 mg/m³ n NOₓ, 150 mg/m³ n SO₂, 50 mg/m³ n CO and 20 mg/m³ n particulates). In fact, it was observed that the SCR catalyst is not necessary for achieving the emission target. Limestone injection is generally not needed for sulfur capture. A description of the plant as well as initial operating experiences has been given in [4].

The Polaniec boiler is also provided with additive feeding systems to control fouling and corrosion, which could happen especially when using the most challenging agro biomass considered in the design. Both kaolin and elemental sulfur can be injected into furnace, if needed.

**LARGE SCALE, HIGH-EFFICIENCY CFB FOR BIOMASS COMBUSTION**

The previously described CFB plants running on 100 % biomass fuels each have a steam temperature of about 540 °C and pressure up to 130 bar. Potential customers of utility size biomass boilers are aiming at maximum steam cycle efficiency, therefore live steam parameters in the order of 170 bar, 570 °C are being targeted with clean biomass. Biomass in this case may be virgin wood pellets or chips, the origin varying in a wide range as described earlier in this paper.

**New Design — 455-MWth CFB with 568/568 °C and 169/36 bar, a Steam**

A conceptual design has been developed and offered for a 455-MWth, 157/143 kg/s, 568/568 °C and 169/36 bar, a utility boiler that operates on virgin wood chips and virgin wood pellets of varying origin. The range in fuel moisture and heat value is wide. Also co-firing of saw dust and high alkali agro biomass fuels are taken into account in the design. Besides high steam parameters, sliding pressure
operation enables high efficiency also in load cycling operation. Advanced Bio CFB design features are implemented also in this boiler concept.

Figure 7 illustrates the CFB boiler, which has approx. 25 m x 8 m x 40 m furnace, three steam-cooled high-efficiency solids separators and final SH/RH heat surfaces located in INTREX units. Other SH/RH surfaces are placed at the top of the furnace and as tube bundles in the heat recovery section. The economizer is located in the third pass, which also houses a slip catalyst to keep the NH₃ emission low while utilizing SNCR for DeNOₓ.

![Figure 7. 455-MWth Biomass CFB with 568 °C / 169 bar steam.](image)

**Further Scale-Up toward 600 — 800 MWₑ**

The increase of biomass utilization in energy production has created a demand for extremely large biomass firing power plants. Current prospects stretch to 400 MWₑ biomass-fired units. Based on continuous development work and extensive reference data, the Advanced Bio CFB boiler concept has been developed to this scale and beyond. The highly efficient design offered for 100 % biomass is available up to 600 MWₑ sized for clean woody biomass, and up to 400 MWₑ when including 20 - 30 % agricultural residues in the biomass.
The boiler scale is well within the existing Amec Foster Wheeler CFB experience range. The design is based on a CFB design for clean biomass fuels utilizing the fully integrated steam cooled solids separator and return leg, INTREX superheater and reheater, and step grid designs. The conceptual design of this high efficient 400 - 600 MW_e scale Advanced Bio CFB is ready for the market.

Subcritical ABC CFB boiler designs are available up to 600 MW_e with steam temperatures of over 560 °C. Supercritical CFB is offered up to 800 MW_e for bituminous coal with a possibility to co-fire 20 % biomass (on energy basis), meeting the highest requirements for plant efficiency and environmental performance.

**SUMMARY**

Biomass plays an important role in reducing the environmental effects of energy production both in pure biomass plants and in coal and biomass co-combustion. Circulating Fluidized Bed boilers (CFB) are ideal for efficient power generation, capable of firing a broad variety of solid biomass fuels for small industrial plants as well as large utility power plants.

Challenges introduced by conventional woody biomass are well understood and reliably predicted by in-house models. Amec Foster Wheeler has experience in over 200 CFB and BFB units sold firing solid biomass fuels. However, investors and plant operators have widened their fuel portfolios to include low cost biomass, such as encroaching wood species and agro biomass pellets. The broader variety of biomass fuels currently available in market demand more sophisticated fuel evaluations due to the complex chemistry of fuel-ash transformation during combustion. Also, firing different biomass fuels in a mixture may involve beneficial or detrimental interactions between harmful elements, bed material and possible additives. Therefore, models and prediction tools capable to assess ash-related challenges in CFB combustion, such as agglomeration, fouling and corrosion, have been developed at Amec Foster Wheeler, and are continuously validated for a broad range of biomass fuels and mixtures, including co-firing with fossil fuels.

The Advanced Bio CFB technology represents the state-of-the-art for large scale solid biomass fuel firing. The technology provides solutions for effective CO_2 reduction in large scale power generation with a broad range of solid biomass fuels. The excellent operating experiences from the GDF Suez Energia's CFB boiler island at the Polaniec Power Station in Poland confirms the competitive edge of CFB technology to fire 100 % biomass to even a larger scale, and the same technology has been adopted in several other projects as well.

The development of the ABC technology has continued toward higher steam parameters to further improve the efficiency in large scale power generation based on a broadening variety of solid biomass fuels.
REFERENCES


