# Combustion of municipal solid waste in fluidized bed or on grate – A comparison

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## ARTICLE INFO

## ABSTRACT

Grate firing is the most common technology used for combustion of municipal solid waste. The more recently developed fluidized bed (FB) combustion is rarely employed for this purpose. The present work compares the technical properties of the two devices to find out why FB has not been more used, considering the recent importance of waste-to-energy. Several drawbacks of FB, the need for fuel preparation and bed material consumption, play a role, but these features also have advantages: combustion is improved by the sorted fuel and less ashes. Silica sand as a bed material has the positive property of being an alkali scavenger. If replaced by an oxygen carrier (e.g. ilmenite) the scavenging effect increases, and, in addition, oxygen carriers even out the non-combusted gaseous fields in the furnace, which improves combustion and allows higher steam data at a given corrosion level. There are other advantages of FB, such as end-superheaters in the circulation loop, heated by the bed material. However, also the environmental performance and energy efficiency of grate firing has been improved, and several advanced solutions have been proposed. In conclusion, it is not clear which of the devices that is the better one. An economic evaluation is made, based on available literature information, but still there is no clear winner.

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## Contents

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**Nomenclature**

| | |
|---|---|
| a | ash component, kg/kg fuel |
| ad | as delivered; adiabatic |
| b | combustible fuel component, kg/kg fuel; bed |
| c | carbon content, kg/kg combustibles |
| $c_p$ | mean specific heat (pma – air, pmg – gas, pi – component i, ad-o – adiabatic/base, exit-out – exit/out, out-o – out/base), kJ/kg,K |
| CFB | Circulating Fluidized Bed |
| daf | dry and ash-free |
| FB | Fluidized Bed |
| G | waste input, % of maximum value, max–maximum value |
| GF | grate fired |
| $g_{out}$ | specific amount of wet flue gas, kg/kg combustibles |
| $H_{eff}$ | effective heating value, kJ/kg combustibles |
| $H_w$ | heat of evaporation of water, kJ/kg water |
| HHV | Higher Heating Value, kJ/kg combustibles |

| | |
|---|---|
| h | hydrogen content, kg/kg combustibles |
| LHV | Lower Heating Value, kJ/kg combustibles |
| $\ell$ | stoichiometric oxygen demand, kg/kg combustibles |
| M | molecular mass (C – carbon, H2O – water, H – hydrogen), kg/kmol |
| o | oxygen content, kg/kg combustibles |
| P | fuel power, % of maximum |
| Q | heat absorption (s – furnace, e – external, loop seal). kJ/kg combustibles |
| T | temperature (a – air, ad – adiabatic, b – bed, exit – exit of furnace, out – at stack, in – inlet to furnace, o--base), K |
| w | moisture content, kg/kg fuel |
| WtE | Waste to Energy |
| $x_i$ | concentration of species i, - |
| η | efficiency, - |
| φ | ratio, - |

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## 1. Introduction

Management of solid waste has gone through various phases of development. First, simple deposition in landfills was the common way to get rid of the waste. Then incineration was introduced to reduce the volume and to save space in the landfills. In the 1970s, concern about the environmental effects of incineration resulted in improved cleaning systems, and, finally, a few decades ago recovery of energy (Waste-to-Energy, WtE) and other valuable components of the waste became of interest. Three types of combustion device serve for conversion of municipal solid waste (MSW): grate-firing (GF), fluidized bed (FB), and rotary furnace. The latter mostly takes care of hazardous and other special wastes. The first two types have similar tasks and are therefore interesting to compare.

The development steps related to environment and energy recovery resulted in improvements of the traditional GF systems, including their heat transfer and cleaning sections. During the latter phases of this development, FB boilers, introduced to burn coal and later biomass, were also employed for MSW. At present (2020) FB is used for commercial operation with MSW, but GF, which has a longer history of development, is more common than FB, as seen from the statistics presented from various parts of the world by, for instance (Makarichi et al. (2018)), showing that FB is used in China (30%), in the US and Canada (20%), while the share in Europe is only 5%. As usual, the difference between the European countries is great, and in Austria about 40% of the waste is incinerated in FB (Bösenhofer et al., 2015).

FB has the reputation of being a modern and environmentally favourable combustion device, while GF is supposed to be inefficient and old-fashioned. Then, one can ask, why FB has not taken a greater share? Perhaps, the advantages of FB were not as significant as anticipated, and further development of GF took place simultaneously, allowing it to maintain its position. Tradition certainly explains the abundance of GF MSW plants, but the question is, are there more reasons? The present survey tries to answer this question by comparing GF and FB combustion for MSW under the

conditions of the present strict emission regulations and the growing efforts to recover energy and materials. First, the essential fuel properties are shortly defined, followed by a description of the two classes of conversion device: GF, represented by the sloping grate, and FB by its bubbling (BFB) and circulating (CFB) forms. A few remarks on costs are also made.

### 1.1. The composition of MSW

The composition of MSW depends on its origin and reflects the material development of a society, as shown in a survey by Hoornweg and Bhada-Tata (2012) on the composition of waste in various parts of the world. Also the properties of the components vary, as seen by the list of Table 1, particularly the heating value. In Europe, measured (lower) heating values (LHV) are 10 MJ/kg on the average (Reimann, 2009). In other parts of the world, such as in South-East Asia, the content of wet organic material leads to lower values. In China the heating value varies over the year from above 6 during winter to 4 MJ/kg during summer (Huang et al., 2013). This is low for combustion on a grate. For instance, Lentjes (no date) declare that their grate operates with air-cooling between 10 and 5.5 MJ/kg and similar data are presented by other manufacturers. The range is extended on the lower side by air preheat (300 °C) (Huang et al., 2013), and in FB co-combustion with a support fuel is suitable. In case of a low heating value, Huang et al. argue that CFB is the best solution. Besides, in China CFB is cheaper with three local designs to choose from. On the other hand, companies with interest in China develop their own GF boilers, which they successfully market, aiming at dominance. They (as well as those related to FB) solve to some extent the moisture problem by keeping the unsorted wet waste in the fuel bunker for a few days for some water to leave the fuel, thereby increasing the heating value.

Table 1 is a special case from one investigation, but it permits to make a few conclusions on the composition of the waste. Little paper and plastics but more food and yard waste reduce the heating value. With separation at the source or at the plant, glass and

**Table 1**
Properties of various MSW components (Example of European data, Leckner (2015, Table 2)).

| Component | Moisture (% ad*) | Ash (% ad*) | Volatiles (%, daf*) | LHV (MJ/kg) |
|---|---|---|---|---|
| Food | 64 | 5 | 78 | 3.0 |
| Yard waste | 38 | 5 | 94 | 6.7 |
| Return paper | 24 | 6 | 93 | 15.0 |
| Packages paper | 24 | 5 | 93 | 10.6 |
| Plastics | 14 | 10 | 88 | 31.5 |
| Glass | 3 | 97 | 0 | 0 |
| Metal | 7 | 93 | 0 | 0 |
| Other combustibles | 20 | 10 | 97 | 16.3 |
| Other non-combustibles | – | 100 | 0 | 0 |
| Rough average | 30–40 | 20–25 | 90 | 10 |

* ad—as delivered, daf—dry and ash-free.
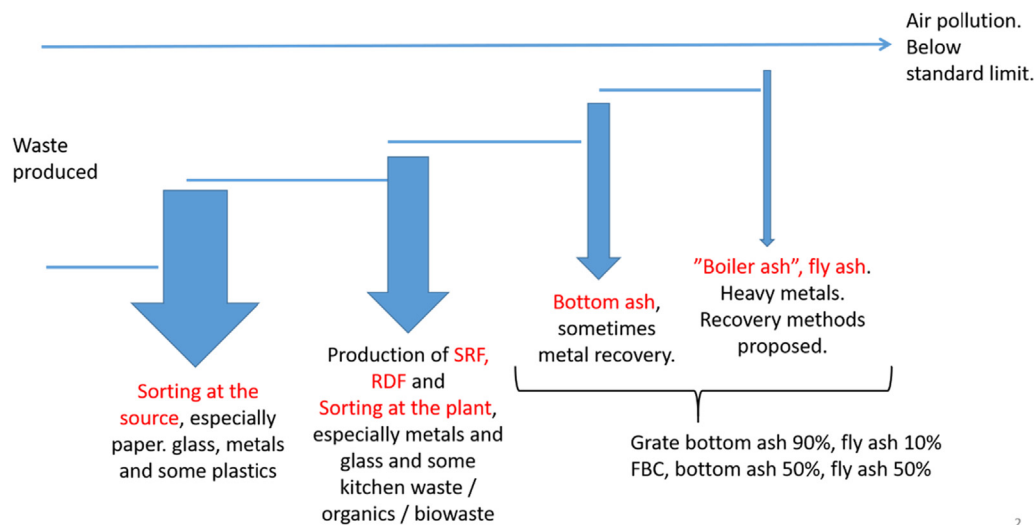


**Fig. 1.** Separation of the components of MSW during the stages of treatment (SRF – Solid Recovered Fuel, RDF – Refuse Derived Fuel, APC – Air Pollution Control) (For fractions of bottom and fly ashes, see Table 2). Sorting at a plant aims at RDF/SRF. Sorting in front of an incinerator is less severe.

metals disappear, and the heating value increases. The composition of MSW and its heating value is not only different in different regions, it also changes because of the various phases of waste treatment, such as separation at the source, separation in a fuel-preparation plant, or separation at a conversion plant, before the waste undergoes thermal conversion. After the thermal conversion, the remaining solids become bottom and fly ashes. Fig. 1 gives an overview of the transformations. In the case of separation at the conversion plant, combustible materials, such as kitchen waste, organics, and biowaste are usually not removed.

Defra (2013) mentions that MSW typically has an energy content of 8–11 MJ/kg, but after processing to RDF, the energy content increases to 12–17 MJ/kg as a result of some drying and removal of glass, metals, heavy materials like stones, kitchen waste, organics and biowaste. The heating value depends on the separation procedure. For instance, the European standard RDF, called SRF (CEN/TS 15359), defines four groups of separation products from MSW with heating values from 3 to 25 MJ/kg.

There is a short-term variation to consider, over hours, but also over longer periods, such as days, weeks or seasons, as shown by the example in Fig. 2. This figure gives an example from a particular place at a particular time. In addition, it illustrates how the situation could change between the years concerned. Together with the previous discussion, it aims at illustrating how a waste treatment plant may be subjected to changes in the operation conditions on a long and a short term.

The storage of the fuel in the reception bunker and the mixing by the feed crane, operated continuously for mixing when it
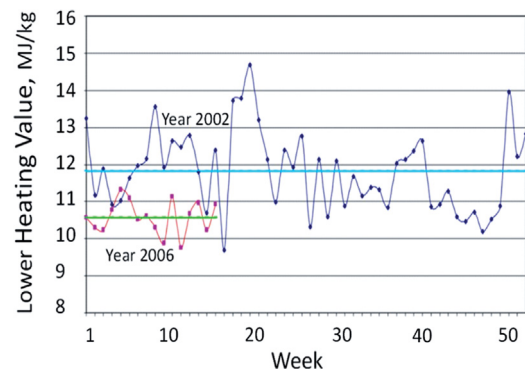


**Fig. 2.** Variation in the heating value of MSW as reported from the MSW plant in Wuppertal/D. Adapted from Lentjes (no date).

becomes available between feeding actions, mitigates the impact of the short-term changes of fuel composition on the operation of the conversion device.

The applied recovery strategies influence the long-term variations: Collection at the source of paper, cans, bottles, plastics, and food rests takes place in many countries. Eurostat's report (MSW statistics, Eurostat, 2017) gives 17% of total MSW produced initially as an EU average of recycling (from source separation and sent to renewed utilization), and this can be expected to increase. Recycling reduces the quantity of waste converted thermally and affects its heating-value.

In conclusion: The operation of a plant depends on its design conditions and on the flexibility of the plant to handle modifications in the fuel composition on a long term (source separation, living conditions, Table 1, Fig. 1), short term (variations of the kind shown in Fig. 2), and instantaneous changes.

## 2. The conversion plants

The following describes GF and FB boilers burning MSW, aimed at WtE, with a focus on the most common or promising designs, leaving out a number of special cases. Both types of boiler produce pressurized steam for expansion in a steam turbine, connected to a generator for the production of electric power. A possible heat demand is satisfied by extraction of heat in the form of steam from the turbine or from the turbine's condenser.

### 2.1. Grate-fired plants

There are several types of inclined moving grate, used for MSW combustion (Grillo, 2013). Fig. 3 presents a simplified sketch of a common type of GF furnace compared with some FB furnaces.

The fuel is fed, usually without preparation, into the fuel shaft of the GF furnace (waste input). It is pressed onto the grate by a feed mechanism (fuel feed). The grate is usually inclined about 10–25° from the horizontal. It consists of rods, moving according to a given scheme (forward or reverse acting), to stir and transport the fuel along the grate while it goes through conversion, a process that takes about an hour. Primary air enters from beneath through the grate in several independent sections (3 to 6 sections, depending on design) to fit the phases of conversion: drying, devolatilisation, resulting in volatile combustion in a flame above the fuel layer, and char combustion. Radiation from refractory arches above the fuel bed and from the flame promotes drying and ignition of the fuel. A reaction front develops and moves downwards in the bed at the same time as the bed moves forwards along the grate by the action of the rods. Fig. 4 illustrates in a simplified way the resulting conversion mode in the fuel layer and the gases released.

The regions depicted in Fig. 4 show qualitatively the sequential processes of drying, devolatilisation, and char conversion. The figure illustrates the high volatile content of the waste (Table 1) and the narrow space for char combustion. The fuel size is considerable and variable, for example, den Boer (2012) measured sizes > 10 cm for half of the MSW investigated. In addition, the movements of the grate stir the fuel, and the regions of fuel conversion on the grate are correspondingly blurred. The intermittent feed (the feed ram pushes the waste into the grate with a certain frequency) and the waste's size-distribution give rise to considerable irregularities, noted in temperature fluctuations in the gas above the fuel layer (Waldner et al., 2013, Fig. 4) and also from in-situ measurements inside the fuel layer with a probe that follows the burning material along the grate (Yang et al., 2003, 2004). The latter authors observed large variations in temperature, probably caused by the periodic movements of the grate in combination with channelling (Yang et al., 2004, Fig. 1). In special cases, such as for very moist fuels, the energy balance does not permit the conversion front to move against the gas flow if it is not supported by air preheat (Thunman and Leckner, 2001), and alternatively, the combustion front might develop from below, if ignited there. Various combustion modes of a packed bed, operating with wet fuel, are summarized by Razmjoo et al. (2016).

The initial thickness of the fuel layer is in the order of a metre. The length of the grate is about 10 m, a little more than needed for burnout of the char. The width of the combustion space is adapted to the fuel power by adding similar parallel grate modules, each of which is a few metres wide, as described by Riemenschneider and Schäfers (2011).

Because of the heating of the fuel, volatile species are released and burn largely in a visible flame above the fuel layer (Hunsinger et al., 1999). Secondary air serves to finalize combustion by stirring the gases, and so, enhancing mixing between gases and oxygen. Flue gas, recirculated to the secondary combustion zone, assists the latter mechanism. However, calculations indicate that mixing is far from satisfactory (Waldner et al., 2013, Fig. 7).

A series of papers from the Technical University of Denmark presents data on the release of gases from the fuel bed on a grate. Bøjer et al. (2010) show that Cl, accompanied by a number of volatile species (K, S, Ca, Na, Pb, Zn, Cu, Sn), leaves the bed predominantly in the beginning of the devolatilisation zone where the gas temperature is about 900 °C. The oxygen concentration,
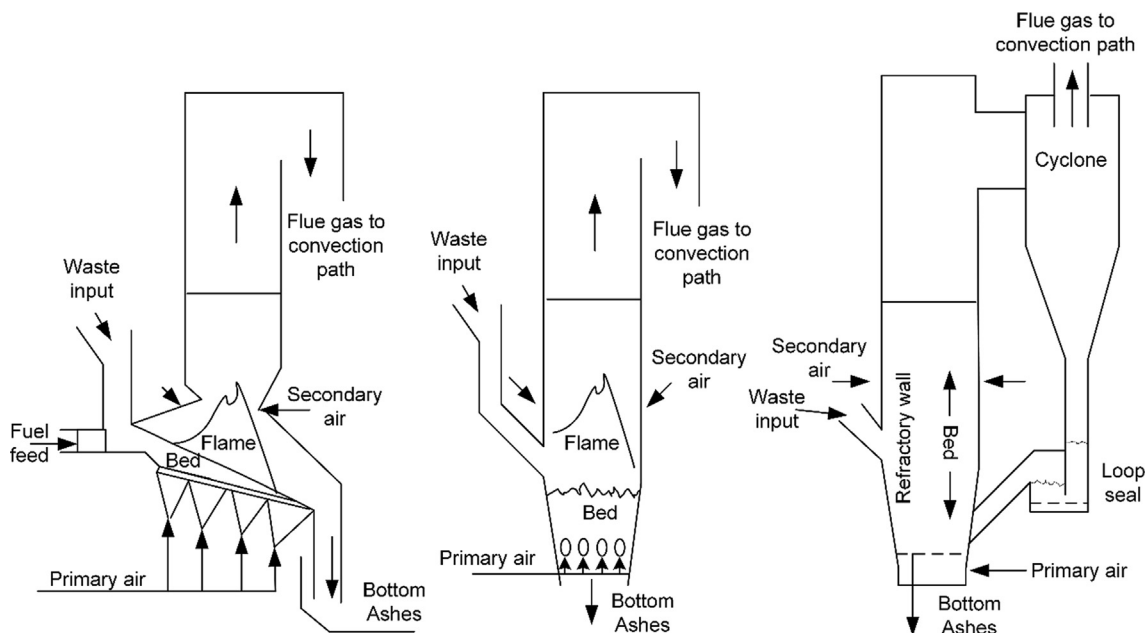


**Fig. 3.** From left to right: principle sketches of a GF boiler, a BFB (Leckner, 2015), and a CFB (Leckner, 2016). The dimensions may not be comparable. The lower refractory-lined part of the furnace is tentatively limited by the horizontal line across the furnace.
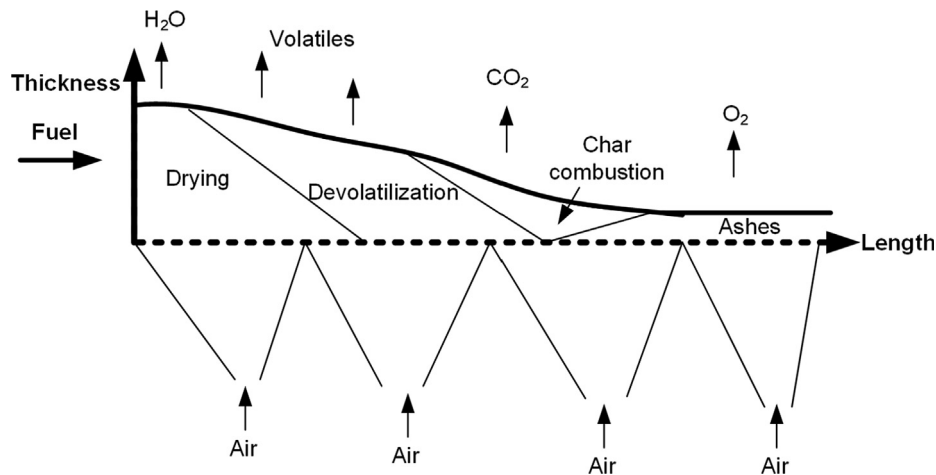
**Fig. 4.** A simplified, principle, picture of the conversion in a fuel bed on a grate. Modified from Rogers (1973).

measured about 1.5 m above the grate, is low in the devolatilisation region but increases along the grate to 21% after the char combustion zone. A few years later, Søe Jepsen et al. (2018) carried out a follow-up work in another boiler where also the NO precursors HCN and $NH_4$ were measured in the devolatilisation zone. The trend was similar to that of the previous work: these gaseous species were most concentrated in the beginning of the devolatilisation zone, and the concentration declined gradually along the grate. The works quoted show that, in general, there is a strong concentration difference along the grate for volatile species and combustion products. The oxygen concentration just above the grate varies in the opposite direction: because of the control of the air supply, and combustion in the respective zone; it is low in the drying and devolatilisation zones but rises further along the grate, because of lack of combustibles and the need for air-cooling of the grate (presumably, the grates used in these tests were air-cooled).

The properties of the fuel, composition (heating value, moisture) and size, affect the progress of conversion, and so does its feed rate (its thermal power and quantity). A change in the fuel properties displaces the location of the zones shown in Fig. 4, and then adjustment of the air supply to the various parts of the grate, the movement of the grate rods, and other actions are required to control combustion. In an advanced GF system, several measures control and modify the operation of the grate. They may include a laser scanner to inform the control system on the type of waste entering, the pressure difference across the fuel bed to measure its height and compactness, video analysis to identify the location of the flame front, etc. (Strobel et al., 2018).

### 2.2. FB-fired plants

There are two common types of FB boiler for conversion of MSW: Circulating (CFB) and non-circulating, called bubbling FB (BFB). The latter is employed in small plants (<10 t/h). Fig. 3 shows principle sketches of the two types. Leckner (2015) has given a detailed description of BFB for biomass combustion and of CFB for combustion of various fuels, Leckner (2016). These descriptions are valid with minor modification also for MSW; a superheater in the furnace has been removed from the original sketch, and the refractory lining is moved to higher positions in the furnace, shown by the horizontal lines across the furnaces in Fig. 3. The figures are not to scale; the BFB may be in the order of 20 m high, while the CFB may be 30 m high.

The cross section of the bed, and of the furnace, is square for small devices, while a rectangular shape, where fuel and air enter

from the long side, is preferred for larger capacities to facilitate mixing of fuel in the bed and by secondary air at a higher level. The fuel may be assisted by an air jet to further spread over the bed's cross section to mix as evenly as possible. The form of the cross section, including tapered walls, intends to facilitate mixing of fuel and primary air, the latter added evenly across the bottom through a set of nozzles.

In FB, the fuel amount is only a few percent in the bed, which consists of silica sand diluted by some ashes from the fuel. According to design, the bed maintains a temperature level of 800–900 °C. The amount of bed material corresponds to a settled bed height of about a metre. This means that a large thermal capacity is stored in the bed, and the bed can handle considerable short-term quality variations in fuel composition and supply (The bed is called a "thermal flywheel", referring to the thermal inertia of the bed, which tends to even out the short-term fuel fluctuations). In the case of a high-volatile fuel like MSW, the amount of unburned is small (Leckner, 1998, Fig. 4). Pollutants form during the oxidation of the fuel, but some of them are reduced in the bed and in the furnace.

### 2.3. Comparison of principal data from FB and GF equipment

Table 2 lists typical data of FB compared with those of a GF boiler.

The table illustrates some differences between FB and GF, but, obviously, there are also variations in each type of device, depending on the particular design. The excess air for a GF boiler can be taken as an example. The high value, 100%, remains from a time when WtE and environmental aspects were not important, whereas values like 40% belong to various innovative designs to be further discussed in Section 6.

In the sequential conversion on a grate, the bottom ashes that form the leftover at the end of the grate are about 90% of the total amount of ashes, while only 10% are fly ashes, mentioned by many references (Table 2). In contrast, in an FB only about 50% are bottom ashes and 50% fly ashes. This ratio varies according to design details, operation, and fuel composition (in co-combustion). Table 2 only gives a few examples. Referring to the different modes of separation, illustrated in Fig. 1, one should remember that the total quantity of ashes is smaller in FB because of the fuel pre-treatment.

## 3. Fuel preparation

The GF system burns MSW of any size that passes the fuel-feed chute. The only preparation is removal of extremely large objects

**Table 2**
Data of waste fuel converters. The data are indicative and may change from case to case. The bold font denotes the most common case.

| Parameter | CFB | BFB | Grate |
|---|---|---|---|
| Bed temperature, (°C) | **850**, a range of 800–950 is possible [a] | **850**, a range 850–920 is possible [b]. | <1100 with large fluctuations (in bed)[r,s] About 1000 in the first half and then declining to about 600 at the end [t], > 1100 (in the freeboard). |
| Excess air (%) | 20–30 [c], 20 [a]. | 40 [d] | 80–100 [p], 50–100 [e], 50–**80**, 30–50 advanced [f], **80** normal, 40 advanced [g][h]. |
| Primary/Secondary air (% of total) | **60/40**, 50/50 [i][a]. Primary air is evenly supplied to the bottom. Secondary air added at several levels occur also in CFB. | **60/40** Primary air 35% of stoichiometric, evenly supplied to the bottom. Secondary air added at several levels: four levels mixed with flue gas [b]. | **60/40** [e], 66/33 [g]. Primary air is distributed to the inlet zones: less to the drying and burnout zones and more to the principal combustion zone. Secondary air may be supplied in several (two) levels [g]. |
| Bed material, size (µm) | **300**, Silica sand and ashes, 200–400 [a]. | **500**, Silica sand and ashes, 800–1200 [b]. | Fuel bed, no bed material. |
| Max waste particle size (mm) | **50–100** [m], <150 [q] Depending on air distributor design. | **50–100** [m] Depending on air distributor design. | Only extremely coarse objects are removed from the fuel. |
| Lower heating value (MJ/kg fuel) | **10** Depending on design 4.5–32 [a]. | **10** 3–20 [b]. | **10** 6–10 without air preheat or water cooling of grate [u]. |
| Superficial velocity, (m/s) | **5** | **2** | **< minimum fluidization** |
| Bed height/pressure drop (m/kPa) | 30/10 (estimate). | **1/5–6** [b]. | **1–0.1** (fixed bed)/pressure drop depends on velocity. |
| Power demand % of thermal output | 4–10 [o]. | **4–10** [w] | 2–5 [o], 150 kWh$_e$/t [g] about 6% of thermal output [v]. |
| Bottom ash/fly ash, (% of total ash). | **50/50**, 58/42 [c], 50/50 [j] 3–5 times more fly ash than bottom ash [n]. | **30/70** [d], 70/30 [j]. | **90/10** [l][k][j]. |

a) Bolhàr-Nordenkampf et al. (2015), b) Kolbitsch et al. (2012), c) 3.8% O$_2$ on wet flue gas from 100% RDF, Langenbrugge: Loumaharju and Viljanen (2014), d) Johansson et al. (2006), e) Grillo (2013), f) B&W Völund (2012), g) Martin et al. (2015), h) Strobel et al. (2018), i) Zotter and Fiedler (2008), j) Saquib and Bäckström (2015), k) Hjelmar (1996), l) Wiles (1994), m) Wilén et al. (2004), n) Nie (2008), o) BREF (2006), p) Niessen (2010), q) Huang et al. (2013), r) Yang et al. (2004), s) Frey et al. (2003), t) Waldner et al. (2013), u) Lentjes (no date), v) Reimann (2012), w) estimated from o).

and some mixing with the crane in the fuel reception silo. The composition of the waste influences the conversion performance, though, and the sequence of the modes of conversion on the grate, illustrated in Fig. 4. In this respect, GF is more sensitive for fuel quality than FB.

Because of their favourable properties with respect to co-combustion, FB plants designed for MSW are simultaneously utilized for other types of waste as mentioned by, for instance, Bolhàr-Nordenkampf et al. (2015). In fact, many (most?) CFB plants burning MSW also add other fuels, such as industrial, forest, and agricultural wastes. In the European case, co-combustion is carried out for practical or economic reasons (to get rid of wastes), and not to sustain combustion of wet waste. However, as soon as MSW is used in an FB combustor, large non-combustible particles negatively affect fluidization. Therefore, FB systems receiving MSW, require pre-treatment of the MSW to reduce its size and to remove heavy particles, which otherwise gather at the bottom of the bed, obstructing fluidization. Also biomass, industrial and agricultural wastes are prepared by simple chipping or cutting into sizes of a few centimetres.

MSW could be pre-treated in different ways (Fitzgerald, 2013). A simple separation system suitable for an FB plant, Fig. 5, comprises shredding to reduce size, removal of some heavy particles (glass and metal), and magnetic and eddy current separation of iron or non-ferric metals, whereas combustible kitchen waste, organics and biowaste should be conducted to the furnace as much as possible. In contrast, in more refined fuel-preparation systems, these process steps are repeated to obtain smaller particles or higher degree of separation, and then they are completed with other size segregating equipment (air classifiers, trommel classifiers etc.) to produce a particular waste fuel, Refuse Derived Fuel (RDF), or for

standardised product qualities, such as in the European Union, SRF, see the BREF document on waste incineration (BREF, 2019) and Flamme and Geiping (2012) for an overview. These refined fuels are the result of centralised preparation with subsequent transportation to waste conversion plants, cement plants, or for co-combustion with conventional fuels in electric utility plants, while the pre-treatment equipment preceding a CFB should be as simple as possible, only intended for a particular plant.

Despite fuel preparation and removal of large-size incombustibles in the fuel, ash components of intermediate size remain in the bed, sink to the bottom, and have to be removed as bottom ash. Fig. 3 shows an example of nozzles in a BFB, forming an "open bottom", consisting of sparge tubes to inject the fluidization air at the same time as bed material is removed downwards (cf. Leckner, 2013, Fig. 5). This is used also in CFB; Zotter and Fiedler (2006) mention such a case with a free area of about 60% of the cross section. There are also arrangements with directed air nozzles, pushing the accumulating ashes to removal chutes in the furnace bottom.

Although pre-treatment of the fuel for FB implies a cost, it is an advantage from a combustion point of view. It increases the heating value, facilitates combustion, removes some of the ash, and reduces the thermal loss with the ashes (the latter is a small quantity).

## 4. The burnout and heat transfer parts, the "incinerator and the "boiler

### 4.1. The system

Incineration on a grate was employed already when waste treatment consisted of reduction of the volume of wastes (inciner-
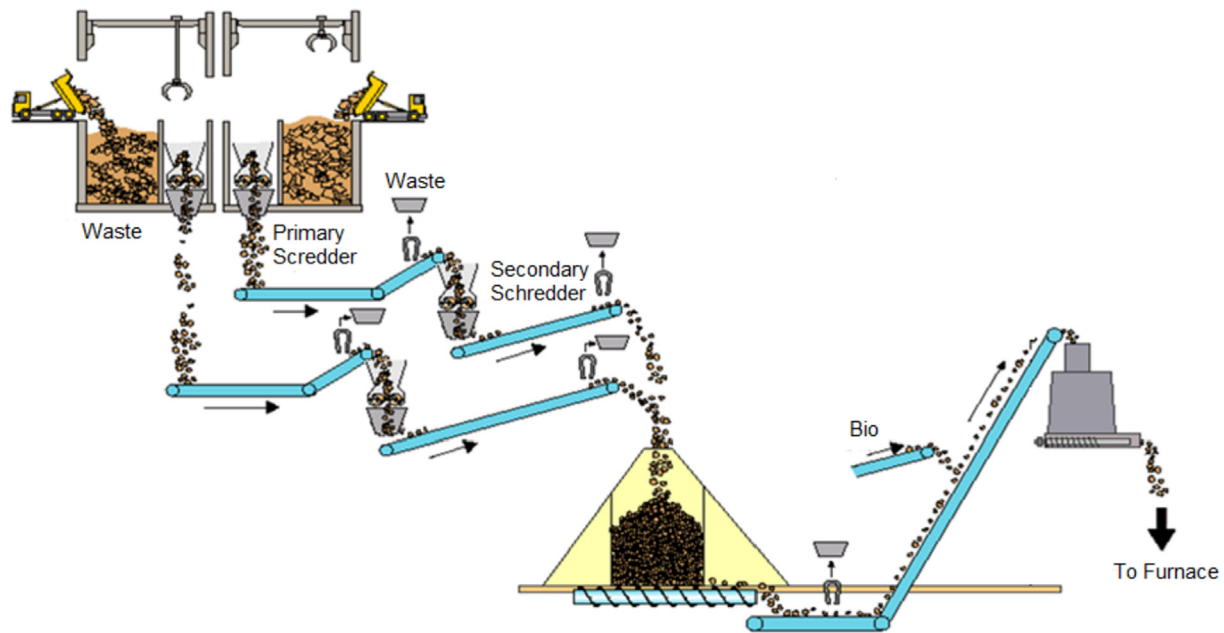
**Fig. 5.** The fuel preparation system at the 75 MWth CFB boiler for MSW in Norrköping, Sweden, consisting of primary shredders to tear up bags and to allow magnetic separation before the secondary size-reduction step, which consists of further shredders and separation of magnetic materials. The sketch is modified from Andersson (2002). Original hammer mills and an eddy current separator have been removed since the introduction of this pre-treatment system. (Presented with permission from Valmet).

ation means reduction to ashes) without caring for energy recovery. After a certain time of incineration of wastes, more than hundred years ago, someone got the idea to use the heat of combustion for evaporation of water to produce steam for heating or engines - and the waste-heat boiler was born. The tradition is strong in the "waste-management society", and there is still a distinction between the "incinerator", the combustion device, and the "boiler", the heat transfer section. This traditional subdivision is depicted in Fig. 6.

Now, waste converters are developed further for recovery of energy (WtE) and for reduction of emissions. During this development, the heating values of the fuel increased and new corrosion protection methods were introduced. The combustion devices became similar to "boilers" and incineration to "combustion" in the general sense of the concepts.

### 4.2. Furnace and back pass

For the comparison between GF and FB boilers it is convenient to split up the analysis in sub-areas of analysis, slightly different from the traditional picture of Fig. 6. For the efficiency aspect, the sub-areas could be: a) *the furnace*, the combustion and heat transfer part between the introduction of fuel and air till the flue gases leave the furnace with a temperature $T_{exit}$, entering into the next sub-area b), which includes *the back passes;* an empty pass, usually present in all waste boiler designs, the convection pass with its heat exchangers, and c) the thermal aspects (if any) of the APC section, until the flue gases leave through the stack with a temperature $T_{out}$. The furnace and the back passes are now called "the boiler". The loss related to electrically driven equipment in the pre-treatment and in the boiler is included in the total efficiency and in the difference between the gross and the net total efficiency. The definition of the furnace is straight-forward for GF and BFB, while from a heat-balance point-of-view the furnace of the CFB also includes cyclone, downcomer, loop-seal and related equipment (sometimes a heat exchanger) because they form a thermal unit. In the latter case the furnace includes the combustion space and the particle circulation system. Finally, besides the thermal aspects of the equipment, it is convenient to directly compare the detailed behaviour of the grate and the fluidized bed. Here,
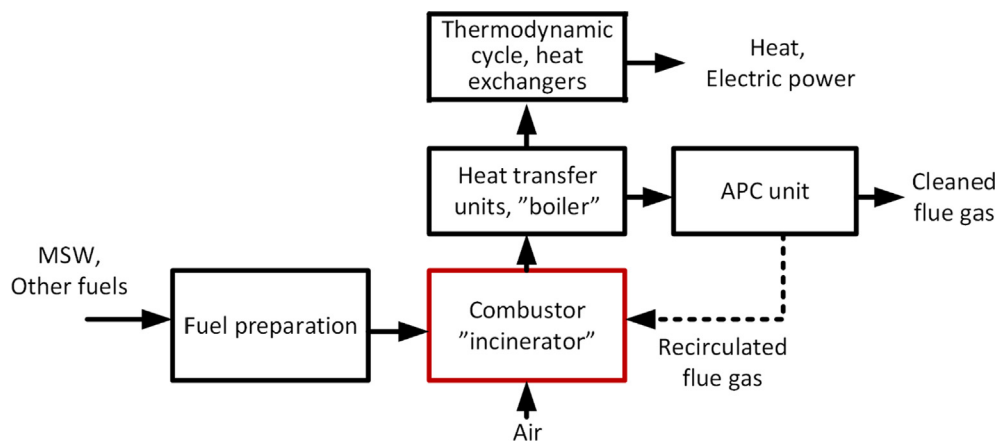


**Fig. 6.** The components of a plant. The traditional MSW plant partition in terms of Incinerator and Boiler.

the analysis of the air-supply system is shared between its thermal performance and that of the combustion equipment.

A heat balance on a furnace, seen as a well-mixed reactor, can be expressed in terms of its temperature,

$$T_b = \frac{H_{eff} - Q_s - Q_e}{g_{out}c_{pmg}} + T_{in} \tag{1}$$

Here, $H_{eff}$ is the effective heating value, $Q_s$ is heat absorption of surfaces in the combustion space, and $Q_e$ is the heat absorption in the loop seal of a CFB boiler. The gas-inlet temperature, including optional air preheat, may supply some heat from outside of the reactor

$$T_{in} = T_o + \frac{4.76\ell\lambda c_{pma}(T_{air} - T_o)}{g_{out}c_{pmg}} \tag{2}$$

where the last term is the heat supplied by air, heated to $T_{air}$, and 4.76↕ is the amount of air related to the oxygen demand ↕. $T_o = 300$ K is a base temperature. $c_p$ is mean specific heat.

If $Q_s = Q_e = 0$, the furnace is adiabatic. Then, in Fig. 7, the maximum thermal loads are represented by the adiabatic temperature $T_b = T_{ad}$ for various heating values

$$H_{eff} = HHV - \left(\frac{w}{b} + \frac{hM_{H_2O}}{2M_h}\right)H_w \tag{3}$$

($HHV$ is the higher heating value, $H_w = 2440$ kJ/kg water, is heat of evaporation of water, w, b are the components in the proximate analysis of moisture and combustibles, respectably, and M the corresponding molecular masses). Each curve in Fig. 7 represents the amounts of air supply (air ratios), attained for the well-mixed furnace without losses or heat removal. The heating value is represented by the moisture content of the fuel w (the abscissa).

(The calculation is made for data of a typical municipal waste, taken from Bogale and Viganó (2014): Proximate analysis: $a = 0.17$ ash content; w = 0, 0.10, 0.30, 0.50 0.70, 0.90 moisture, variable; $b = 1-w-a$ combustible part. Elemental analysis: $c = 0.572$, $h = 0.088$, $o = 0.321$ kg/kg combustibles (only the main components c,h,o). Recalculated from x kg/kg wet fuel to kg/kg combustibles by dividing by $(1-a-w) = 0.481$ where $a = 0.17$ and $w = 0.3489$. $1/(1-a-w)$ is kg fuel/kg combustibles. The higher heating value is HHV = 25.27 MJ/kg combustibles).

In the well-stirred furnace $T_b = T_{ad} = T_{exit}$, the exit temperature of the gas leaving the furnace. A reasonable gas-exit temperature could be that of the EU waste-combustion regulation Directive 2008/98/EC, demanding that the gas temperature should exceed 850 °C from the last addition of air for at least 2 s. This is marked in the diagram as "Desired exit temperature". The difference between the adiabatic lines and the "Desired exit temperature" is

the heat available for heat transfer in the furnace, the "thermal range", heat that has to be removed to bring the well-mixed furnace temperature down from the adiabatic state to the desired exit value. The thermal range is derived from Eq. (1) for a given fuel and moisture content ($H_{eff}$), as

$$T_{ad} - T_{exit} = \frac{Q_s + Q_e}{g_{out}c_{pmg}} \tag{4}$$

where $Q_e$ only exists in a CFB with an external heat exchanger. Otherwise $Q_e = 0$. Fig. 7 shows, for instance, the difference in thermal range between a GF boiler with an air-ratio of 1.5 to 2 and an FB with 1.4.

In contrast to the various thermal ranges shown in Fig. 7, the energy of the gas leaving for the back pass is given by the fixed exit temperature $T_{exit}$ and the quantity of gas (greatest at high excess air and moisture). A simplified energy balance on a waste boiler is

$$GH_{eff} = Gg_{out}c_{p,ad-o}(T_{ad} - T_{exit}) + Gg_{out}c_{p,exit-out}(T_{exit} - T_{out}) + Gg_{out}c_{p,out-o}(T_{out} - T_o) \tag{5}$$

Here $GH_{eff}$ is energy in fuel supplied, $T_{ad}$ is the adiabatic temperature from Eq. (1), $T_{exit}$ is the temperature at the exit of the furnace, for instance at 900 °C, $T_{out}$ is the temperature at the stack, neglecting various possible arrangements at the end of the APC and simply assuming a temperature suitable for a filter and above the acid dew point, 150 °C. $c_p$ are mean specific heats related to the various temperature differences and gas concentrations. No air preheat was included in this calculation.

Thus, from Eq. (5) three ratios to be compared can be expressed

$$\varphi_1 = g_{out}c_{p,ad-o}(T_{ad} - T_{exit})/H_{eff} \text{ (the furnace)} \tag{5a}$$

$$\varphi_2 = g_{out}c_{p,exit-out}(T_{exit} - T_{out})/H_{eff} \quad \text{(the back passes)} \tag{5b}$$

$$\varphi_3 = g_{out}c_{p,out-o}(T_{out} - T_o)/H_{eff} \quad \text{(the loss)} \tag{5c}$$

These ratios are presented in Fig. 8. High adiabatic temperature gives the largest thermal range in the combustion space, leaving less energy for the back pass (because of lower flue-gas flow (less moisture and excess air)), while the low adiabatic temperatures have a greater relative energy release in the back pass because of a large flue-gas flow. This has some significance for the allocation of heat transfer surfaces (evaporators, superheaters, economisers, and air preheaters), but it is difficult to generalize more than to say that the plants with high adiabatic temperature have more room for heat absorption in the high-temperature range in the
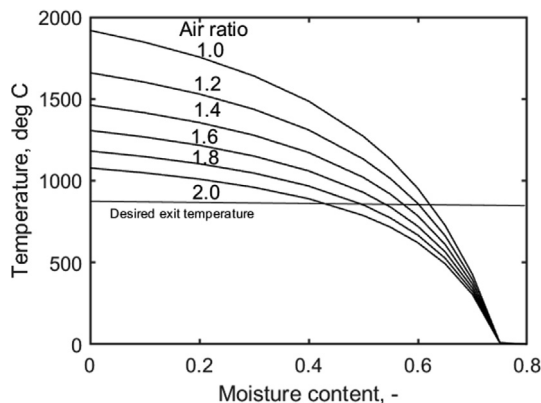


Fig. 7. The adiabatic temperature of the furnace, illustrating the influence of excess air and moisture content of the fuel. Air enters at a temperature $T_{in}$.
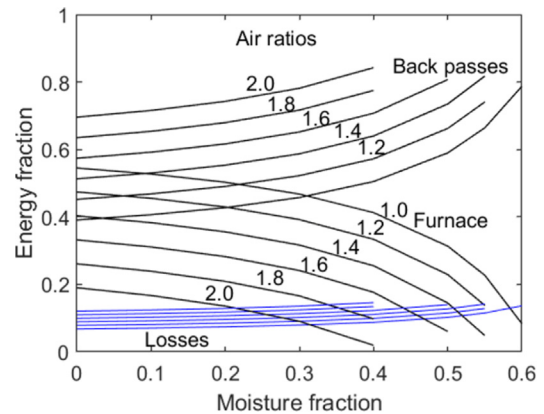


Fig. 8. The fractions of energy recovered in the furnace, in the back passes, and losses with the off-gas from the stack. The exit temperature from the furnace was put to 900 °C and the flue gas temperature in the off-gas 150 °C. The losses (the lower curves) are largest at a high excess air.

furnace (provided that corrosion can be handled), thereby freeing thermal space for more air preheaters in the low-temperature range of the back pass.

The furnace is designed for a desired exit temperature. It is usually refractory lined to a certain height to maintain a sufficient temperature in case of waste with low calorific value, but also to protect boiler tubes from corrosion. The height and the thickness of the refractory and the protective metal layers covering the heat-transfer tubes on the walls depend on the thermal space. In CFB, there is a possibility to control the furnace temperature also by means of heat extraction $Q_e$ from the circulating particle flow, passing by the cyclone ("the circulation loop"). This is a unique option, that creates a near-adiabatic combustor, reducing the heat transfer in the furnace, $Q_s$ is small. The main purpose is to operate a furnace with favourable combustion conditions without the danger of corrosion on metal tubes or deposits on hot refractory. Such a solution was proposed by Zotter and Fiedler (2006) in the form of a refractory-covered furnace and an external heat exchanger $Q_e > 0$ (in connection with the loop seal) where the heat of the above-mentioned "thermal range" is absorbed. However, even this solution is not without problems. Wengenroth (2014) mentions severe corrosion on heat exchanger tubes in contact with the gas and a need for maintenance of the refractory that offsets the advantage of higher steam data. However, refractory is used in grate furnaces as well, so there is no difference in this respect. Corrosion on metal surfaces is mitigated by covering with corrosion-resistant material, as used in many furnaces burning waste. Bolhàr-Nordenkampf et al. (2015) propose various methods to fight corrosion, among others to operate the furnace at as high a temperature as possible and to cover the tubes in a loop-seal heat-exchanger by a layer in order to increase their surface temperature, thereby preventing the condensation of alkali vapours and, as a consequence, reducing corrosion. A loop-seal heat-exchanger has some additional advantages, if corrosion can be prevented. It allows variation of $Q_e$, as was shown by Leckner and Karlsson (1993), who handled different heat releases in a conventional CFB combustor while operating a co-combustion case at constant load, bed temperature, and excess air with mixes of coal and wood ranging from 100% wood to 100% coal. This did not concern MSW, but it demonstrates the ability of CFB to treat variations in fuel properties during both short and long periods of time. In addition, changes in the fuel properties can be accommodated by minor changes in the bed temperature, and to a small extent by air preheat. Short-term changes in the fuel composition are handled without problem, owing to the large thermal capacity stored in the bed.

### 4.3. Load variation

A load diagram expresses the range of operation of a boiler

$$P = GH_{eff} \tag{6}$$

where $P$ is the fuel input power in % of the value corresponding to Maximum Continuous Rating (MCR) and $G$ is the dimensionless waste input in % of its maximum value, corresponding to MCR.

The diagram in Fig. 9 represents Eq. (6) and consists of a series of straight lines with the inclination $H_{eff}$, related to the input fuel. The area of operation is limited by the capacity of the fuel feed system (waste input) $G_{max}$ and by the MCR. The diagram also shows the range of operation and its limitations: the low load (the lower horizontal line) and the thermal restrictions. At low $H_{eff}$, the threat of insufficient grate temperature demands for air-heating, and at high $H_{eff}$, excessive heating, requires efficient cooling of the grate (water cooling). A similar diagram can be established for an FB, but the heating and cooling aspects are different.
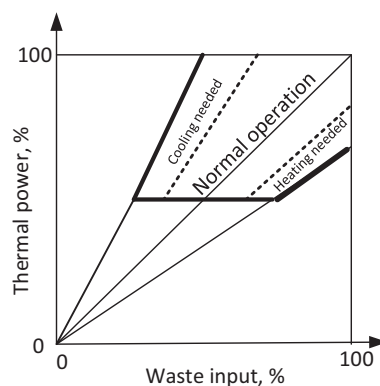


Fig. 9. Capacity diagram for a GF waste boiler showing the area of operation. The dashed lines indicate regions where cooling or heating is needed.

The manufacturing companies often publish diagrams of this kind to demonstrate the ranges of operation, see Table 3.

The thermal management of a combustor is centred at its most probable heating value according to design, and then there is a variation around this value. Typically, FB has a higher central heating value than GF. This is most likely because the fuel is upgraded in the pre-treatment process, and, also, industrial and other wastes with higher heating values are added. In the GF case, air preheat is the first measure to permit operation down to the low limit. At very low heating values, additional fuel supply could help, at least in FB. It is more complicated to mix an additional fuel into the MSW intended for GF. In FB, air preheat has an insignificant impact on the bed temperature because of the high thermal capacity of the bed compared to that of the gas. At higher heating values, the grate suffers from overheating and air cooling is no longer sufficient, water cooling is necessary. In the case of FB, some increase in bed temperature handles increases in the heating value, but, as mentioned above, an external, controllable, heat exchanger is the most convenient tool to take care of changes in the heating value. Finally, at least theoretically, in an FB it is possible to manipulate the ratio of primary/secondary air supply to influence the particle concentration in the upper part of the furnace, and thereby the heat transfer and the suspension temperature. As seen from the load diagrams, changes in heating value can also be taken care of by GF, but the adjustment of the configuration of the grate for various conditions is more complex than in an FB because the air supply to the grate has to be co-ordinated with the gradual conversion of the fuel along the grate. Therefore, the conversion on a grate becomes more sensitive than in an FB to occasional variations in the composition, heating value (and size) of the fuel.

### 4.4. Air supply

Fig. 3 shows the locations of the secondary air ports, quite similar in all applications. There is a difference between CFB and the other cases, though. In a CFB, the suspension of bed material absorbs the heat released locally, and it mitigates the temperature rise that may occur as a consequence of the combustion caused by the secondary air, while in BFB and GF furnaces, where combustion of the volatiles and fly-char takes place in the gas phase without accompanying inert particles. Then the local temperature may increase with a few hundred degrees (Leckner, 2013).

Air preheat improves the efficiencies of both FB and GF boilers by using the low-temperature heat in the flue gases before they leave through the stack (Eq. (7)). Eqs. (1) and (2) indicate that air preheat has a small impact on the heat balance, and it does not affect FB much because of the large heat capacity of the bed compared to what is supplied by preheated air or even by fuel. How-

**Table 3**

Examples of limits expressed by capacity diagrams. The measures taken to attain the given limits are usually not clearly indicated in the source publications

| Company/Source | Type of boiler | Low load, % of MCR | Low $H_{eff}$ | High $H_{eff}$ |
|---|---|---|---|---|
| Vølund (2012) examples | GF | 76 | 9.2 | 12.5 |
| Vølund (2012) examples | GF air preheat | 54 | 7 | 9.2 |
| Vølund (2012) examples | GF auxiliary fuel | 24 | 3.3 | 7 |
| Piechura (2003) | GF, forward-acting, air cooling | 20 | 5.5 | 10 |
| Piechura (2003) | GF, forward-acting, water cooling | Not given | 14 | 18 @65% fuel feed |
| Steinmüller-Babcock, Eckhart and Sohnemann (2014) | GF | 60 | 7 | 14 |
| Piechura (2003) | CFB, various fuels | 20 | 6.5 @60% load<br>11 @100% load<br>Added fuel, low | 30 |
| Bolhàr-Nordenkampf et al. (2015) | CFB | 64–82 | 8.5 @ 82% load<br>10 @ 100% load | 16 |

ever, it may be easier to take care of this heat in an FB whose primary-air nozzles are mounted in the furnace floor, which is cooled by evaporator tubes in most designs, and there is no risk for over-heating by heated inlet air. In the case of GF, the heating value of the fuel determines the feasibility of air-preheat (see Fig. 9). In case of a fuel with high-heating value, when the grate has to be cooled, air-preheat counteracts the cooling. Only in the case of a low heating-value fuel, heating of the air is useful, at least in the front part of the grate. The rear part may still need cooling. A way to overcome problems with too high temperature of pre-heated air would be to use steam-air preheaters.

Air-preheat in GF contributes to the local temperature in the combustion front moving down the packed bed of moist fuel. With moist fuel, the front may have problems in moving down against the air flow. Here, air preheat supports the heat balance of the combustion front and assists in its propagation.

Heated secondary air is also possible, but for GF and BFB the local temperature rise has to be taken into account, and the secondary air has to be supplied gradually to avoid "temperature excursions", locally high temperatures.

As indicated in Fig. 3, above the secondary-air inlet, the furnaces are quite similar. Only the cyclone and the related equipment of the CFB implies a difference. Downstream of the combustion chamber, most boilers for combustion of MSW have an empty pass (without heat exchanging tubes, except on the walls). This pass serves several purposes. One purpose (in Europe) is to satisfy the condition of the "Waste directive" (Directive 2008/98/EC. Another purpose is to reduce the gas temperature at the end of this pass to about 650 °C before the first convection tubes in the following convection pass to reduce corrosion. The convection pass, containing super-heaters, economizers, and perhaps air pre-heaters, is similar in the various combustion devices, except for the greater flow of fly ash in a CFB boiler.

### 4.5. Arrangement of combustion

The fuel preparation is an important difference between GF and FB that is both a complication and an advantage for FB, since the fuel becomes more homogeneous. The other important difference is in the local addition of primary air. On the grate, the conversion is sequential (plug-flow-like) with a supply of primary air that should vary along the grate to correspond the local air demand, while FB is a mixed reactor where the air supply is evenly distributed over the bottom cross-section, and the fuel is mixed in the bed.

In the BFB, heating of the fuel particles, devolatilisation, and char combustion take place in the bed, while the volatiles tend to burn in the freeboard above the bed, similar to what occurs in GF. In CFB, the bed and fuel particles meet a velocity that exceeds the terminal velocity of most bed particles. Then, particles are carried away by the ascending gas, and the conversion takes place in

the entire reactor, but it is greatest in the bottom part where the coarsest particles remain. The particle flow moves upwards with the gas and enters the cyclone from where the particles recirculate to the bottom bed with the exception of the very fine fraction, with a maximum size of about 20–40 μm (depending on the cyclone efficiency), which escapes with the flue gases and forms fly ash (Bolhàr-Nordenkampf et al., 2015).

In both GF and FB, there are imperfections. In the GF case, the air enters through a limited number of air ducts, each air-supply section covering a few metres of the grate. If the fuel properties change, the conversion zones in the fuel bed are displaced, and the air supply has to be adjusted to fit the change. This cannot be carried out with great precision and leads to conversion imperfections, not to mention the imperfections caused by the need to cool certain parts of the grate with an enhanced airflow because of variations in the moisture and ash contents of the fuel. If the air-cooling is insufficient for fuels with high calorific values, the grate or certain parts of the grate can be water-cooled, but this is expensive. In the FB case, the fuel is fed from the side of the furnace, and fines dry and devolatilize before they disperse evenly in the bed. Then, the FB reactor is not well-stirred, and the mal-distribution following the initial fuel conversion has to be evened out by secondary air.

In both combustor types, secondary-air injection aims at removing irregularities in primary fuel conversion, in some cases with the assistance of reinjected flue gas to improve mixing. Finally, in both cases, the combustion chamber is tall to allow burnout of gases and fly char. In the presence of excess air and at a temperature above 850 °C, both gas-phase and fly-char reactions have sufficient residence time for burnout. Therefore, the essential problem is not insufficient reaction rates but mixing of air and reactants. It seems difficult to further improve the mixing, so the remedy is to increase the excess air, up to about 100% in the GF case and to 30 to 40% in the FB case (Table 2). The high excess air improves burnout, and it creates an oxidising atmosphere that reduces corrosion. However, it decreases the boiler efficiency and increases the size of the related equipment. In this context, the CFB has an advantage consisting in the cyclone(s) that serve as a prolongation of the combustion chamber where the vortices created promote burn-up of gases and char, as well as reactions avoiding ammonia slip from an SNCR.

## 5. Efficiency

In modern waste management concepts, recovery of resources, in this case of energy, is important. Therefore, in the European Union there is a distinction between Recovery and Disposal of waste. A plant whose efficiency is high enough is a recovery plant and has certain legislative advantages. The decisive efficiency measure expresses the energy utilization of a plant in the form of heat and electricity by a quantity "R1", an estimate of the annual effi-

ciency, calculated by a formula defined by the Directive 2008/98/EC, Annex II. The R1 formula favors plants producing heat (or heat and electricity) compared with a plant only producing electricity; it is more demanding to reach a sufficiently high efficiency in a plant for electric power only than for plants producing both heat and electric power. Therefore, a correction coefficient was introduced in the R1 formula as a fair compensation for plants in climates where heat is not needed for space heating. To treat the more discriminating case, the present search for distinctions between GF and FB-plants focuses on electricity production. It must be admitted, however, that a high electricity production in a combined heat and power plant is not necessarily a goal in an energy system dominated by nature energy (hydro, wind, and solar) or nuclear power, occupying the base load. A choice of moderate steam parameters in the MSW plant may be found optimal taking into account also the actual energy system.

The boiler efficiency η depends of several factors, as analysed by Spliethoff (2010). Most of them, including combustion efficiency, have a small impact, so the only loss considered here is that of the exit flue-gas $g_{out}$ with temperature $T_{out}$.

$$\eta = 1 - g_{out}c_{pmg}(T_{out} - T_o)/H_{eff} \qquad (7)$$

The variation of the efficiency with air ratio and moisture content is illustrated by the lower set of curves in Fig. 8 for a given off-gas temperature $T_{out}$. As evident from Eq. (7) the flue-gas temperature $T_{out}$ plays a significant role. The efficiency depends on how far down (above the acid dew-point) the temperature could be brought by air preheat.

The total efficiency of the plant depends on η and the efficiency of the electricity production, usually by a Rankine (steam) cycle. For the present comparison between GF and FB plants the thermodynamic efficiency of power production, that is, the steam enthalpy (steam temperature and pressure), is the most important component.

Corrosion on heat transfer surfaces is significant in all MSW combustors and depends on the metal temperature of the heat transfer tubes. This limits the steam temperature, and so, the efficiency of electric energy production. Steam data are often similar in FB and GF plants, and the measures taken to reduce corrosion are often the same. However, in some plant descriptions, the steam data in FB plants are higher than those from GF plants. This could be a consequence of co-combustion with a less harmful fuel, or of the more favourable combustion conditions in an FB. Moreover, the boiler efficiency is usually higher in FB.

## 6. Boiler-related issues and innovations

Bed material, typically silica sand, has to be added to an FB for renewal of bed material to avoid agglomeration in the bed and to compensate for losses. The bed material turnover related to the waste fuel burnt is often 6 kg/MWh (compared to 3 kg/MWh for good-quality biomass) (Gyllén, 2019). This implies a cost. The positive aspect is that alkali compounds, formed from the fuel, react with the bed material and are removed from the combustion chamber, thus avoiding agglomeration and deposits on tubes. Other bed materials than silica sand may be even more efficient in capturing alkali. An example is ilmenite where potassium diffuses into the particle (Corcoran et al., 2018) instead of covering its surface, such as for silica sand (Leckner, 2013). It has been reported by Lind et al. (2018) that the make-up of bed material could be reduced from 6 to 3 kg/MWh in a CFB waste combustor, employing ilmenite instead of silica sand. However, ilmenite is useful as a bed material for other reasons: it is an oxygen carrier that is oxidised in the oxidising environments of the bed and reduced in the reducing regions, thereby transporting oxygen locally, enhancing combustion of CO and hydrocarbons (Lind

et al., 2016). Ilmenite has been tested in long-term trials in a 75 MW$_{th}$ CFB boiler (Lind et al., 2017), showing an improvement of the combustion situation together with the pre-treated fuel. So far, the potential reduction of corrosion in a more oxidising environment has not been systematically investigated on a boiler scale.

The more difficult combustion situation and the related higher excess air in the GF device result in larger gas passes and APC equipment, and larger loss of heat with the off-gas. FB, on the other hand, suffers from consumption of fan power for fluidization, and, furthermore, from the cost of make-up bed material. This cost can be reduced by regeneration of the bed material, Fig. 10a. In the case of an active bed material, such as ilmenite, the regeneration can be further improved by magnetic separation, as shown in Fig. 10b.

Measures are taken to improve the conditions for WtE. Considerable improvements are possible in the GF case, but there are innovations in FB as well. Sometimes the thermal efficiencies are higher in FB plants. However, the MSW plants located in Amsterdam, Brecia, and Bilbao show that with special measures also GF plants can reach high electric efficiencies (Bogale and Viganó, 2014).

Utilization of the uneven gas composition above a grate has led to several proposals for improvements, Fig. 11. Martin et al. (2007, 2015) have suggested to recirculate the oxygen-rich gas externally from the final part of the grate to the central/upper part of the furnace to provide an oxygen-rich gas to this region, thereby reducing the excess air and the NO$_x$ concentration, Fig. 11a. Bøjer et al. (2010) and Dam-Johansen et al. (2008) proposed to separate the devolatilisation part of a grate and its final oxygen-rich part by a wall, allowing the less corrosive gases from the rear part of the grate to supply heat to an end-superheater in the furnace, Fig. 11b. Hunsinger (2009) proposed to remove the low-oxygen, high-volatile gases from the central part of the grate and then, after cleaning, using these gases in a secondary combustion chamber to rise the steam temperature for enhanced electric power production, Fig. 11c.

Another approach to utilize the uneven over-bed gas concentration was made by Waldner et al. (2013, Fig. 8) who proposed to inject recirculated flue gas just above the rear part of the grate to push the oxygen-rich gas horizontally to regions with less oxygen above the devolatilisation zone. As a result, mixing and reaction improve, and the air excess is reduced, as mentioned in Table 2.

A loop-seal superheater in CFB makes it possible to increase the steam temperature (Bolhàr-Nordenkampf et al., 2015). This heat exchanger can also be used for adjusting the bed temperature.

CFB is useful for gasification of SRF, as shown in Lahti, Finland (Isakson, 2015), where a gasifier produces gas, which is filtered for impurities after cooling to about 400 °C. The cleaned gas is no longer considered waste in the EU legislation (it has reached the "end-of-waste" state) and burns in a conventional (non-waste) boiler with high steam data.

Recirculation of SO$_2$ to the combustion chamber to reduce deposits and dioxin (Andersson et al., 2014), is a method proposed for GF, but it most likely applies to FB as well.

The above-mentioned active bed materials for FB is rather new and, like many of the other proposals, needs further experience.

## 7. Emission control

There is a lack of direct comparisons between the emissions of GF and FB boilers under strictly the same operation conditions. Comparison is difficult because of differences in the MSW used and the fact that FB boilers (especially CFB) usually operate with fuel mixes, including also industrial or forest waste (biomass). These fuels are similar to MSW in the sense that they are highly volatile, but they are different as far as impurities are concerned.
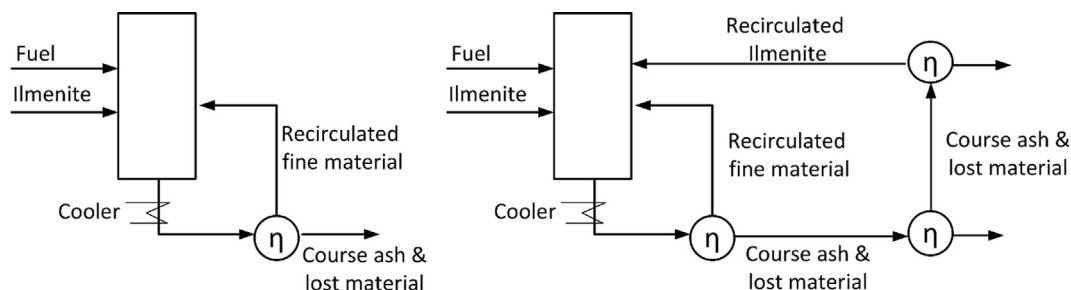
**Fig. 10.** Regeneration system for bed material. Left) Simple separator. Right) Separator including magnetic separation for ilmenite.
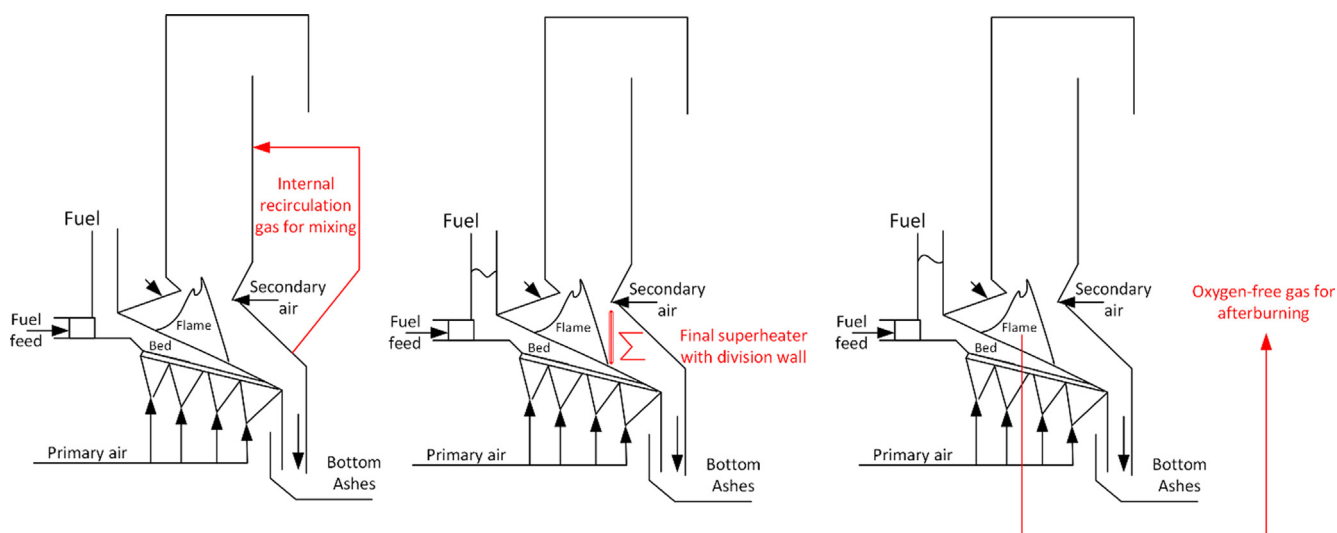


**Fig. 11.** Innovative proposals for improvements of GF burning MSW. From left to right: (a) Reciculation of oxygen-rich gas for secondary combustion (Martin et al., 2007, 2015); (b) Internal final superheater in the oxygen-rich region of the grate (Bøjer et al., 2010, Dam-Johansen et al., 2008 (Vølund)); (c) Utilization of the volatile gases from an oxygen-poor region of the grate for after-burning (Hunsinger, 2009).

In waste combustion, primary measures for the reduction of harmful emissions are not sufficient to satisfy the severe conditions of the emission regulations, and flue-gas cleaning is necessary. The emissions are often reported downstream of the APC equipment, showing that they fulfil available regulations. The APC systems may contain wet, dry, and half-dry components. The dry and half-dry components may use lime or sodium bicarbonate to capture sulphur and HCl. Furthermore, injection of active carbon reduces the concentrations of dioxin and mercury. Injection of ammonia or urea in the flue gas (non-catalytic reduction) or in catalytic reactors reduces the emission of nitrogen oxide. There are several options for APC where there is a choice between the cost of the equipment, efficiency and operation efforts. The APC is required in all cases and reduces the differences between GF and FB; many of the environmental advantages of FB are therefore less significant in this comparison.

### 7.1. Nitrogen oxides.

The precursors of $NO_x$ leave the moving bed in an oxygen-deficient region (Bøjer et al., 2008). In both FB and GF, oxygen-deficient zones contribute to the reduction of the NO emissions. Some $NO_x$ forms directly in the bed, but the reduction and avoidance of formation are considerable in the region upstream of the high-temperature, secondary-air injection zone, which is similar in GF, BFB, and CFB. The differences consist in higher $O_2$ concentra-

tion and most likely higher temperature in GF leading to higher NO. In CFB, the thermal capacity of the particle suspension lowers the local temperature rise, forming less $NO_x$. However, the advantage of FB to reduce NO on char in the bed is almost absent in MSW-biomass combustion because of the low char concentration in the high-volatile fuels, see a comparison coal-biomass by Leckner (2016, Fig. 16). In all cases, the design of the furnaces can achieve gas temperatures that fit the conditions of selective non-catalytic reduction by ammonia or urea to remove about 50% of the $NO_x$ formed initially.

### 7.2. Hydrocarbons and CO.

Some hydrocarbon gas components originating from the volatiles are precursors to dioxin. The mixing provided by the secondary air reduces these precursors, and the temperature/residence-time requirement imposed by the EU plays a role to further reduce the precursors in all boilers firing waste. The role of oxygen-carrier bed-materials in reducing dioxin has not been investigated, but it is likely that the concentration of precursors will be lowered. Reduction of the concentrations of CO and hydrocarbons by oxygen carriers has been demonstrated by measurements in a 12 $MW_{th}$ CFB boiler, operated with wood chips at 1.6 vol% $O_2$ dry in the exit gas: the average CO concentration in the exit gas was decreased by 80% during operation with ilmenite compared to silica sand, Thunman et al. (2013).

## 7.3. Fine particles and trace elements.

Some trace elements tend to evaporate at combustion temperatures and then re-condense homogeneously, forming submicron particles, or heterogeneously on ash particles, when the temperature falls in the heat transfer sections of a boiler. Lind et al. (2007) measured particle concentrations and sizes in the flue gas downstream of the convection pass and upstream of the fabric filter in a GF and a CFB boiler, firing sorted MSW mixed with industrial waste, rather similar in both plants. The investigators found two modes of particle in both plants: a submicron mode (PM 1.0) consisting of re-condensed particles and a coarse-particle mode (>1 μm) consisting of ash particles, originating from the fuel without condensation. The concentration of submicron particles was greater in the GF plant. The authors attributed this to the higher temperatures in the reaction zone of the GF boiler. However, the total ash flow was larger in the CFB boiler, and some of the devolatilised material could have condensed on these particles. In both plants, the filters were very efficient also for the small particles, and the emission values were far below the limits of the emission regulations.

## 7.4. Sulphur

The motivation for introducing FB combustors for coal combustion in the 1970s was their ability to capture sulphur by addition of limestone to the bed. For staged air supply, like in the present application, BFB operates under predominantly reducing conditions and sulphur capture becomes less efficient (Lyngfelt et al., 1993). In a CFB, on the other hand, sufficient bed material, including lime, is present in the oxidising region downstream of the secondary air addition, and the sulphur capture is reasonable. Normally, the sulphur content in the waste materials concerned is low (a characteristic value is 0.4%, Brunner and Rechberger, 2015), and sulphur and HCl can be captured by addition of a sorbent to the flue gases. In all systems, sulphur may be useful for reduction of alkali deposits and for reduction of dioxin (Andersson et al., 2014), and this may be another reason not to remove it by limestone addition to the bed.

## 8. Operation and capital costs

Costs related to the purchase and operation of the plants are important for the comparison of GF vs. FB. Such data can be derived by a manufacturing company, offering the two types of plant for the same conditions, and by a user with experience from operation of the plants concerned under the same conditions. It is uncertain, though, to take data from the literature, because the same conditions are rarely maintained, and specifications are incomplete in publications. However, there are a few publications directly comparing the economic conditions for GF and FB. In the 2006 version of the BREF (2006, Table 10.43) there is a comparison of the costs for a GF system and corresponding FB systems: BFB and CFB. This comparison includes combustor, boiler, energy utilisation equipment. Pretreatment of the input waste is handled separately. The comparison is made for the same MSW input, but the fuel pre-treatment upgrades the waste from 10 to 15 MJ/kg in the FBs (it was assumed that the ash content decreased from 25% to 10% of the waste quantity during the pre-treatment), so the boilers treat different quantities of waste (70,000 vs 100,000 t/a for the BFB and 200,000 vs 300,000 t/a for the CFB). The corresponding costs without fuel treatment are given as 36.52 vs 36.01 €/t for BFB vs GF, and 21.75 vs 31.18 €/t for CFB vs GF. The fuel preparation cost is claimed to be between 10 and 30 €/t without further specification.

An additional comparison has been published by Zhao et al. (2016), related to Chinese conditions, but the authors included plants of foreign origin for comparison. It is stated that the investment in foreign FBs is 10% lower than for a foreign GF, which agrees with the BREF case mentioned above. The cost of the equipment manufactured in China is 30% lower than that of the imported plants, but the relation between GF and FB plants is similar; the FB plant is cheaper than the GF plant. Also the operation costs are lower for FB. However, these are for Chinese conditions with MSW of low heating values (co-combustion with coal was applied in the FB case to maintain the combustion temperature) and therefore the operation data only give an indication for a comparison with conditions outside of China. Tentatively, one could refer to the power demands quoted in Table 2 and the cost for bed material make-up, both of which indicate that the operation cost is higher in FB than in GF. In Table 2 is seen that the amount of fly ash is higher in CFB than in GF units. This is a disadvantage for CFB, since the fly as is usually considered hazardous waste and more expensive to deposit than bottom ash. On the other hand, catalytic equipment for NOx reduction can usually be avoided in CBF where non-catalytic reduction is sufficient, and that implies avoidance of costs for catalysts.

Obviously, a key question is: what is the fuel preparation cost in the case of FB? A fuel preparation system suitable for FB should be simple compared to the mechanical-biological treatments of MSW, which aim at RDF. It should reduce the material size to <5–10 cm, depending on how the air-nozzle bottom is designed in the FB, and it should remove most metals, magnetic and other. Preferably, glass particles and heavy particles should also be removed. So, the system could consist of a shredder, a magnetic separator, an eddy current separator, and a ballistic separator. This could be related to the 200,000 t/a plant mentioned above (650 t/day assuming 300 days/a of operation, or 25 t/h assuming 8000 h/a). A similar MSW preparation system has been analysed by Arina et al. (2014). They derived a mechanical pre-treatment cost of 15 €/t for a pre-treatment plant of 80 t/h operating during 2000 h/a. If this plant is utilized with a capacity of 25 t/h during 8000 h/a, the cost would be about 12 €/t. Others, Caputo and Pelagagge (2002) have derived costs for various layouts of MSW pretreatment systems, resulting in costs between 21.18 and 1.28 €/t for systems treating 100% MSW, depending on the complexity of the systems, the heating value, and the desired size of the final fuel product.

The additional costs of operation for fuel preparation are difficult to estimate in a general way. However, the benefits and drawbacks can be summarized. Benefits are a) improved operation of the combustion unit b) income from some of the sorted items, such as metals, which can be sold together with the corresponding materials from the bottom ash. Costs are a) operation and maintenance of the equipment b) handling of the remaining extracted material that can be deposited together with the bottom ashes.

The economic comparisons presented are rough, and there may be differences in scope and in what is included in each calculation, but it seems that the numbers given allow some indicative conclusions: FB is cheaper than GF boilers, and there are indications that its efficiency is higher. The principle drawback of FB for combustion of MSW is the necessity to remove large and heavy objects from the waste. This is handled in two ways, applied together: on the one hand, the bottom of the FB furnace is made open for easy removal of possible large objects that have passed the pretreatment, and on the other hand, the waste flow delivered is prepared by shredding and sorting. The latter implies an additional cost. Roughly, in the absence of refined calculations based on comparable systems, it can only be assumed that the difference in cost of an FB compared to a GF plant is about similar to the cost for the

pre-treatment system, so the resulting cost difference between the two systems is not large.

## 9. Conclusions

The main differences between GF and FB boilers for combustion of MSW are:

GF has a significant advantage in that there is more experience in this dominant method of MSW combustion, whereas FB has been introduced in this field more recently and its properties are less known and less developed for MSW combustion.

FB boilers need fuel preparation. This is an economic disadvantage, but the improved fuel from pre-treatment facilitates combustion and ash handling in the furnace. Similarly, addition of bed material implies a cost for FB, but with active bed materials, unburned gases are further reduced. The improved combustion situation permits lower excess air and increased steam data. The gas flow is reduced, and so are the dimensions of the equipment.

The investment cost of an FB system, excluding fuel pre-treatment, is about 10% lower than that of a GF plant, according to two literature sources where comparisons were made.

A great advantage of FB is its ability to handle short and long-term variations in the fuel composition and a wider choice of fuels for co-combustion.

A CFB furnace can utilize the relatively protected region in its loop-seal for an end-superheater, and this permits higher steam temperatures. A loop-seal heat exchanger can also compensate for variations in the heating value and fuel mix.

Combustion on a grate is sequential from the fuel entrance to the exit of the ashes, while FB is a mixed reactor. GF is then more demanding to control than that FB, since the air supply has to fit the conditions of the fuel along the grate, and, totally, the necessary air excess is inherently greater in the GF case. Moreover, excess air arises from the need to cool the grate. Water-cooling is possible, but more expensive, and utilised only for high calorific-value fuels.

Recently, various measures (proposed, and in some cases implemented) have considerably improved GF furnaces: staged combustion, utilisation of the sequential combustion situation on the grate, the oxygen-rich and pollutant-free rear part, and the oxygen-free gas containing volatiles in the centre of the grate. These improvements allow an increase in the efficiency of electric power production.

Downstream of the secondary air-nozzles, or downstream of the cyclone in a CFB, GF and FB plants are quite similar.

The environmental advantages of FB (sulphur capture with limestone, low $NO_x$, CO, and hydrocarbons) are less important from an emission point of view, because all combustion devices need to have an APC to meet severe emission restrictions, and this evens out the differences between GF and FB.

The higher gas velocity of CFB yields higher specific heat-release, and the cross section of a CFB is smaller than that of a grate. However, this concerns the combustion devices only. The upper part of the furnace is made narrower also in GF furnaces.

The final conclusion is that there are advantages and disadvantages with both devices, and it is uncertain to select a winner. Instead, refined economic judgements could give the answer.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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