**Bubbling fluidized beds: When to use this technology**

J.A. Pascual Peña
Foster Wheeler Global Power Group, Madrid, Spain

*Keywords:* BFB, CFB, grate, Foster Wheeler, fouling, slagging, agglomeration, corrosion

**Abstract**—Over the years, fluidized bed technology has been taking over other combustion technologies, being particularly effective when burning reactive fuels with low heating values and high moisture and ash contents, usually referred to as “difficult”. The development of fluidized bed technology over the years has allowed to achieve higher efficiency levels while reducing emissions and increasing fuel flexibility, which are key under current global market and environmental conditions. Foster Wheeler has pushed the technology, redefining the fluidized bed state of the art, building large supercritical power plants using circulating fluidized bed boilers (CFB) and initiating break-through trends such as oxy-combustion. Along this process several improvements have been also introduced in smaller sized, 100% biomass firing units.

This paper sets out the available technologies for biomass combustion, focusing on bubbling fluidized bed (BFB) as a good alternative to grate boilers, and provides themain criteria to select the most suitable technology (CFB, BFB, grate) for each specific application.

The different advantages and disadvantages of each technology will be presented in this paper, together with their applicability, current global market situation and trends, and finally ongoing projects and opportunities for BFB technology development in the South African power market.

BFB technology offers good performance in terms of efficiency, fuel flexibility, emissions, and especially in regard to the installation and maintenance costs, being in some cases a better solution than that offered by other technologies.

**INTRODUCTION**

Nowadays, the market offers several solutions and incentives to use different kinds of biomass fuels to produce energy. Technological developments over time have increased the ability to burn different kinds of fuels (by means of specific boiler concepts) and the flexibility to burn different fuels in a boiler. Even though, there is not still any definitive solution that permits to valorise any kind of biomass. Complexity is increased when these biomass fuels are mixed and burned together with other fuels such as coal, sludge or any other available process residual waste.

The fuel analysis, the fuel type and available quantity, the required steam conditions or process efficiency and required emissions limits, among others, are some of the factors that determine the steam generator design. This wide range of factors sometimes makes it difficult to precisely select the most convenient technology for each case.

Meanwhile an application that allows us to burn an extensive range of fuels is developed, it is critical to know what are the available options to burn biomass and what are the factors to take into account when selecting a combustion technology.
**AVAILABLE TECHNOLOGIES**

**Bubbling fluidized-bed (BFB) technology**

Bubbling fluidized bed boilers (BFB) are often preferred in small-scale applications, with fuels having low heat value and high moisture content. Foster Wheeler (FW) has supplied more than 130 BFB boilers, mainly for industrial use. Boiler efficiency figures (over LHV) are normally over 90% (Figure 1).

The core of the BFB boiler is the combustion chamber or furnace. It features water-cooled walls and bottom. The bottom has a full refractory lining and the lower portion of the water wall is also refractory lined. The bed is fluidised by means of an arrangement of nozzles at the bottom of the furnace which create turbulence that enhances the mixing of the fuel, increasing the boiler’s efficiency by converting unburned carbons remaining to usable energy. The bed is usually formed by sand and with a small amount of fuel. Solids fluidization occurs when a gaseous stream (primary air) passes through a bed of solid particles at a high enough velocity (above the minimum fluidization velocity) to overcome the particles gravity force. Limestone might be added to the bed to eliminate sulphur and/or chlorine.

Primary air is injected through the bottom grid to fluidize the bed. Primary air is about thirty percent of the combustion air, being the remaining air injected through the secondary and tertiary air ports above the furnace, enhancing staged combustion.

BFB operation range is between the minimum fluidisation velocity and the entrainment velocity on which the bed particles would be dragged by the passing gas, being usually 1.2 m/s (4 ft/s) at full load. Combustion temperature is typically between 800 and 950°C (1472–1742°F), being 850°C (1562°F) a usual bed temperature.

The boiler overall constructive simplicity, together with the turbulent, low temperature bed and the ability to regulate the fluidisation velocity and secondary and tertiary air quantities, is what drives the BFB to excel other non-fluidised technologies in terms of fuel flexibility, efficiency, emissions and lower capital and maintenance costs. Only another fluidised bed technology, Circulating fluidised bed (CFB) has better performance.

![Figure 1. BFB steam generator](image-url)
**Circulating fluidized-bed (CFB) technology**

CFB boilers are normally used in larger applications, being similar in basic concept to the BFB. CFB has enhanced flexibility over BFBs for firing multi-fuels with high moisture content and significantly higher efficiency up to 95% (Figure 2).

FW is the global leader in CFB technology having references for the largest CFB burning 100% biomass (190 MW, Poland), the largest CFB supercritical units (4×550 MW, South Korea) and the world’s first oxy-combustion CFB boiler (30 MW, Spain).

CFB configuration includes solid separators that separate the entrained particles from the flue gas stream and recycles them to the lower furnace. The collected particles are returned to the furnace via the loop seal. The addition of the solid separators as well as other measures as the INTREX™ superheater allows CFB technology to reach the higher values regarding efficiency and availability and provides excellent fuel flexibility.

The entrainment velocity is the limit point that defines the transition from a BFB to a CFB. The CFB operation range is fixed over that entrainment velocity. Beyond this velocity the bed material becomes entrained and the solids are distributed throughout the furnace with a gradually decreasing density from the bottom to the top of the furnace. Fluidizing velocity is higher than in a BFB and can be between 4.5–6.7 m/s (15–22 ft/s).

![Figure 2. Typical CFB unit cross section](image-url)
Grate technology

Grate boilers, as well as BFB boilers, are used in units below 100 MWel and normally for industrial uses. FW has more than 200 references worldwide burning very different fuels such as chicken litter, bagasse, bark and forestry residues (Figure 3).

Grate technology can burn a range of fuels wider than a BFB, but worse emissions and efficiency as BFB. Grate boiler provides very good performance burning low moisture and high alkali content fuels. Grate can burn difficult fuels as straw, chicken litter, high alkaline agro crops that BFB/CFB can’t burn due to high agglomeration tendency.

Inside of allowed BFB fuels range and inside of CFB fuels range, fluidized bed technologies have more fuel flexibility than grate technology.

There are different grate technologies available with different characteristics, mainly depending on the fuel to be burned, such as: travelling, rotary, reciprocating or vibrating grates amongst others. All grates are mechanically driven and rely mostly on the primary air for cooling, although some grates are additionally water cooled. All grates work on the principle of translating the fuel being burned from one side to the other of the boiler, in order to attain the sufficient residence time to burn as much fuel as possible.

Unlike BFB steady combustion, the nature of fuel distribution over the grate and the form it travels from one side to the other of the furnace creates uneven distribution and consequential uneven burning of the fuel. This uneven combustion promotes higher emissions and increases the unburned content in the ashes and decreases the boiler efficiency. In order to assure as best as possible an even fuel distribution, both fuel feeding and fuel size must be continuously and carefully controlled. Homogeneous fuel size is mandatory. Typical furnace gas velocities are 2.4–3.04 m/s (8–10 ft/sec).
TECHNOLOGY SELECTION

Features to consider

There are *four basic considerations* to be evaluated when selecting the most reliable technology that can be chosen and developed for a biomass unit. The said considerations are summarized in the diagram below:

![Diagram of technology selection]

**Capital cost of the steam generator.** Plant capital cost is a key issue at the time of evaluating a commercial plant feasibility and obtaining financing, which translates into the plant being profitable, independently of the chosen technology.

Failure to fully understand the implications of the different available technologies by the plant developer/promoter, might drive it to achieve incorrect evaluations of the plant capital cost, efficiency, auxiliary power consumption, availability and maintenance costs, amongst others. Consequences of an improperly evaluated project, choosing the inadequate technology, might range from the project not being feasible or financed, to having an unsustainable project built and not being profitable or not being able to maintain profitability if some market conditions change.

A usual example of misunderstanding the technology is the market general idea that a grate boiler will have a lower cost than a BFB boiler. While grate boilers are often less expensive to buy than a BFB, the plant owner must look at total life cycle cost for the plant to get the true economic value of BFB boilers.

Having said this, life cycle cost difference between a Grate unit and a BFB heavily relies on the design criteria used by the boiler manufacturer. Design criteria are heavily influenced by the manufacturer’s experience and its own know-how.

When designing a boiler, there are four phenomena that must be carefully taken into account: slagging, fouling, corrosion and bed agglomeration (in the case of fluidised bed boilers) or sintering (in grate boilers). These phenomena are directly related to the required steam temperature and the fuel composition, which will be discussed later.

There are several approaches used by different manufacturers to either try to avoid the occurrence and/or to mitigate the consequences of these phenomena. Some of the different solutions are: control of furnace temperatures by means of increasing evaporative surface, larger superheaters, installation of advanced in-furnace cleaning devices, increased tube
thickness or the use of novel corrosion-resistant materials, all of them with an important impact on the capital cost of the unit, when compared to the same unit without this mitigation or correction.

If the developer fails to recognize the potential problems associated with biomass fuels, and misses to evaluate and tabulates the different designs and technologies adequately, the developer might be lured to wrongly select the option with the lower capital cost as the most competitive. Inadequate control of these phenomena will translate in lower availability and efficiency of the plant together with higher maintenance costs. That means the power plant is less profitable, if profitable at all.

In the global market developers live in today, not all boiler manufacturers have the knowledge to carry out these solutions or might choose not to introduce these solutions in order to provide the lowest possible price. If these phenomena are not timely detected in the early engineering phase of the plant and correctly managed before purchasing/designing the equipment, the consequences might be important, especially if detected once the plant is in operation.

**Fuel.** The availability of the fuel, especially biomass, is a common project driver. This means that the developer must select the correct technology to cope with the difficulties of the currently available fuel (which might vary over time) instead of selecting the most convenient fuel for the most convenient technology.

Fouling, slagging, bed agglomeration and high temperature corrosion are the main phenomena that affect to a right boiler operation and are directly related to the fuel to be burnt and the required steam conditions.

Key issues to be watched in a fuel are the following:

- **Alkali content:** A distinctive feature of biomass is their tendency to have high organic alkali contents. Above all, the potassium content of the agricultural wastes is quite high. The organic alkalis in the fuel vaporize at high temperatures and can recombine with other ash and fuel elements (especially silica and phosphorus) to produce low melting compound that can cause sintering and agglomeration on the furnace and backpass surfaces. High potassium content is especially associated with backpass fouling, while sodium is more often associated with in-furnace sinter formation. Typically, potassium content is higher than sodium in biomass fuels. Sintering resulting from fuel-bound alkali scan be at least partially mitigated by the addition of compounds high in alumina and to a lesser extent by the addition of compounds with high calcium and magnesium content.

- **Chlorine content:** Chlorine in biomass, in combination with alkalis, is an important concern because of the tendency to sinter and/or deposit formation. Additionally, chlorine produces deposits that harden once the boiler gets dirty by alkalis. Deposits in the back pass trend to concentrate chlorine on the metal surface, causing corrosion on the tubes. The corrosion combined with erosion can rapidly result in tube leakages. There are several studies looking for materials that are corrosion resistant, however, as of today there is not a definitive solution for grates boilers or BFBs. One partial solution is to add sulphur to the bed (or the gas stream) to avoid chlorine deposit on the tubes. On the other hand, INTREX™ superheater has provided very good results in CFB boilers, as a mean of controlling bed temperature.

- **Moisture:** Moisture in fuel could be a limiting characteristic. Typical wood-origin biomass common moisture level is over 25-30% wt, while biomass from other sources (agricultural waste, straw, bagasse) have lower moisture levels. The water in the biomass is instantaneously evaporated in the lower combustion chamber and the volatilisation proceeds very fast. As will be explained later, moisture, in addition to other fuel characteristics, could trigger the election of one technology over another.

When selecting a combustion technology, **fuel flexibility** is one of the major points to be considered. Higher fuel flexibility will allow us to take advantage of many low-cost, opportunity fuels that other technologies cannot easily accommodate or cannot accommodate at all.
Fluidised-bed technology offers a good solution regarding flexibility. Fresh fuel and combustible matter make up less than 3% by weight of the hot solids present in the bed. This large source of thermal energy provides an extremely steady combustion environment that is relatively insensitive to variations in fuel quality. The fuel particles fed to the furnace are quickly dispersed into the large mass of bed solids, which rapidly heat the fuel particles above their ignition temperature without any significant drop in the temperature of the bed solids. This feature makes it possible to burn almost any fuel without the use of auxiliary fuels and allows for several fuels to be burnt without major changes in the hardware. However, as stated previously, fluidized bed technology cannot burn high alkalis content because of bed agglomeration issues. A case by case fuel evaluation is needed.

**Emissions.** One of the key issues that have driven the continuous growth of installed fluidized bed technology units is their improved responsiveness to required emission levels. SO\textsubscript{x}, NO\textsubscript{x}, particles and CO emissions will be reviewed.

**NO\textsubscript{x} emissions:** There are mainly three factors participating in the NO\textsubscript{x} production: combustion temperatures, fuel composition (volatile content and moisture), and combustion air staging. The adequate control of these factors will allow us to limit the NO\textsubscript{x} emissions to a minimum.

Because of the high volatile content of biomass, the ignition temperature is lower than in other fuels, and the boiler can be designed for lower temperatures in the lower furnace. At the same time, this high volatile content and lower temperature increase the quantity of unburned fuel in the upper furnace. Technologies such as BFB and even CFB take advantage of these phenomena and stage the combustion air to control NO\textsubscript{x} formation. However, for grate technology, air staging is limited to keep the unit cost low.

Finally, well balanced combustion air staging(by means of primary, secondary and tertiary air injection) as well as adequate flue gas recirculation, plays a critical role in NO\textsubscript{x} control.

It is important to highlight that NO\textsubscript{x} emissions are inherently higher in a grate unit when compared to an equivalent BFB due to the fact that the combustion temperatures are significantly higher in the grate unit, increasing the formation of thermal NO\textsubscript{x}.

**SO\textsubscript{x} emissions:** SO\textsubscript{x} emissions are not typically a big concern in biomass fuels because of the low contents of sulphur in them. In case of biofuels with high sulphur content, limestone can be used as a sorbent to capture the sulphur in CFB boilers. Fuel ash can also act as sorbent, especially in biomass, due to the calcium that is normally contained in the fuel. Grate units have limited capacity to capture SO\textsubscript{x} in the furnace, forcing the use of additional measures, such as scrubbers, under strict emissions requirements.

**CO emissions:** Contrary to NO\textsubscript{x}, higher furnace temperatures reduce CO emissions. Therefore, the CO emission level must be balanced against the NO\textsubscript{x} emissions. Although grate units have higher furnace temperatures, the steadiness of the combustion in a BFB bed allows the BFB to achieve lower CO emissions.

**Particles (PM):** PM control is mainly achieved in the bagfilter/electrostatic precipitator. These technologies are quite advanced and typically there are no big challenges to reach the highest environmental limits. Bagfilter use is normally limited by the gas temperature. High temperatures can damage the bags. Also when a bagfilter is installed after a grate boiler anti-spark equipment is needed.

**Steam conditions.** This is a critical aspect regarding the design of a steam generator. As a general rule, the higher the steam temperature is, the higher the fouling and slagging of the unit together with the corrosion of the superheaters will be. All these phenomena are highly dependent on the furnace temperature and therefore on the steam conditions.

Selection of the most adequate furnace temperature for a given application is probably the most important challenge a boiler manufacturer must face. The lower the furnace temperature is, the less exposure to fouling, slagging and corrosion will be, while increasing availability of the unit, but also increasing the capital cost of the unit.

There are several ways to control the temperature in the furnace: furnace area (usually in terms of furnace height), combustion air distribution, flue gas recirculation, INTREX (in CFBs), etc. On the other hand there are mechanisms to remedy the occurrence of fouling, as for instance, the installation of advanced in furnace clean devices.
THE CHOICE

As explained above, the proper technology must be selected based on the required cost, available fuel, required steam conditions (cycle/boiler efficiency) and emissions to be reached.

Chronologically and in terms of evolution of the technology, biomass boilers’ development started with grate boilers, continuing with BFB technology and finalizing with the current most advanced technology steam generator, the CFB. In this regard, grate units are being offered by a large number of vendors, while BFB is limited to a selected group of technology providers and the CFBs are only offered by even fewer vendors. Table 1 provides a first approach of the application of each technology.

Table 1. Technology selection

<table>
<thead>
<tr>
<th>ALKALIS CONTENT</th>
<th>PRICE &amp; FLEXIBILITY</th>
<th>STEAM TEMPERATURE/ EFFICIENCY/ AVAILABILITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Lower, Medium, Higher</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>Grate, Grate, N/A</td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>BFB, BFB, CFB</td>
<td></td>
</tr>
</tbody>
</table>

The matrix can be read as follows:

Grate boilers should be used when the alkalis content of fuel is extreme, since high alkalis content and/or high bed temperature could produce bed agglomeration. Otherwise, the use of fluidised bed technology is recommended, since fluidised bed technology has lower emissions and higher combustion efficiency.

Grate units will achieve lower efficiencies, higher emissions and will result in higher maintenance costs. Maintenance costs are usually overlooked by developers and it is an important issue to be taken into consideration, especially for grate units, due to the maintenance for grate (mobile elements) and eventually for the scrubber, if required.

Fluidized bed technology inherently allows lower NOx (low temperatures) and SOx (sorbent in bed) emissions. In a grate unit this would need to introduce auxiliary equipment such a selective/non-selective NOx reduction (SCR/SNCR) or a flue gas scrubber. Both equipment will deeply impact environmental permits and will increase the complexity of the plant operation and maintenance.

The reasoning in this paper might be extended and applied to retrofits. Due to the advantages of a BFB boiler against a grate boiler and the similar geometries on their pressure parts and non-pressure parts, some owners decide to upgrade their existing grate boilers to BFB. This conversion is usually driven when the owner is seeking for higher fuel flexibility or better emissions.

A couple of examples for the use of the decision matrix (Table 1) are detailed below.

**Project 1.** A company is considering to install a biomass boiler. The boiler is expected to burn chicken litter, a fuel with a high alkalis (~3% d.s.) and chlorine content (1.5% d.s.). Efficiency requirement is not too high, but availability is a key issue. Fuel availability is the driver. No other fuels are expected to be burnt in the boiler. Cost investment should be limited. Emissions must be controlled.

For project 1, a grate boiler should be recommended. High content in alkalis avoid the use of fluidized bed technology. Availability would be considerably higher than that obtained for a BFB/CFB which is subject to possible bed agglomeration. High content in alkalis and chlorine will require the use of measures as advanced cleaning system, high quality materials in superheaters etc. Emissions could be a limiting factor.Fuel must be carefully studied in the case a SNCR system is required.

**Project 2.** A paper mill is evaluating the possibility of extending their cogeneration plant by means of the installation of a new boiler. This boiler is expected to burn eucalyptus bark, process sludge and pine chips. The project budget is limited. High availability figures are required to secure project profit. EU emissions limitations are applicable.
For project 2, a BFB should be used. BFB can provide enough flexibility to burn bark, chips and sludge. BFB availability will be typically over 90%. Investment cost will be lower than in a CFB. A BFB burning biomass can regularly reach the tighter emissions levels.

**Project 3.** A utility company is planning to install a power plant. The main fuel to be burnt will be discard coal. The ash content in coal is high. The HHV is quite low. In addition to that it is expected to have an amount of biomass coming from a near forest. Flexibility is mandatory. High efficiency is highly recommended. To reach low emission levels is a must.

For project 3, the use of a CFB should be advised. CFB provides the highest degree of flexibility. CFB allows burning coal together with biomass. Coals with limited HHV are burnt quite easily in a CFB. The ash in coal will be used as sorbent and could reduce the amount of limestone to add in the bed. CFB is the solution with the highest efficiency even with fuels with low heat value. Foster Wheeler has proven technology in subcritical and supercritical units. CFB will assure the best emission values achievable in the market.

**Project 4.** A paper mill has a grate boiler which load is given thanks to burn 50% biomass and 50% fuel/natural gas. The owner wish to increase the percentage of biomass to be burnt up to 100% without affecting emissions, efficiency, etc.

BFB is the best solution for this case. Retrofitting a grate boiler to change it into a BFB boiler will provide a better fuel flexibility, emissions, availability, efficiency, etc.

**CONCLUSIONS**

The market provides several possibilities to burn biomass. This paper evaluates these possibilities and suggests when to use each boiler technology.

Foster Wheeler is the worldwide boiler manufacturer having the largest biomass boilers portfolio. Foster Wheeler biomass boiler range goes from grate steam generators passing through BFB boilers to CFB supercritical units. This wide variety of combustion technologies allows Foster Wheeler to select the right technology for each project regardless of other commercial interests.

In this paper several design conditions have been evaluated within the steam generator selection. Four main considerations have been selected as most important factors in the boiler selection technology: capital cost, fuel composition, steam conditions and emissions level.

Our evaluation presents grate boiler as the best solution when the fuel contains high alkalis percentages or very low moisture. Otherwise, fluidized bed technology should be chosen. Within the fluidized bed technology, CFB is the best option regarding emissions and efficiency, although CFB also has the higher capital cost. For all other applications, BFB should be used as explained above.

Being capital cost defined as a critical issue in a project, the possibility of using a BFB boiler should be studied. This technology has higher combustion efficiency and lower emissions than a grate. BFB technology has been successfully used burning an important variety of fuels as bark, chips or sludge. Before selecting BFB technology, fouling, slagging, bed agglomeration and high temperature corrosion phenomena must be carefully studied.

**REFERENCES**
