Technical and Environmental Comparison of Circulating Fluidized Bed (CFB) and Moving Grate Reactors

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EXECUTIVE SUMMARY

The subject of this thesis is the combustion of municipal solid waste (MSW) in waste-to-energy (WTE) power plants. In particular, it compares the two principal WTE technologies used in China: Moving Grate (MG) and Circulating Fluidized Bed (CFB) reactors. Following a description of these technologies in the first part of the thesis, the second part is dedicated to comparing the advantages and potential drawbacks of the newer CFB technology, relatively to the older and widely used MG technology, by using data obtained from the literature, industrial sources, and obtained during a summer internship of the author at Zhejiang University, in Hangzhou, China.

The third part of this thesis focuses on the relatively large fraction of fly ash generated in the CFB process. A specific advantage of the CFB technology is its ability to burn high-moisture waste efficiently and the very high heat flux per square meter of combustion chamber cross section A CFB disadvantage is that it produces a large amount of fly ash (about 12% of the weight of MSW processed), in comparison to the moving grate systems (about 3% of the MSW). However, it is believed that the CFB fly ash can be reduced by altering the cyclone configuration after the combustion chamber. Some preliminary experiments on reducing the fly ash generated in the Zhejiang University 10 ton/day CFB pilot system were carried out by the author, in collaboration with Prof. Qunxing Huang of Zhejiang University and his students. The addition of a second cyclone was proven to be efficient in capturing the remaining fraction passing through the first cyclone, but at the cost of increased pressure drop through the system. The U-beam system, on the other hand, has been shown to be an efficient system and requires less additional power than adding a second cyclone. Several solutions are proposed that may overcome this drawback, along with an estimate of their costs and benefits. This part also includes the description of experiments that were conducted by the author at Zhejiang University to evaluate the proposed solutions for reducing the fly ash fraction of CFB.

Finally, the author draws conclusions on the comparison of CFB and MG reactors in the context of MSW combustion and on the potential of these two types of these reactors to combust high moisture waste.

Keywords: Municipal Solid Waste, MSW, Waste-to-Energy, WTE, Combustion, China, Moisture, Circulating Fluidized Bed, Moving Grate, Fly Ash

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Introduction

In recent decades, waste management has become crucial all over the world because of the dramatic increase in the amount of waste produced by municipalities - doubling of the amount of waste generated in the last decade (World Bank, 2012). This upward trend is expected to continue and another doubling of current Municipal Solid Waste (MSW) levels is projected by 2025 (World Bank, 2012).

The question of which waste management option to choose - waste-to-energy (WTE), landfill, recycling, to cite only a few of them - has become a high stake issue at the municipality, regional (i.e., province, state), and the national government levels. The Earth Engineering Center (EEC), at Columbia, has developed tools to classify waste management options by sustainability level. Sustainable Development is often defined as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (World Commission on Environment and Development, 1987) and the EEC has listed all waste management options by increasing sustainability level, looking for each one at the complete life-cycle of the technology. The result is known as the EEC Waste Management Hierarchy presented in Figure 1 below.

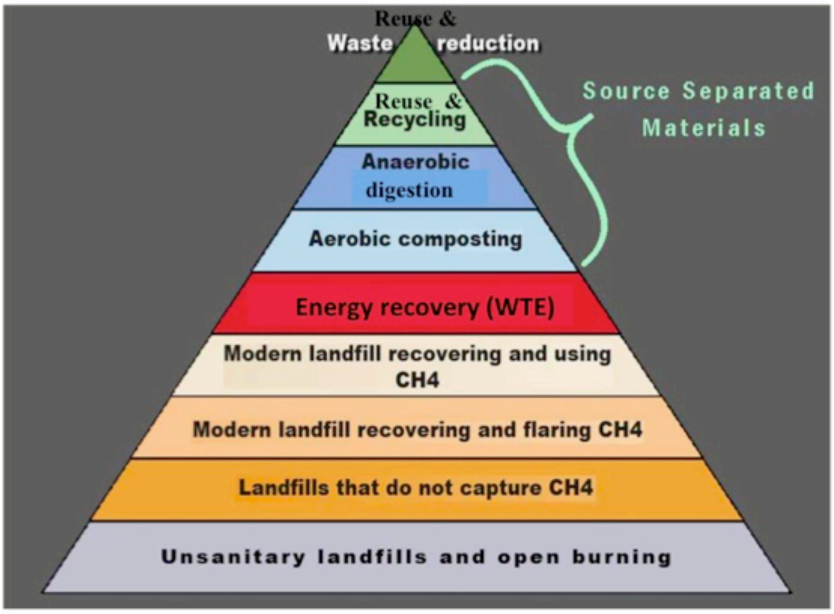


Figure 1: Waste management hierarchy, EEC

Figure 1 shows that WTE is part of a sustainable solution, and is preferable to landfill for all the waste that could not be Reused, Reduced or Recycled (RRR), where recycling here is meant to include composting. Even though landfilling has many different facets, and the best form, sanitary landfilling, encompasses the partial capture of methane and its beneficial use, it is generally considered as a less sustainable solution than waste-to-energy.

According to the literature (Themelis, 2013 - 2), currently and globally, post-recycling waste can be broken down according to its global disposal in the following way:

- treated by WTE (200 million tons)
- treated by sanitary landfills with partial CH_4 recovery (200 million tons)
- and treated by unsanitary landfills (more than 800 million tons)

These numbers show that the room for progress is huge in terms of environmentally sound waste management.

The fact that WTE is part of a sustainable waste management solution can also be seen in Figure 2 below, called the Sustainability Ladder, developed by EEC.

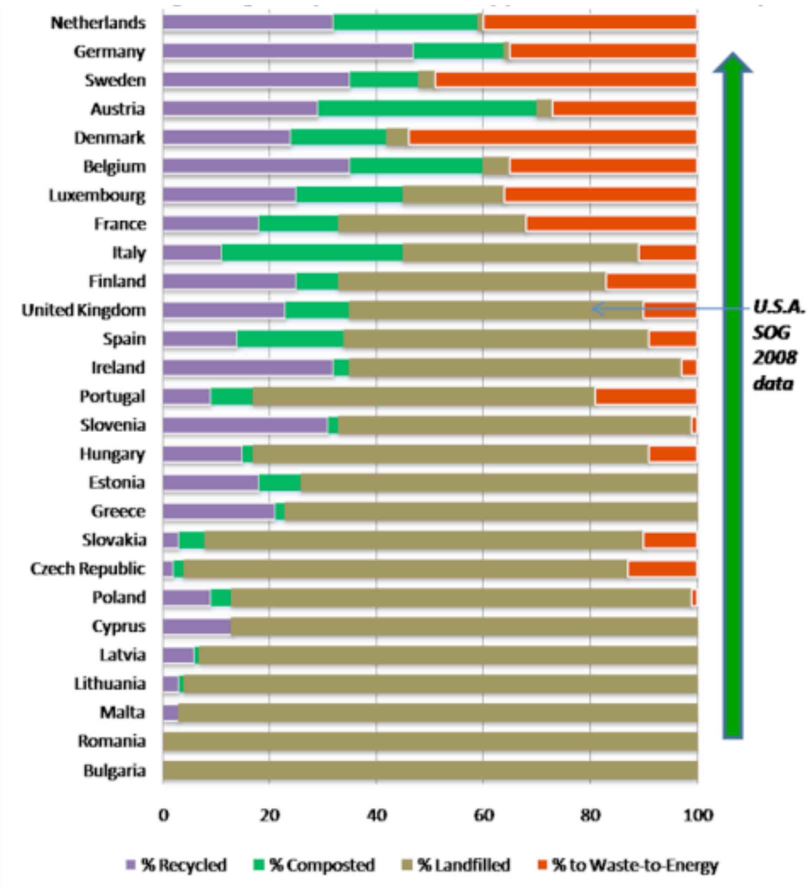


Figure 2: Sustainability ladder, EEC

Figure 2 provides a list of many countries ordered by increasing landfill diversion, expressed as a percentage of total waste. In this figure, it is also clear that countries that have achieved a very low landfill use, i.e. a very high landfill diversion, have done so by using a recycling/composting and WTE. WTE is therefore an integral part of sustainable waste management.

In order to face the challenge of waste growth by using the WTE option, two main thermal treatment technologies have been developed.

Firstly, the Moving Grate (MG) technology has been in use for several decades and was initially derived from coal combustion. In countries where Waste-to-Energy was first adopted, the high plastic and paper content of the waste impart a relatively high heating value per kilogram of municipal solid waste (MSW). In such a context, the Moving Grate technology was developed to meet several criteria such as: burning raw, as-received non-pretreated waste, thus having low operating cost and high a capacity factor (i.e. number of ours in full operation per year). This technology has been developed continuously since the middle of the last century and by now, meets the above challenges and is the dominant technology with over 800 WTE plants in about 40 nations. A schematic diagram of the MG combustion chamber is shown in Figure 3.

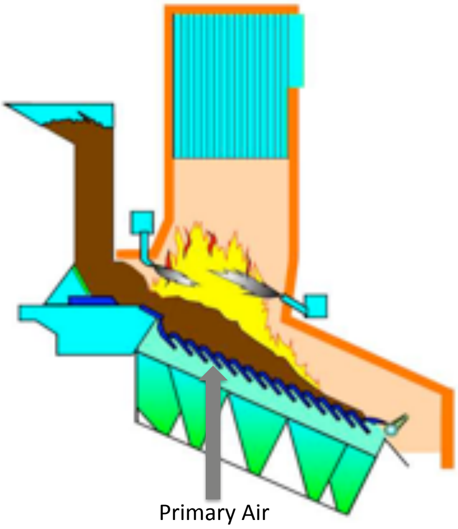


Figure 4: Schematic diagram of the MG combustion chamber

Figure 3: Schematic diagram of the CFB combustion chamber (Andritz, 2014)

However, in China, and in many other "developing" countries, the MSW contains a high fraction of food wastes - often well above 50% of the mass of waste – a relatively small fraction of paper, and a very high moisture content, in comparison to American and European wastes (Huang, 2013). The direct consequence is the low heating value of Chinese MSW, which can be as low as 4-6 MJ/kg waste (Huang, 2013) in comparison to the 11 MJ/kg of U.S. MSW. and 8-11 MJ/kg across Europe. Therefore, when traditional WTE moving grate incinerators started operation in China, after a drive of the Chinese government in favor of "harmless waste management" options, several issues arose when trying to burn the Chinese high moisture waste. When burning raw MSW alone on a moving grate, obtaining a stable combustion process was hard and some moisture had to be removed prior to combustion, in the form of leachate. Also, sometimes, coal or oil had to be co-combusted with MSW when the waste was too wet to ignite by itself.

Therefore, another main technology of waste incineration was developed in China to burn high-moisture waste: the fluidized bed combustion (FBC) technology. This technology differs from the moving grate reactor in three main elements: a different shape of combustion chamber, an increased airflow velocity through the reactor and the fact that the MSW must be pre-shredded before introduction to the furnace.

The Circulating Fluidized Bed (CFB) technology is a particular type of FBC that is characterized by its higher airflow velocity, usually in the 3 to 9 m/s range (Van Caneghem, 2012). This high velocity propels the lighter particles through the fluid bed reactor after which the gas/particle flow passes through a cyclone separator situated after the combustion chamber, where most of the suspended particles are removed from the flue gas and are returned to the fluid bed reactor. This results in a fluid bed that is literally circulating (Huang, 2013), as illustrated in Figure 4.

The CFB technology was originally developed for coal combustion in the second half of the 20th century. It was applied to biomass, refuse-derived fuel (RDF) and MSW combustion in Europe where 38 plants are currently operating (Leckner, 2014), especially in Austria. However,, China was the first country where CFB was specifically designed and developed to burn high-moisture waste.

The purpose of the first two parts of this thesis is to compare Moving Grate and Circulating Fluidized Bed Technologies, and to analyze advantages and drawbacks of CFBs compared to MGs. In the third part, the author focuses on the major disadvantage of CFBs, that is a high fly ash fraction, and proposes several solutions to alleviate this issue. Costs and benefits of those solutions are also presented. The appendix is dedicated to the future conduct of an environmental assessment of both technologies, using a life cycle assessment (LCA) framework. In the final section, the author tries to draw conclusions as to the optimal thermal treatment technology for energy recovery from high moisture waste.

1. Description of Waste-to-Energy technologies: Moving Grate and Fluid Bed

1.1. The dominant technology: the moving grate reactor

Developed for relatively high heating value wastes, the MG technology was designed to meet several criteria such as burning raw, non-pretreated waste, having low operating costs and a high capacity factor (i.e., number of hours in full operation per year). Because it reached the required goals (e.g. capacity factor >90%), the moving grate is currently the leading technology for the thermal treating of MSW, worldwide. This technology is illustrated in Figure 5.

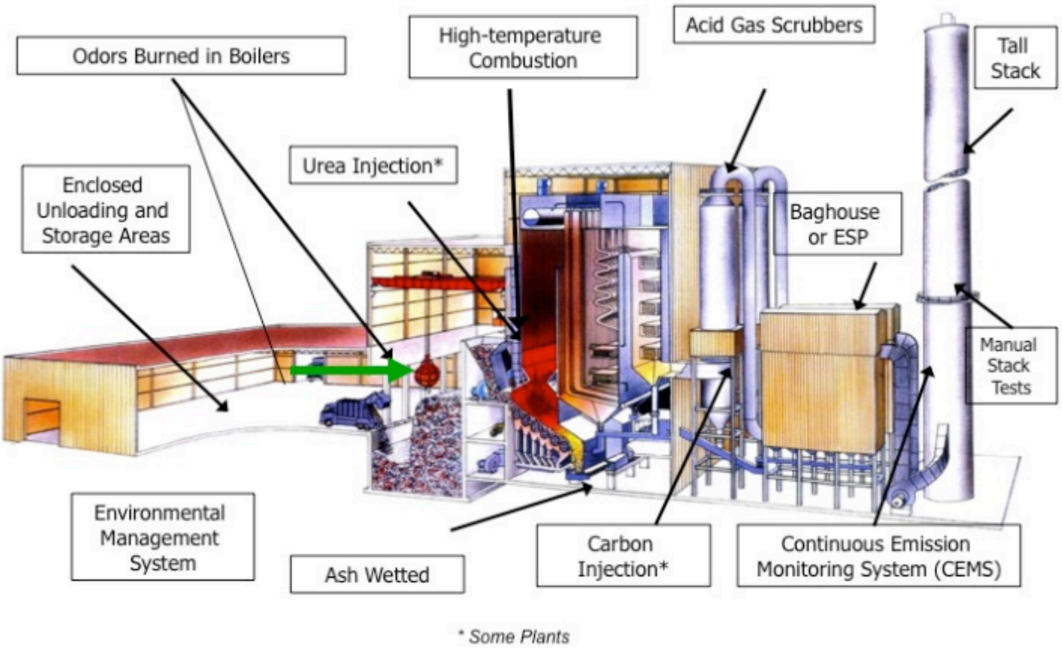


Figure 5: Typical Moving Grate Waste-to-Energy Plant (Castaldi, 2010)

In the MG technology, the as-received MSW is dumped by garbage trucks into a huge pit, usually without any pre-screening (Van Caneghem, 2012). Overhead cranes grab the waste and dump it into the hopper that feeds the moving grate of one or more furnaces (called "lines"). There, the waste material slowly descends to the furnace level and is pushed by a piston onto the feed end of the grate; by means of gravity and also the motion of the grate, the waste moves through the combustion chamber. It slowly heats up because of the increasing proximity of the fire. Once it is dry enough, it starts volatilizing and burning. The air needed for the combustion is introduced partly below the moving grate (primary air) and partly above the moving grate (secondary air).

Water walls on both sides of the combustion chamber, and superheaters downstream of the combustion furnace receive the heat generated by the combustion. Water is transformed into superheated steam that is used to power a steam turbine that generates electricity. After the boiler, the flue gases are treated and cleaned from most of its pollutants, and released through the stack.

This process results in the generation of two types of ashes. First, bottom ash is collected at the bottom of the reactor. It consists of non-combustible materials - metals, glass - and the ashes produced during combustion. Fly ash is collected from the flue gas downstream of the combustion chamber, principally by means of bag filters; this ash contains residues from combustion that were carried over in the heat recovery and Air Pollution Control systems. It is considered a hazardous material since it contains some heavy metals and dioxins. It has to be disposed in accordance with its hazardous nature.

1.2. Fluid bed technologies

Fluidized bed combustion (FBC) technologies differ from the moving grate technology because of three main elements:

- A different bed shape
- An increased airflow velocity in the reactor
- The fact that waste must be shredded before combustion in the FBC reactors.

All FBC technologies have in common the injection of a high velocity flow of air into the boiler. What differentiates fluid bed technologies is the airflow velocity (Koornneef, 2006), as shown in Figure 6. Two main types of FBC technologies exist. Ordered by increasing airflow velocity they are Bubbling Fluidized Bed Reactors (BFB) and Circulating Fluidized Bed Reactors (CFB).

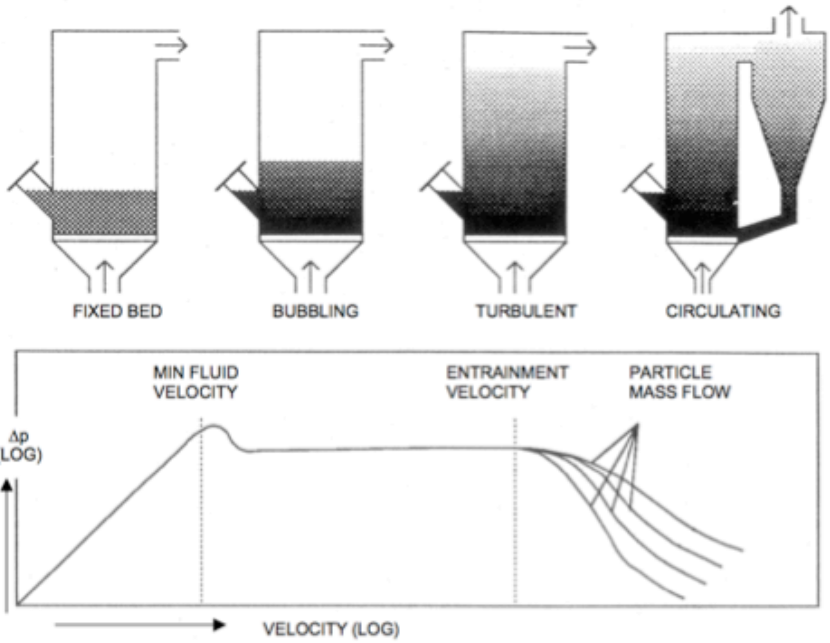


Figure 6: Change in regimes of Fluidized Bed Systems (Castiella Franco, 2013)

The first technology, the Bubbling Fluid Bed (BFB), utilizes a bed of inert material such as sand or ash, to which is added shredded waste. It is brought to a fluidized state by the primary flow of air through the bed, becoming a bed of churning material. The majority of the fuel material reacts with the oxygen primary flow inside the bed or just above the bed (Koornneef, 2006). A secondary flow can be added higher up in the reactor, in order to burn volatile gases and particles suspended in the flue gases above the bed (Koornneef, 2006). The combustion chamber is followed by a cyclone separator that collects particles, which are then conveyed back to the combustion chamber to ensure complete combustion (Van Caneghem, 2012 and Woodash Database, 2014). The fluidization "superficial" velocity (volumetric flow of air divided by cross sectional area of reactor) is usually in the 0.5 to 3 m.s^{-1} range (Van Caneghem, 2012).

The Circulating Fluidized Bed (CFB) technology differs from BFB because of its higher airflow velocity, usually in the 3 to 9 m.s^{-1} range (Van Caneghem, 2012). This high gas velocity entrains most fine particles which are then removed from the gas flow in the cyclone separator situated at the top of the bed; therefore, the bed is literally circulating (Huang, 2013), as shown in Figure 7.

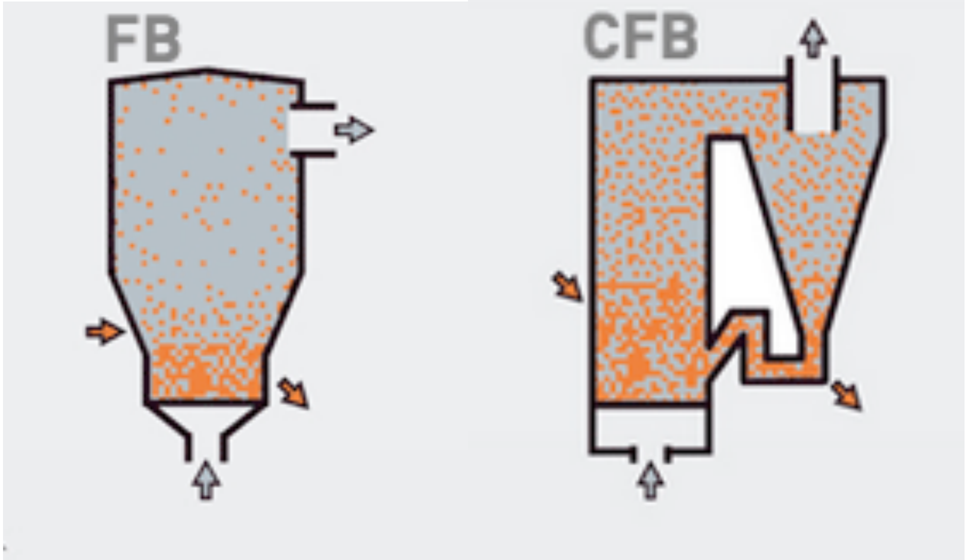


Figure 7: Left: BFB Diagram (Outotec, 2013); Right: CFB Diagram (Outotec, 2013)

A third type of FBC reactor exists: it's a hybrid technology, between the two pre-cited ones (Koornneef, 2006). However, it has a small market share (Koornneef, 2006) and is therefore not addressed in this report.

1.3. Scale of implementation of both technologies

A good way to assess the relative importance of FB and MG technologies is to compare the number of plants of each technology in operation worldwide. Doing so, it is easy to note the dominance of the Moving Grate technology:

- In the U.S.A. in 2010, there is no FB plant burns MSW, out of the 86 WTE plants. However, the SEMASS WTE plant, near Rochester, MA, pre-shreds the MSW and introduces it in a way that is partially combusted in suspension (Themelis, 2013 - 3). Most of the U.S. plants use a moving grate: five use a rotary kiln while 81 use some type of moving grate (Michaels, 2010).
- In Europe, according to the International Solid Waste Association (ISWA), 329 are equipped with MG and 38 plants with FB combustion. The rest of the 433 incineration plants are fixed bed or rotary kiln combustors (Leckner, 2014)
- In Japan, 40 plants use fluidized bed combustion, versus 197 MG plants, while the 66 remaining plants use rotary or direct smelting processes. (Themelis, 2013)
- In China 2012, 59 plants are equipped with FB combustion, and 77 are equipped with MG out of the 142 plants in the country (Zheng, 2014)

Therefore, based on data for these four regions that account for most of the global waste incineration capacity, and in terms of number of plants, MG has 71.0% market share with 584 plants under operation, while FB's share is 14.2% with 137 plants.

Also, with regard to the total operating WTE capacity in the world, MG accounts for 174 million annual tons, FB for 12 million annual tons, and other technologies (e.g., direct smelting, rotary kiln, etc.) for 2.9

million annual tons (Themelis, 2013 - 3). Therefore, in terms of waste combustion capacity, MG accounts for 92.1% of the global capacity, and FB for only 6.4%.

A comparison of these two main technologies is of high interest, especially in the light of the high rate of development of CFB technology in China, in recent years. Indeed, it is possible that the FB technology may overcome the MG technology, especially in the developing world where the calorific value of the MSW is relatively low. Therefore a comparative assessment of these two technologies is necessary.

2. Technical comparison of Moving Grate and Fluidized Bed technologies

In this section, the objective is to compare the key characteristics of the Fluidized Bed technology to the Moving Grate. In the first part, a rapid comparison of CFB and BFB is presented. After explaining why the author chose to focus on the CFB technology, the latter will be compared to MG in the second part of this section.

Before beginning these comparative assessments, the author wants to underline the importance of some technical parameters in the description of the combustion process for each type of reactor. A parameter that varies greatly across different technologies is the airflow velocity. Other parameters that will be useful in this comparison include particle size, temperature inside the furnace, percentage of waste input that ends in fly and bottom ash, excess air used over the stoichiometric requirement, and minimum heating value of input waste accepted by the furnace.

2.1. Comparison of BFB and CFB reactors

Koornneef et al. published a very good comparison table that highlights some of the differences between the BFB and CFB technologies: BFB can process larger particles (up to 50 mm) than CFB; therefore, BFB reactors require less pre-processing of waste (Koornneef, 2006). Additionally, they have a high concentration of particles in the lower part of the bed and a low one in the upper part, whereas a CFB reactor has a more homogenized particle concentration, resulting in a homogenized temperature and pressure pattern. BFB have a lower erosion rate than CFB, mainly because of the reduced gas velocity (Khana, 2009). Lastly, BFBs combustion chambers resemble much more grate combustors than CFBs, and it is therefore easier to retrofit a MG reactor to a BFB (Wood Ash Database, 2014).

As noted earlier, the velocity in CFB reactors ranges from 3 to 9 m s^{-1}. This has been shown to decrease pollutant levels of NO_x, HCl and SO_2 (Huang, 2013). Moreover, CFB have higher turbulence inside the reactor, as well as a high thermal inertia (Huang, 2013). Furthermore, the boiler temperature is slightly higher in CFBs as well as steam temperature, pressure and flow. However, this difference in steam temperature and pressure is mainly due to the processing of lower quality fuels by BFB in the studied cases (Koornneef, 2006).

Finally the cost of BFB can be considered significantly higher than CFB. Indeed, a cost per daily ton of capacity in the range of $32,500 to $40,000 (based on Chinese plants) can be assumed for CFB (Huang, 2013), while the cost for BFB is around $100,000 per daily ton of waste processed (Themelis, 2013 - 3). However this cost is still lower than a moving grate combustion plant: $200,000/daily ton (Themelis, 2013 - 3).

The differences mentioned above and the corresponding advantages of the above technologies are summarized in Table 1.

Table 1: Advantages of each FB technology

Advantages of BFB	Advantages of CFB
Larger particle sizes (less pre-processing) (Koornneef, 2006)	Higher temperature and efficiency (Koornneef, 2006)
When retrofitting a MG reactor, it's easier to convert it into a BFB (Wood Ash Database, 2014)	Scaling (Koornneef, 2006)
	Sulfur, NOx, HCl Removal (Koornneef, 2006 and Q. Huang, 2013)
Lower heating value fuels	Thermal inertia (Huang, 2013)
Lower erosion rate (Khana, 2009)	Lower cost (Huang, 2013 and Themelis, 2013 - 3)

Companies that design and /or build CFB plants worldwide are listed in Table 2 below.

Table 2: List of companies that manufacture FB plants

BFB	CFB
EPI / Outotec (U.S.)	EPI / Outotec (U.S.)
Metso (Finland)	Zhejiang University (China)
Strabag (Austria)	Andritz (Austria)

This thesis focuses on the CFB technology, for several reasons. Firstly, because the latter has been undergoing very intense research and development for a few years, notably in China, with many plants being opened recently there. The very dynamic research and development around CFB can be underlined by the fact that CFB accounts for the overwhelming majority of fluid bed reactors in the whole energy market (i.e., not only WTE, but also biomass, coal, waste fuels etc.), as shown in Figure 8.

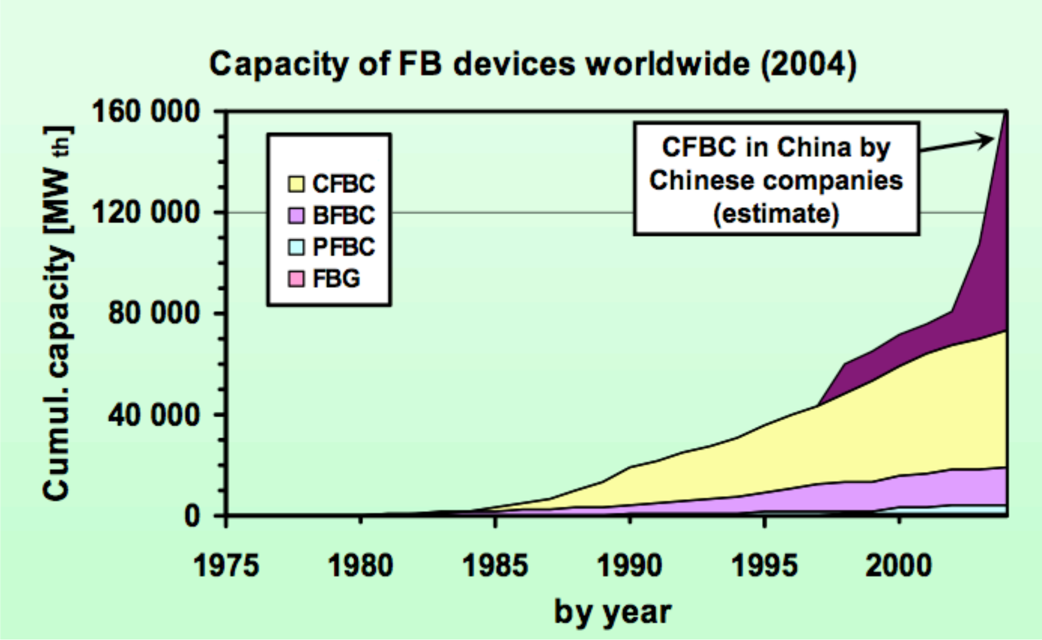


Figure 8: Capacity of FB devices worldwide (Hupa, 2005)

A second point is the availability of data on CFB reactors used for MSW incineration, in the literature as well as from industrial sources available to the author. The final reason is the fact that CFB seems to have a very bright future thanks to its application to burning high-moisture waste. For these reasons, the following section compares MG and CFB reactors.

2.2. Technical comparison of MG and CFB

A few papers in the literature compare MG and FB reactors but, in most of them, the comparison is rather incomplete. For example, Van Caneghem et al. (Van Caneghem, 2012) provided a quick description of advantages and drawbacks of Fluidized Beds compared to MG, but did not present much quantitative data. Nixon (Nixon, 2013) compared a MG and a FB plant in UK, while Leckner (Leckner, 2014) did a brief comparative assessment, using data for excess air requirements, temperatures and ash content. Granatstein (Granatstein, 2004) compiled and presented data on FB plants in U.S. Sweden, Japan, Spain, UK, and France. The most complete comparison was conducted by McDougall et al. (McDougall, 2001) who presented a comprehensive comparative review summary, but the process engineering was only briefly described, and the study dates back to 2001.

Therefore, a comprehensive comparison, including industrial data, process engineering explanations, and experimental results would be a useful addition to the existing published literature.

First elements of the comparison

Because this has not been done in previous work, as explained in the literature review, an apple-to-apple comparison of the MG and CFB technologies will be useful in understanding the differences and the advantages of each technology.

In order to do a comparison with specific data, we focus here on one particular CFB plant (Cixi, China) that is compared to a typical MG plant (Brescia, Italy). The Cixi WTE plant consists of four units of total capacity of 2,300 tons per day; however the data presented refers to the newest and largest unit of 800 tons per day. This unit was built on the basis of the process design provided by Zhejiang University located in Hangzhou, China. Also, the Brescia plant consists of several units, but the data presented refers to one on them that has a capacity of 792 tons/day. The Brescia plant received the "Industry Award" Prize of the Waste to Energy Research and Technology Council (WTERT) in 2006 (A2A, 2014). Some data for these two plants is shown in Table 3. The information is based on original information given by the Brescia plant, and Zhejiang University. These two units were chosen because both are of nearly the same capacity (about 800 tons per day).

Table 3: Technical data on one MG reactor and one FB reactor

Plant	Brescia, Italy	Zhejiang University, Cixi
Reactor type	MG	CFB
Starting year	1998	2012
Capacity, Tons/day	792	800
Height, m	22	16.8
Grate area, m^2	102.4	21.8
Combustion chamber cross section area, m^2	62	21.8
Volume of combustion chamber, m^3	1,210	366.24
Process gas volume, Nm^3/hour	135,003	85,000
Flue gas flow, Nm^3/ton	4,091	2,553
Velocity of gas in main section of chamber, m/s	2.5	4.5
Average minimum residence time, s	8.79	3.8
Grate combustion intensity, tons/day/m^2	7.73	36.7
Net electricity (kwh/Ton)	682	279
Net electricity generation, MW	23	9.3
Heat value of fuel, kJ/Kg	11,300	3,980
Heat release rate, MJ/(h m2)	3,139	6,085.6
Heat release, MW/m^2	1.01	1.69
Net electricity generation, MW/m^2	0.22	0.43
Overall efficiency (heat to electricity)	21.7%	25.2%

Figure 9 presents a general diagram of the CFB design in Cixi that summarizes some of the data presented in Table 3.

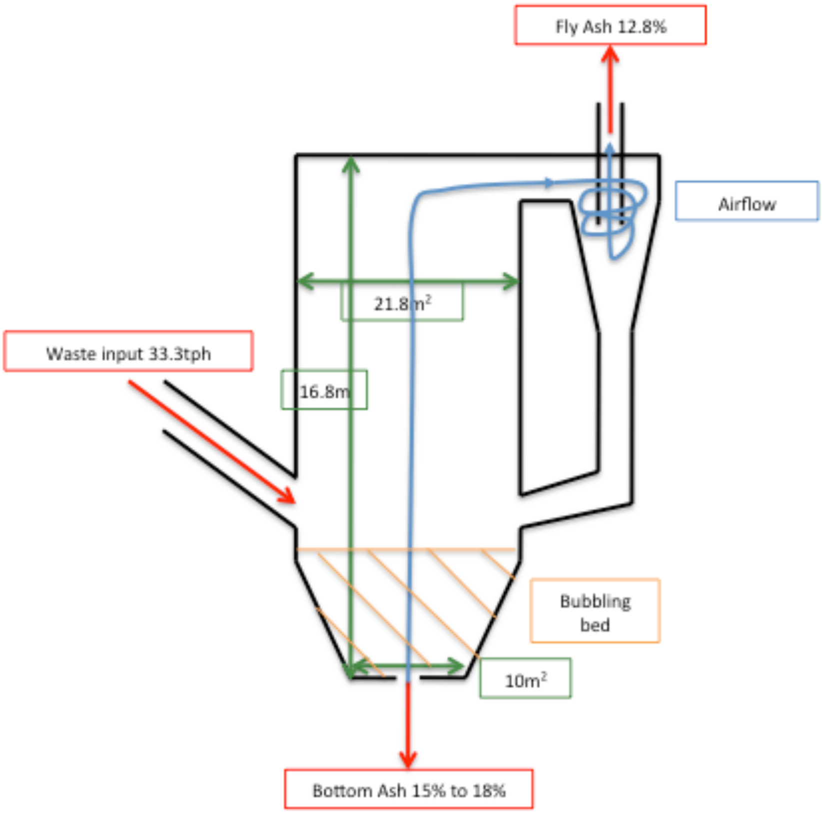


Figure 9: General schematic of the CFB design

In Part 2.2.1, several operating parameters of the Cixi unit are reviewed.

2.2.1 Cixi CFB plant detailed parameters and results

1. Plant design parameters

i. Waste properties

For the Cixi 800 tpd system, under normal operation, the heating value of the waste ranges between 4.2 MJ/kg and 5 MJ/kg (Huang, 2013). It varies depending on the season, and on the daily weather. Zhejiang University provided the typical waste input characteristics presented in Table 4. According to this proximate analysis, moisture accounts for 48.4% of the total waste composition. Ashes account for 27% of the waste mass.

Table 4: Typical input waste characteristics in Cixi, China

Carbon	10 %
Hydrogen	2.78 %
Oxygen	11.3 %
Nitrogen	0.44 %
Sulfur	0.22 %
Ash	26.86 %
Moisture	48.4 %
Net Heating Value	3,980 kJ/kg

ii. Excess air amount

With the chemical composition given in Table 4, when calculating how much oxygen is needed at 0% excess air to burn C to CO_2 and H to H_20, one can find:

$$Air\_required = \frac{1000kg/t \times \left(\frac{10\% \times 2}{0.012} + \frac{2.78\%}{0.001 \times 2} - \frac{11.3\%}{0.016} \right)}{21\%_{O2concentration\_in\_air}} \times \frac{22.4}{1000} m^3/mole = 2{,}511 m^3{}_{air}/tonMSW$$

This means that out of the 2553m^3/ton of air supplied in the design, 2,511m^3/ton are required for stoichiometric combustion. Therefore, a 2% excess air is calculated with this method. It is very different from data given by Zhejiang University: 40% excess air. This underlines that the formula $C_6H_{10}O_4$, usually applied for American waste (Themelis, 2000), is not valid in this case. Indeed, when calculating the formula from the waste characteristics given in Table 4, we find the following formula: $C_6H_{20}O_5$. This underlines the fact that the waste is very different in its composition from typical American waste.

Additionally, when looking more closely at the excess air amount of 40%, it is notable that this amount is considerably lower than the usual 80-90% excess air in moving grate WTE reactors. This low number, enabled by better mixing in the reactor, is implemented mainly to reduce heat losses. A lower excess air requirement is a characteristic of CFBs as also noted by Leckner (Leckner, 2014), even though he also notes that some state-of-the-art MG plants achieve excess air ratios of 40%.

iii. Dimensions and process engineering

Pre-treatment

Raw waste is discharged from trucks into a huge concrete bunker, where cranes pile it up in the middle part of the bunker for storage. The same cranes transport the waste to the two shredders that are reversible M&J Metso shredders, which shred the waste in small particles (less than 15cm) which then fall back at each end of the bunker, forming two piles of shredded waste under each shredder. Cranes grab once again the waste, now shredded, and drop it in the furnace hopper, where a conveyer belt directs it to the furnace. The desirable particle size for MSW feed is 15cm, and shredders provide such small particles. It is important to note that no other treatment than shredding is necessary: no pre-screening is done. The only thing that may be required from time to time is to remove unshreddeable chunks that block the shredder operation. This happens very seldom though.

The cutting rolls of the two shredders have to be sharpened every 500h. During maintenance of one shredder, the other shredder of the plant continues to shred waste, so that the plant can keep on with continuous operation. This maintenance requirement results in the fact that, most of the time, one shredder is functioning while the other one is being repaired.

Furnace

There is no risk of hot air coming out of the furnace through the conveyer belt because the waste entrance in the furnace is located at a height where the pressure is lower than the atmospheric pressure. This setting enables to avoid the use of a piston like in typical WTE MG plants. A schematic is presented in

Figure 10. Some outside air leaks into the furnace through the conveyer belt, but this amount is kept to a minimum.

Bottom ash exit

The bottom exit for bottom ash consists of two holes of 400mm by 600mm. A system of gravitational sieves enable to select smaller particles in the bottom ash flow and to recirculate them inside the main furnace to ensure complete combustion. Bigger particles are sent directly to the bottom ash pile, as they are usually large particles of metal and stone that will not burn anyway (Figure 10). This bubbling bed enables to avoid fresh waste coming right to the bottom exit and going out in the bottom ash without being combusted.

Also, Prof. Hung suggested thatsome of the fly ash coming out after the high-temperature air preheater can be considered as bottom ash, since its toxicity levels are low enough.

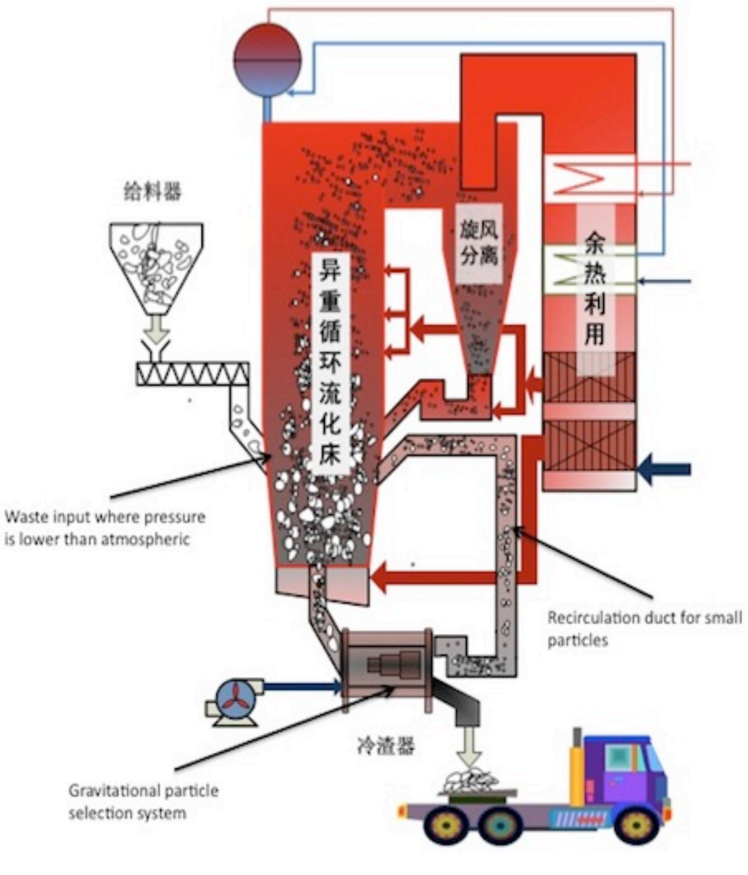


Figure 10: General schematic of the CFB reactor

Leachate disposal method

On average for the Cixi plant, the waste stays three days in the bunker where some leachate collects at the bottom of the bunker and has to be taken care of. Leachate coming out of the bunker is treated in a wastewater treatment plant onsite.

Dimensions

From Table 3 it is important to note the difference in grate area between the two technologies. The compactness of FB reactor enables it to have a much higher heat release (1.69 MW/m^2 compared to 1.01 MW/m^2 for MG), which reduces significantly the capital cost of the metals and refractories used to construct the combustion chamber as well as operating expenses for its maintenance. McDougall et al. (McDougall, 2001) also noted this characteristic of CFB plants.

iv. Overall plant efficiency

About 34 tons of superheated steam (485°C, 5.3Mpa) are generated per hour in the whole Cixi plant (2,300 tons/day) and since this steam is mixed in the same pipe for the four units of Cixi, it is difficult to calculate the exact power output of the 800 ton/day unit. A rough estimate of the power output is around 9.3 MW.

The thermal efficiency (electricity produced over energy input of the waste) is therefore around 25%, which is slightly higher than an MG unit fueled with higher energy fuel. In terms of boiler thermal efficiency, 70.2% of the heat contained in the waste is transformed into steam at Cixi.

Parasitic loads (crane, conveyers and shredders loads) for the Cixi plant equal approximately 20% of the total electricity produced.

2. Particle properties

i. Circulation inside the bed

When taking into account the measured concentration of particles entering the cyclone separator (3.96 kg/Nm^3) and the flue gas flow (85,000 Nm^3/hr) one can derive a 336 tons/hour of carryover, circulating material. This corresponds to about 10 times the feed input flow of waste in the reactor. This huge number is quite breathtaking and enables one to realize the truly "circulating" characteristic of this reactor.

While smaller particles are carried many times in the circulating flow through the reactor and the cyclone separator, particles that are too large to be carried in the gas flow are engaged in bubbling flow in the bottom part of the reactor and eventually leave in the form of bottom ash and they are not carried over even once. Therefore, some small particles actually circulate much more than 10 times through the recirculation path.

ii. Residence times

First, we will try to quantify the total mass inside the reactor at any time. This can be done by using the height of the fixed bed, when the reactor is shut down for some reason. This has been measured to be in the range of 1.2 to 1.5 m. Assuming a bulk density of 2 tons/m^3, and an area at the bed distributor of 10m^2, the mass inside the furnace at any time is around 30 tons.

Based on the mass of waste inside the reactor at any time - around 30 tons - and based on a feed flow of 33.3 tons/hour (800 t/day), a 54 minutes residence time of waste inside the bed can be derived for an average particle entering the reactor. This is comparable to Moving Grate (MG) reactors that usually have a 1-hour residence time.

However, the residence time varies with particle sizes.
We shall now try to estimate the residence times for heavy particles (in bubbling bed) and for circulating particles.
The input feed is 33.3 tph. This mass flow can be assumed to consist of two parts: one flow that is made of particles engaged in circulating flow and the other of particles engaged in the bubbling bed flow. We can estimate these flows based on the ash content (F stands for mass flow):

$$Flow_{circulating} = F_{feed} \times \frac{F_{flyash}}{F_{bottomash} + F_{flyash}} = 14.5tph$$

$$Flow_{bubbling} = F_{feed} \times \frac{F_{bottomash}}{F_{bottomash} + F_{flyash}} = 18.8tph$$

Circulating material

The amount of circulating waste is equal to:

$$M_{circulating} = 3.96kg/Nm^3 \times (\# Nm^3{}_{inside\_furnace})$$

The volume of the furnace is 366m^3 without accounting for the recirculation duct. Let us assume that the total volume of the reactor is 400m^3. This equals to 97Nm^3 at 850°C. Then, multiplying by the particle density in the upper reactor (3.96kg/m^3), the total weight of circulating material inside the furnace is 0.385tons. Therefore, the mass of solids engaged in circulating flow at any instant is one hundredth of the bubbling bed flow.
The residence time of the carried over material can be determined by:

$$\tau_{circulating} = \frac{0.385tons}{14.5tph} = 95.6\sec$$

Bubbling material

Because $M_{circulating}$ = 0.385 tons and M_{total} = 30 tons, $M_{bubbling}$ = 29.6 tons. Therefore:

$$\tau_{bubbling} = \frac{29.6}{18.8} = 1.58hour$$

The residence time in the bubbling bed amounts to approximately 1h30.

Gas residence time

The gas has a residence time of about 3.8 seconds in the furnace (16.8m height of reactor divided by the airf low velocity of 4.5m/s). It is therefore above the required residence time at high temperature of 2 seconds required by the U.S. Environmental Protection Agency (EPA) (2s); it is less than the average residence time in MG reactors (6-8 seconds). However, due to high turbulence and very flat velocity in a CFB reactor, the 3.8 seconds residence time is adequate..

iii. Particle size distributions

The particle size distributions of particles in the reactor and in bottom and fly ash are approximately the following:

- Fly ash: 1 to 100 microns
- Bottom ash: 1 to 50 mm
- Particles in the circulating flow (i.e. when the concentration of 3.96 kg/Nm3 was determined): 50 to 500 microns.

Figures 11 to 13 show some actually measured diagrams of particle size distributions of CFB fly ash.

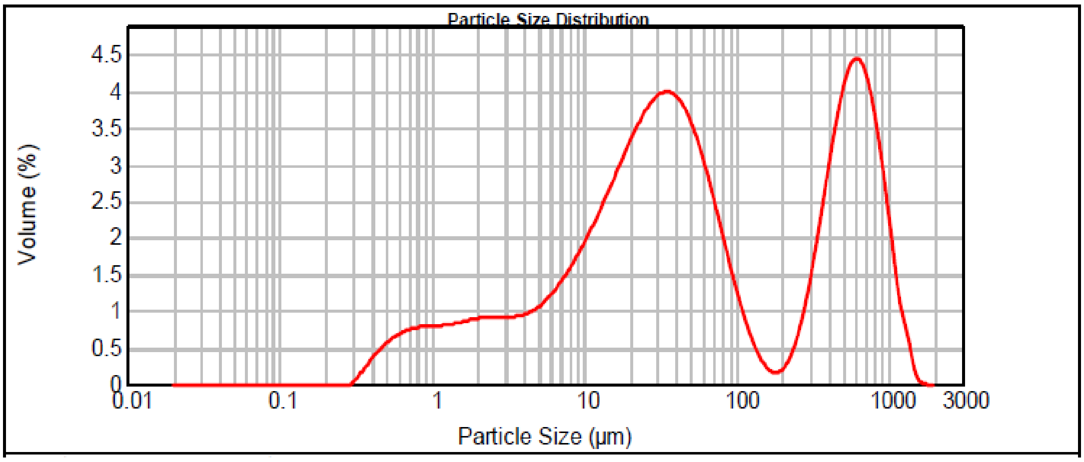


Figure 11: Particle distribution of sample collected at high temperature air preheater (private communication, Zhejiang University, July 2014)

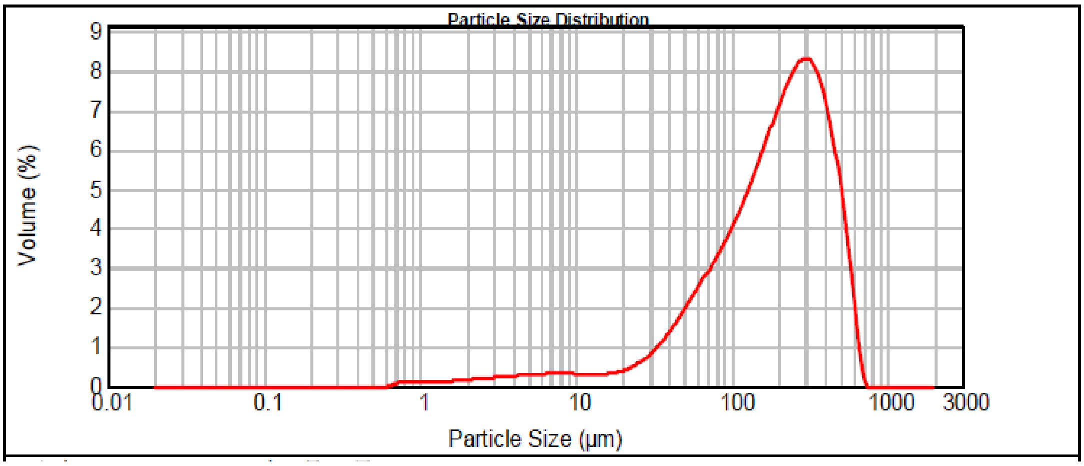


Figure 12: Particle distribution of sample collected at low temperature air preheater (private communication, Zhejiang University, July 2014)

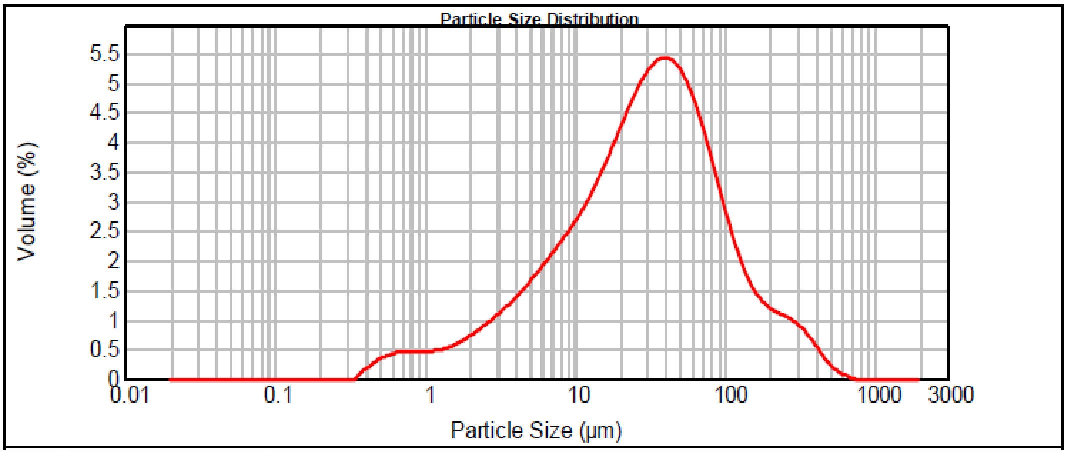


Figure 13: Particle distribution of sample collected at baghouse (private communication, Zhejiang University, July 2014)

iv. Calculation of the maximum size of carried over particles

A carried-over particle (one that will be transported from the furnace through the cyclone separator and back into the furnace) is subject to two main forces: the drag force and gravity (neglecting the buoyancy forces that are not significant in a low density gas like air). The mass of the maximum size of a particle to be lifted by the airflow is expressed by the following equation:

$$mg = \frac{1}{2} C_D \rho_g A U_t^{\,2}$$

where Ut is the terminal velocity (here the airflow velocity), A is the surface area of the particle, and C_D is a dimensionless coefficient. Therefore,

$$m_{\max} = \frac{1}{2g} C_D \rho_g A U_t^{\,2}$$

When the Reynolds number is comprised between 10^{-4} and 0.5 (particle diameter below 50μm), the Stokes law applies (Wark, 1993) and:

$$m_{\max} = \frac{12}{gd} \mu_g A U_t$$

where d is the diameter of the particle and Ut the viscosity of the gas

Because A = π*d²/4 and m=4/3*π* ρ *(d/2)3,

$$d_{\max}{}^{2} = \frac{18 \mu_g V_t}{g \rho_{particle}}$$

If we assume a particle density of 1000 kg/m3, and assume that the viscosity of the gas is $3.765.10^{-5}$ kg/ms at 850°C and the air density 0.331 kg/m3 (Engineering Toolbox, 2014), then

dmax = 358 μm.

This value exceeds the Stokes law range (Wark, 1993), but gives an approximation of the maximum diameter of the circulating particles.

In order to determine more accurately the maximum diameter, one needs to use equations beyond the Stokes law range; the following two equations can be used:

- The Air Pollution Prevention and Control book equation (Wark, 1993):

$$C_D = 0.22 + \frac{24}{\mathrm{Re}}\left[1 + 0.15\,\mathrm{Re}^{0.6}\right]$$

- Professor Fthenakis' class (Fthenakis, 2014) provided a slightly different formula:

$$C_D = \frac{24}{\mathrm{Re}}\left[1 + 0.14\,\mathrm{Re}^{0.7}\right]$$

These equations are not linear and must be solved using a tool like Excel. When doing so, the respective solutions are:

- **d_{max} = 922 microns**
- **d_{max} = 812 microns**

Therefore, the maximum particle size that will circulate around the combustion chamber is 800-900 microns. This number is in agreement with the CFB fly ash particle size distributions presented earlier.

v. Velocity inside the bed

As a reminder, the flow velocity inside the air distributor is 11.2m/s, while that inside the furnace is 4.5m/s.

Let us now consider the effect of increasing the furnace cross sectional area, from 21.8 m^2 to A square meters, thus reducing the superficial gas velocity, on the cyclone efficiency. Therefore, the new gas velocity will be

U = 85,000*(850+273)/273/A/3600

A reduced velocity would have two effects:

- First, it would reduce the size of particles that would be carried out of the reactor (see equation presented earlier that applies under Stokes law)

$$d_{\max}{}^2 = \frac{18\mu_g V_t}{g\rho_{particle}}$$

- Second, if the cyclone size remained the same, it would decrease the cyclone efficiency. According to the Air Pollution, Its Origin and Control textbook (Wark, 1993) the cyclone efficiency is proportional to the air velocity:

$$\eta = \frac{\pi N V_g d^2 \rho_p}{9 w \mu}$$

These two effects would act in opposite directions for the fly ash content. Overall one can think the effect of reducing the velocity would not be beneficial. Indeed, bigger particles would less be carried over, but they are well captured by cyclones (Wark, 1993) whereas small particles would still be carried over and the cyclone efficiency would be decreased for small particles in particular. Therefore the overall amount of fly ash should be increased, which is not desirable, as will be discussed later.

3. Comparison of ash generation

Using Cixi plant data, and based on the reported after-cyclone particle concentration of the flue gas (0.0454 kg/Nm3), a fly ash flow of approximately 3.86 tons/hour is derived. This represents 12.8% of the input feed and is four times greater than the 3% of MG reactors. This is caused by the very high rate of recirculation of the circulating bed (about 10 times per circulating particle on average). Indeed, even if the cyclone has a very high efficiency, the fact that it has to handle 10 times the MSW feed rate results in a considerable amount of fly ash, when it is expressed in terms of percentage of this 33.3 tph input rate.

In addition, data provided by Zhejiang University indicates that the bottom ash amounts to 16% of the MSW feed. Thus, the total CFB ash generated adds up to 28% of the waste input, which is a little more than the 25% of MG reactors. This could be due to waste input differences.

In the Cixi plant, the exact fly ash production rate is 3.86 tph while the recirculation rate is 336 tph. These figures enable to calculate the cyclone separator efficiency: 98.5%. It can be seen that if the recirculation rate were to be cut, for example, to 150 tons/hour, at the same cyclone efficiency the fly ash generation rate would also be cut by one half.

Sources of Cixi ash

Considering the relatively high amount of organic wastes and moisture in the Cixi MSW, the fact that the total ash generation is nearly the same as in U.S, MG plants is rather surprising. It is interesting to probe what are the ash-producing materials in the MSW feedstock to Cixi - e.g. from food, from plastics, etc. First, we will compare the Cixi total ash output of 27% to other WTE plants in China.

According to the Huang et al paper on circulating fluid beds (Huang, 2013) the waste in Beijing, Shanghai and Hangzhou has the composition shown in Table 5; also, on the basis of the World Bank study (World Bank, 1999) the ash content of these types of MSW is calculated and shown in Table 5.

Table 5: Derivation of the amount of ash in Chinese waste from its composition

	Ash as a percentage of wet waste (%) (World Bank, 1999)	Beijing		Shanghai		Hangzhou	
		Waste breakdown (%) (Huang, 2013)	Quantity Ash (%)	Waste breakdown (%) (Huang, 2013)	Quantity Ash (%)	Waste breakdown (%) (Huang, 2013)	Quantity Ash (%)
Food	4.52	64.48	2.92	62.83	2.84	67.10	3.03
Paper	2.97	6.71	0.20	8.57	0.25	7.81	0.23
Plastics	5.54	8.12	0.45	10.83	0.60	9.61	0.53
Textile	2.68	1.22	0.03	4.17	0.11	1.05	0.03
Wood	3.38	0.05	0.00	0.96	0.03	3.45	0.12
Glass	97.00	2.02	1.96	2.17	2.10	0.97	0.94
Metal	94.00	0.31	0.29	0.00	0.00	0.33	0.31
Others	90.00	17.09	15.38	10.47	9.42	9.68	8.71
		Total	**21.23**	**Total**	**15.37**	**Total**	**13.91**

This estimation is relatively basic, and sensitive to the “Others” category. We find a total ash content of 13.91% to 21.23% (as a percentage of the wet waste input). These numbers do not match the Cixi ash generation of 27% ash.. This must be due to a lot of residential ash and/or soil finds its way to the Cixi plant, instead of a construction and demolition landfill.

Lastly, the reader is referred to a paper in the literature that compares ash properties from fluidized bed and moving grate reactors (Chang, 2006). A lot of useful information is present in this paper, notably the difference in particle size distributions in bottom and fly ash, due to different agglomeration processes. This article notably underlines that FB fly ash is less toxic than MG and Rotary furnace fly ash.]

2.2.1. Conclusion of the comparison

1. General comparison

Table 6 compares the characteristics of MG and CFB WTE units that were discussed in the previous section of this thesis. Important results on ash content, residence times and excess air amount on the two types of technologies (a typical U.S. moving grate WTE and the 800t/day Circulating Fluid Bed reactor located in Cixi, China are summarized in Table 6. As noted earlier, the ash amounts are radically different; excess air amounts and gas residence times are significantly different as well; and particle residence times are comparable.

Secondly, as explained above, the compactness of the FB reactor significantly participates in the reduction of capital and operating costs achieved by CFBs reactors. Also, the compactness, associated with a higher superficial velocity in the CFB unit results in a lower gas residence time than in the MG plant. However, for CFBs, the low gas residence time still complies with minimum gas residence time imposed by environmental regulators (the EPA in the US) due to the higher turbulence and flat velocity profile in the CFB reactor.

Table 6: Combustion parameters for Cixi and typical MG plants, derived from calculations above

Plant	Typical results for MG WTE units	The Cixi CFB unit
WTE technology	MG	CFB
Fly ash amount (as a percentage of waste input)	3%	12%
Bottom ash amount (as a percentage of waste input)	22%	16%
Average particle residence time	1 hr	54 minutes
Average gas residence time	8 seconds	3.8 seconds
Excess air amount	80 - 90%	40%

It is interesting to note that the low velocity in the MG furnace is achieved in spite of the increased excess air requirements by MG plants (80 - 90 % versus 40%), because of the much larger furnace cross section area.

Also, as noted above, a huge difference between MG and FB technologies is the fact that waste has to be pre-treated prior to entering the FB reactor. This simpler operation of the MG explains in large part, the dominance of the MG technology: shredding adds complexity to the process and the industry has been resistant to using shredding for MG plants.

Shredding can increase capital cost significantly, especially when it has to be done in a separate building. Despite the increased costs, some companies have a separate building to shred the waste. RHKW is one of them, as shown in Figure 14, that is a photograph of a plant in Linz, Austria.

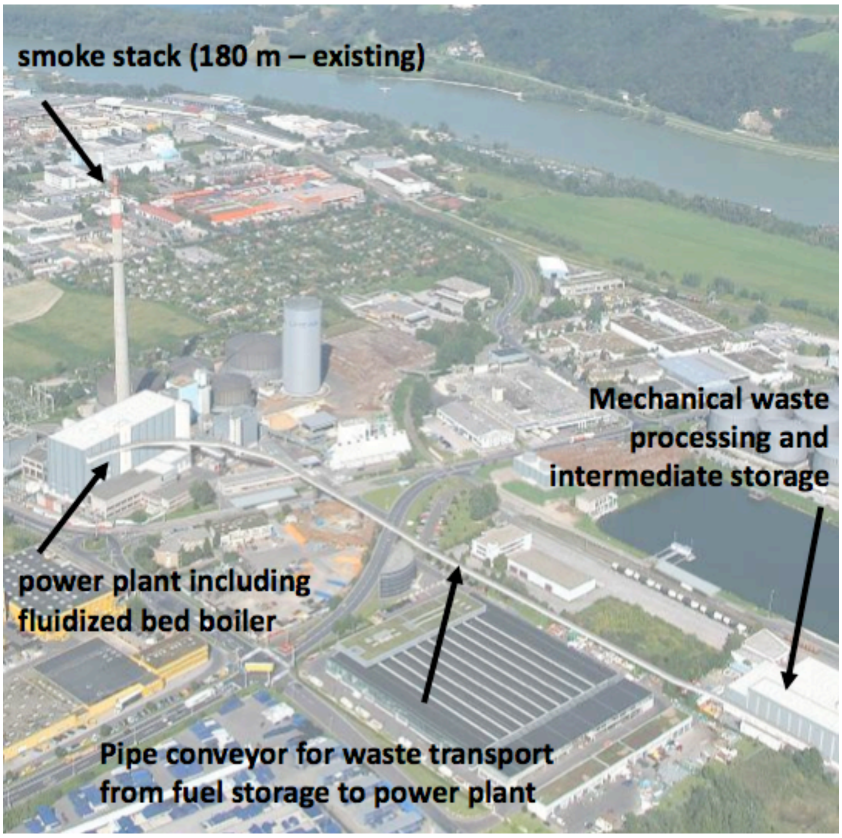


Figure 14: Overview of Linz plant, Austria (Neubacher, 2012)

Some other designs, like Energos (Ellyin, 2012), Strabag (Stragab, 2012) and the CFB technology of Zhejiang University include the shredding process in the same building as the fluidized bed, often just upstream of the garbage pit. Figure 15 shows an example of how it can be done. Other companies such as Andritz, Metso do not state clearly how the shredding process is done.

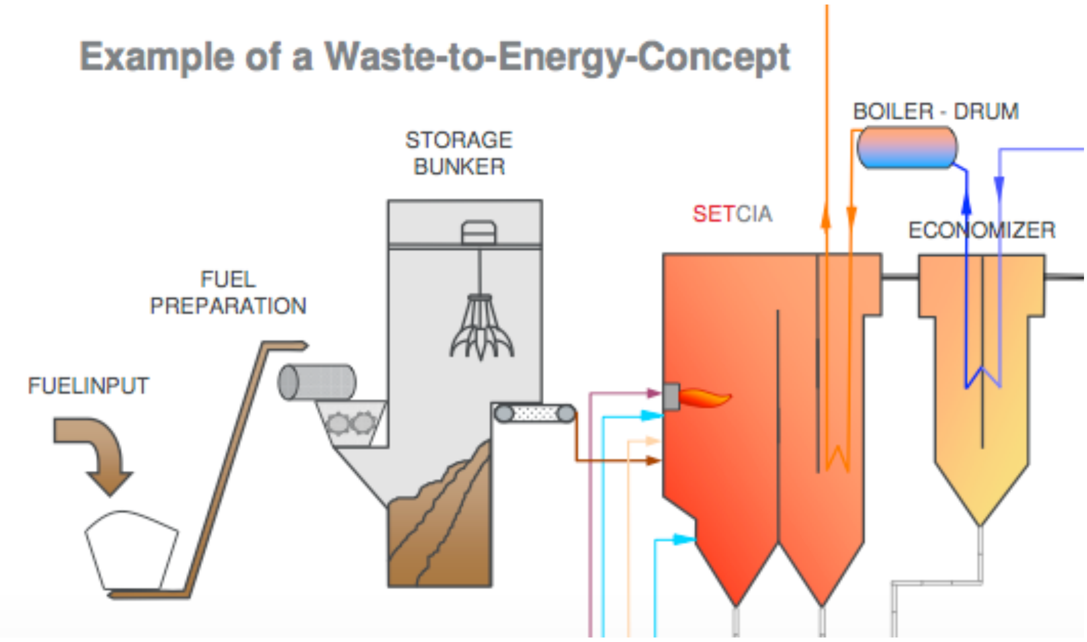


Figure 15: Fluidized Bed Process with Shredding (Strabag, 2012)

As a final point, the comparison of these technologies has shown that ash repartition between fly ash and bottom ash amounts is very different. Even if the overall ash output of both technologies is comparable, CFB has much more fly ash (42% of overall ash mass) than MG (12% of overall ash mass). The latter point will be the subject of the third part of the present document.

2. Comparison in the context of burning high-moisture waste

This section takes into account the characteristics of the MG and CFB processes, presented in the previous section in an effort to understand how the moving grate technology acts under a high moisture waste environment, using the characteristics for typical waste input in Cixi (presented in Table 4).

In order to understand the challenge of burning very wet waste, such as the CiXi MSW (moisture – 48.4 %) we shall calculate the percentage of the heating value of the MSW that is needed to evaporate the moisture contained in the waste, at 40°C:

$$P = \frac{HV_{needed}}{HV_{waste}} = \frac{0.484 \times \left[2{,}257 + (100^{\circ}C - 40^{\circ}C) \times 4.186\right]}{5{,}000} = 24.3\%$$

In other words, almost one fourth of the chemical heat of the waste is used to dry up the waste.

The solution to evaporate the moisture varies between the two technologies. The CFB solution is to shred the waste. Once shredded and introduced into the bubbling bed, the water evaporates fast, and there is no need for pre-drying or other process to reduce moisture in the MSW of any additional removal process. The fact that shredding is sufficient to enable moisture to be removed can be seen in the very high combustion efficiency: more than nine tenth of the combustible material are effectively combusted in Cixi plant.]

However, when very wet and as-received MSW is loaded onto a moving grate, there is very little or no mixing and it takes a large part of the grate for the MSW to be heated and its water content to evaporate. Therefore, in order to burn the waste efficiently, solutions that can be adopted are the following: increasing the grate length (Yongfeng, 2008), so that water has more time to evaporate, or get rid of the water before the reactor, that is by allowing drainage in the bunker. For the latter solution large quantities of leachate need to be treated and disposed, which is an additional burden to the operation (Needigest, 2014, Yongfeng, 2008).

The solutions that have been adopted by moving grate reactors for processing high moisture and very low heating value MSW increase, such as increasing the width and the length of the grate, increase the capital and operating costs of the WTE plant. Also, treating and disposing of the leachate collected in the bunker is costly (Yongfeng, 2008).

In summary, it seems that CFB is more sustainable and cost competitive than MG for burning high-moisture waste. The only disadvantage of the CFB technology is the high fly ash amount. The third part of this thesis will address this issue and suggest some possible solutions to alleviate this problem.

3. Possible solutions to reduce fly ash proportion in CFB reactors

The WTE fly ash contains the volatile metal and dioxin/furans removed from the flue gas in the Air Pollution Control (APC) system. In the U.S., the bottom and fly ash amount to approximately 20-25% of the MSW feedstock; these two streams are mixed and called “combined” ash. This combined ash passes the very stringent Toxic Contaminant Leaching Procedure (TCLP) of EPAand is used in sanitary landfills as Alternate Daily Cover and for maintenance purposes. Apparently, the unused calcium oxide used in the APC scrubbers immobilizes the volatile metals and other contaminants in the fly ash.

In China and in some European Countries, fly ash and bottom ash are separated and have different end of lives. While bottom ash passes the TGLP test and can be used beneficially to build roads or to manufacture construction material; in contrast, the fly ash contains heavy metals and dioxins that make it a hazardous waste. In Europe, the fly ash is stabilized chemically or is disposed in extinct salt mines. Disposing of fly ash is much more costly than disposing of bottom ash, per unit weight. It is, therefore, very important to reduce the amount of fly ash produced per ton of MSW combusted. In the near future, it is envisaged that in the U.S. the WTE bottom ash will also be used beneficially outside landfills. Under these circumstances, the high fly ash fraction generated in the CFB process is not acceptable and poses a serious hurdle to the export of the CFB technology to other countries.

This part presents experiments that were conducted to test methods that can reduce the fly ash amount. The objective of fly ash reduction is to reach a typical MG fly/bottom ash repartition, i.e. 3%/22%.

3.1. Material and Methods

In order to evaluate methods to reduce the fly ash amount in CFB reactors, the following experiments were conducted at Zhejiang University during the author's summer internship there. A laboratory-scale simplified furnace was designed and manufactured, as presented in Figure 16. From bottom to top, the base case system contained the following elements: electric air pump equipped with a flow meter, air distributor, cylindrical furnace, liaison duct, cyclone and exit duct. The bed material was put in the main furnace, and the air blown with the air pump at the bottom.

In comparison with this base case, three fly ash reduction systems were tested: addition of U-beams in the exit duct, directly downstream of the main furnace, before the cyclone separators, addition of a second cyclone in series downstream of the first one, and a combination of the latter options. These three systems are described in Figure 17 to Figure 19.

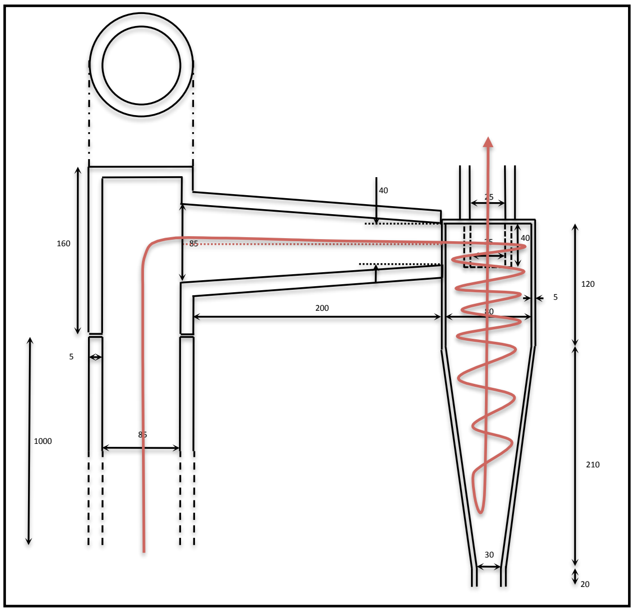


Figure 16: Schematic of the base case furnace - in red airflow

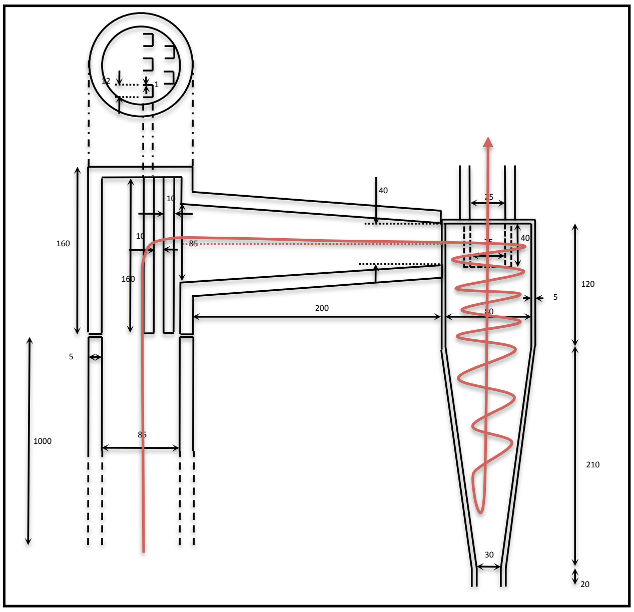


Figure 17: Schematic of the U-beam equipped furnace - in red airflow

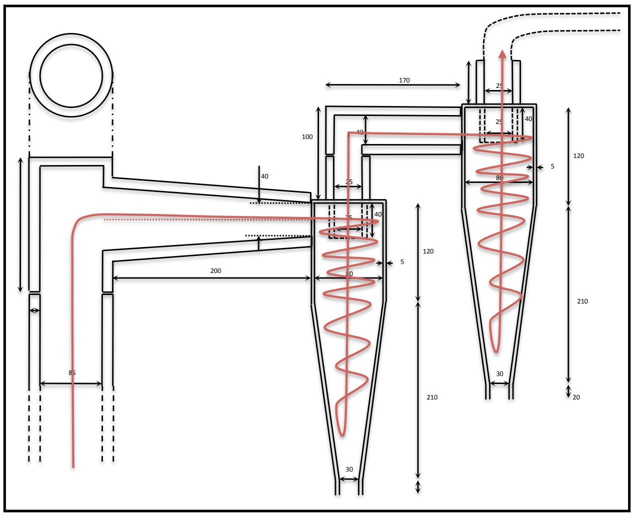


Figure 19: Schematic of the two-cyclone furnace - in red airflow

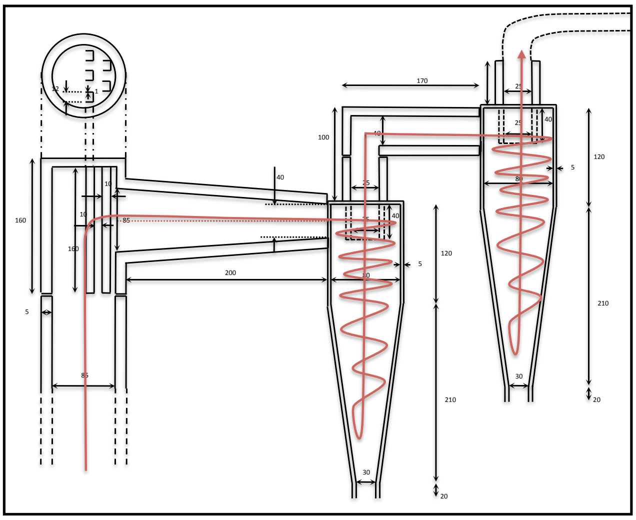


Figure 18: Schematic of the two-cyclone and U-beam equipped furnace - in red airflow

For each of these settings, three air flows were tested: 10 m^3/h, 15 m^3/h, and 23m^3/h, respectively corresponding to velocities of 0.49 m/s, 0.73 m/s and 1.13 m/s inside the main part of the combustion chamber, that is, also corresponding to velocities of 3.48 m/s, 5.22 m/s and 8 m/s at the cyclone inlet. For each of these flow rates, the weight of ash at the bottom of the 1st and 2nd cyclones was measured for several points in time.

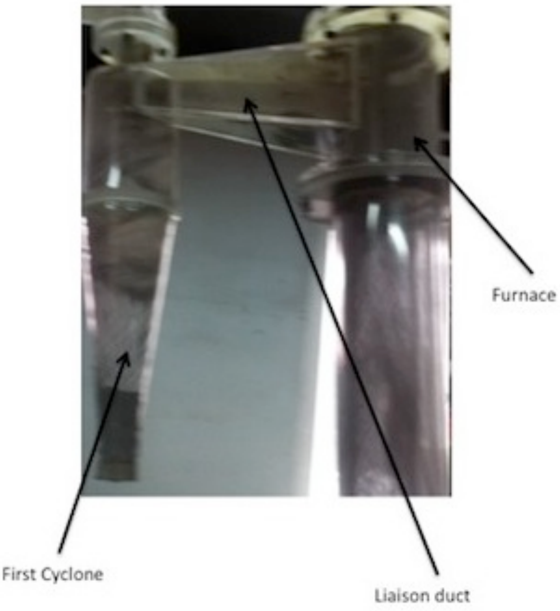


Figure 20: Photo of the furnace and first cyclone during an experiment

Figure 21: Checking the flow meter

Figures 20 illustrates how the bed material travels from the main furnace into the liaison duct, through the cyclone and out to the flue gas outlet pipe. In Figure 21 one can see the flow meter used to measure the airflow before it reaches the bottom of the furnace. The flow meter was located just downstream of the air pump.

Figure 22 illustrates how the U-beam system works: bed material particles agglomerate into chunks in the U-beam. Once the gravitational forces overcome forces that make the chunk stick to the beam, the lump of particles falls back into the furnace.

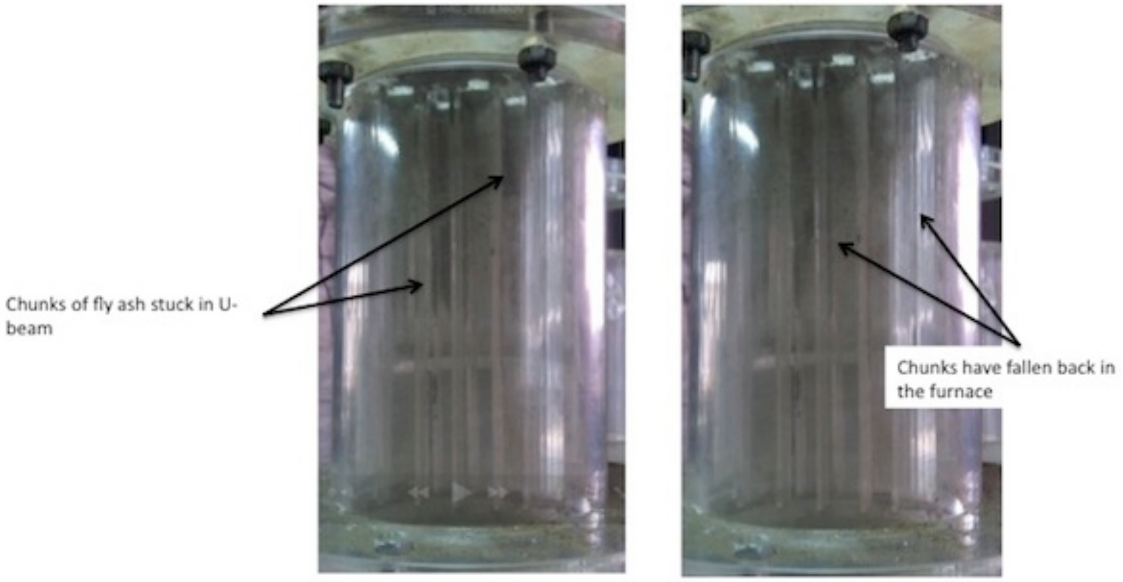
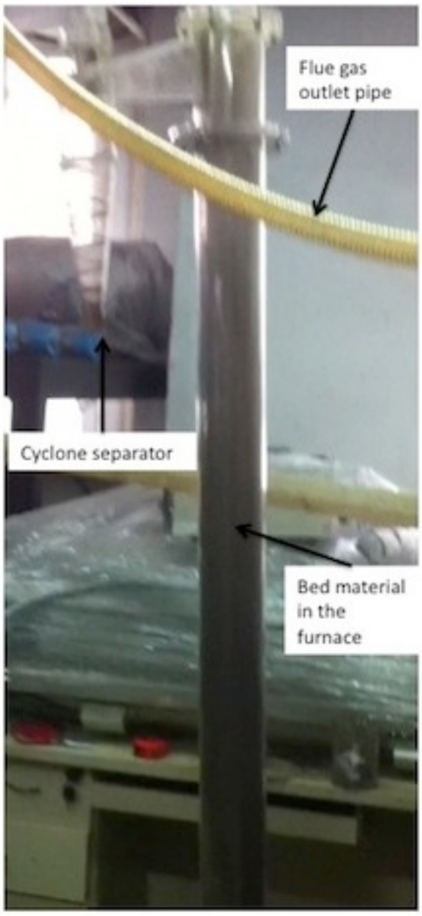


Figure 22: U-beam operation mechanism illustrated



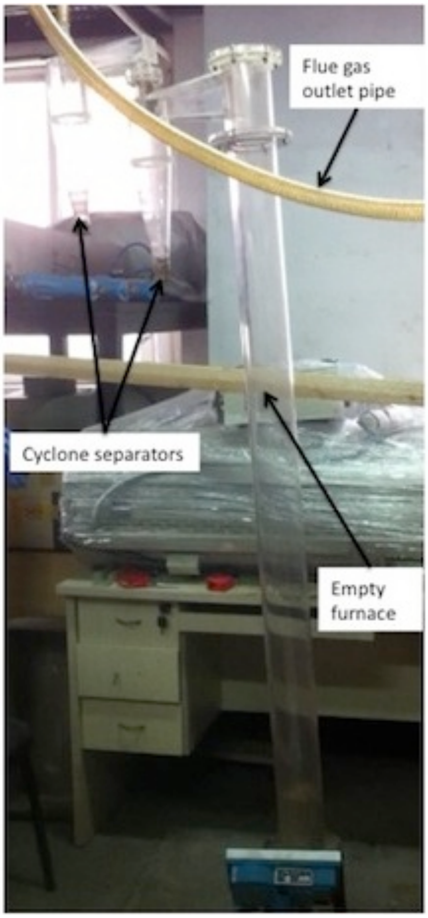


Figure 24: Photo of the empty furnace and of cyclone separators

Figure 23: Photo of the furnace with circulating bed material

Figures 23 and 24 illustrate the setting of the experiments, with the main furnace, the cyclone separators and the flue gas outlet pipe.

The bed material was fly ash from Cixi CFB plant. It had the characteristics given in the previous part of this document in terms of particle size distribution.

3.2. Results

3.2.1. Addition of a second cyclone in series

Background
This solution is based on the fact that efficiencies add up for cyclones in series. However an important inconvenient of this option, in addition to the cost of the extra cyclone, is the increased pressure drop of the whole system, that increases power costs of the fan.
Let's calculate the theoretical increase in pressure drop. Wark et al. (Wark, 1993) give the following equation for pressure drop:

$$\Delta P = \frac{V_g^{\,2}\rho_g}{2g\rho_L} K \frac{HW}{D_e^{\,2}}$$

with the following parameters: V_g the inlet gas velocity, ρ_g the density of the gas, ρ_g the density of the liquid in which is expressed the pressure drop (e.g. water for inches of water), K is a constant depending on the type of cyclone, H, W and D_E being cyclone proportions (height, width of the cyclone inlet, and diameter of the cyclone outlet).

Applying this equation to a model of cyclone built in the laboratory for experiments gives, at 20°C:

$\Delta P = \frac{8^2 \times 1.18}{2 \times 9.81 \times 1000} 16 \frac{40 \times 20}{25^2} = 0.078 m_{water}$ Or, in millibars: $\Delta P = 7.65 millibar$

This theoretical calculation of the pressure drop increase is valid for each additional cyclone.

Experimental results

Pressure drop results are in good agreement with the theoretical calculations above. Indeed, the pressure drop incurred by the second cyclone was measured at 5.7 millibars with U-beams, and at 6.95 millibars without U-beams.

Now let's look at the results of the addition of a second cyclone on particle separation efficiency. Figures 25 and 26 summarize those results.

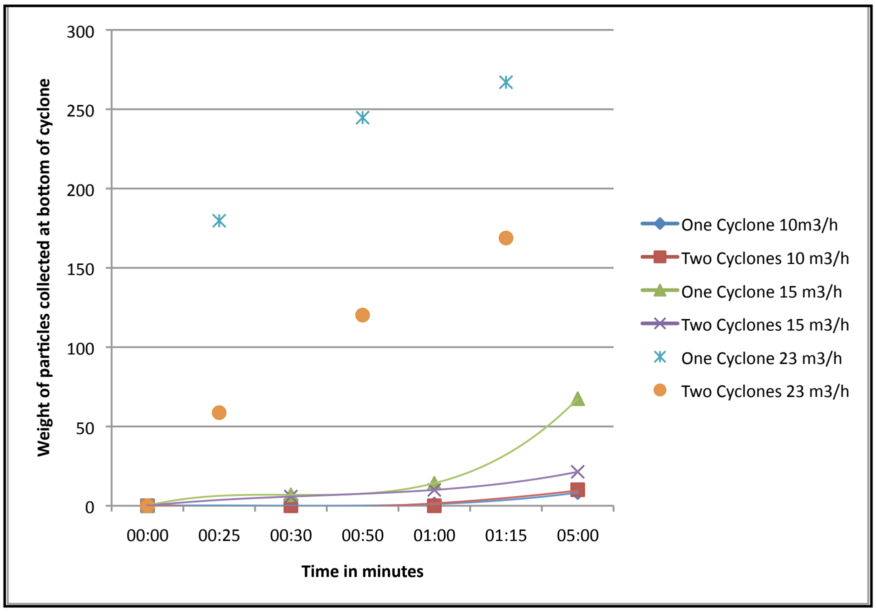


Figure 25: Comparison of particle collection with one and 2 cyclones, without U-beams

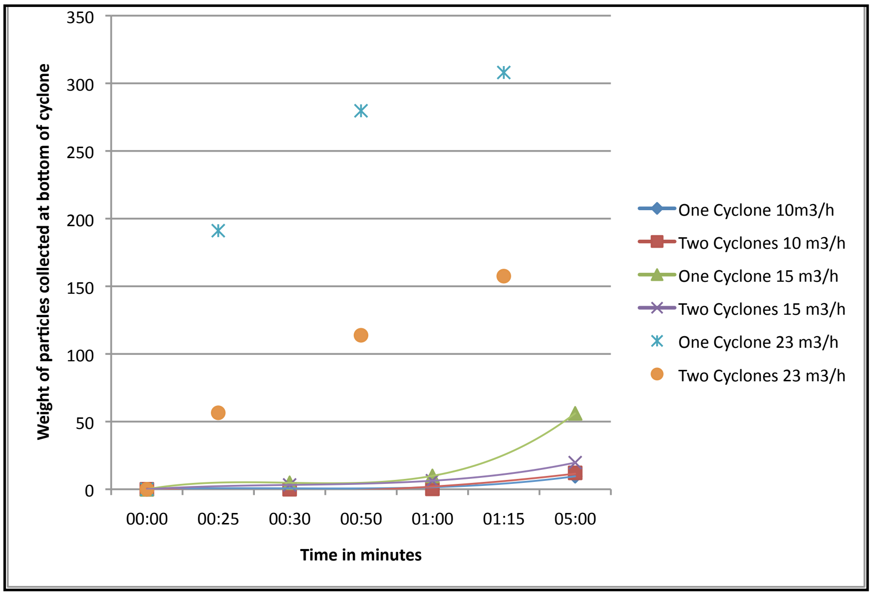


Figure 26: Comparison of particle collection with one and two cyclones, with U-beams

3.2.2. Addition of U beams upstream of the recirculation path

The idea here is to use the flue gas velocity at the top of the reactor before the cyclone entrance, to collect the particles on beams shaped in U. Figure 27 explains the way the beams were manufactured at a laboratory scale.

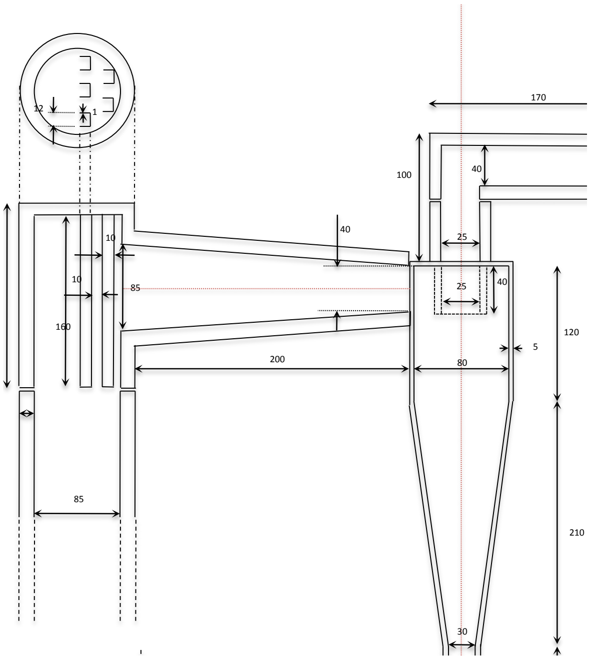


Figure 27: Drawing of the U-beam system

The inertial forces make the biggest particles hit the beams before entering the cyclone. They are trapped by the U-shape of the beam, then agglomerate with other trapped particles, before going down the beam due to gravitational forces, when a big enough chunk has formed.

The overall system efficiency is therefore the combination of both the efficiency of the U beam system, and the cyclone.

Pressure drop results are displayed in Table 7 and show an incurred decrease in pressure of approximately 10% (except one case where a measurement imprecision must have wronged the result).

Table 7: Pressure drops due to the addition of U-beams

Airflow	Pressure decrease with one cyclone	Pressure decrease with two cyclones
10 m³/h	11.2%	9.1%
15 m³/h	11.1%	-8.5%
23 m³/h	14.3%	2%

Now let’s look at the increase in particle collection efficiency due to this U-beam device in Figures 28 and 29.

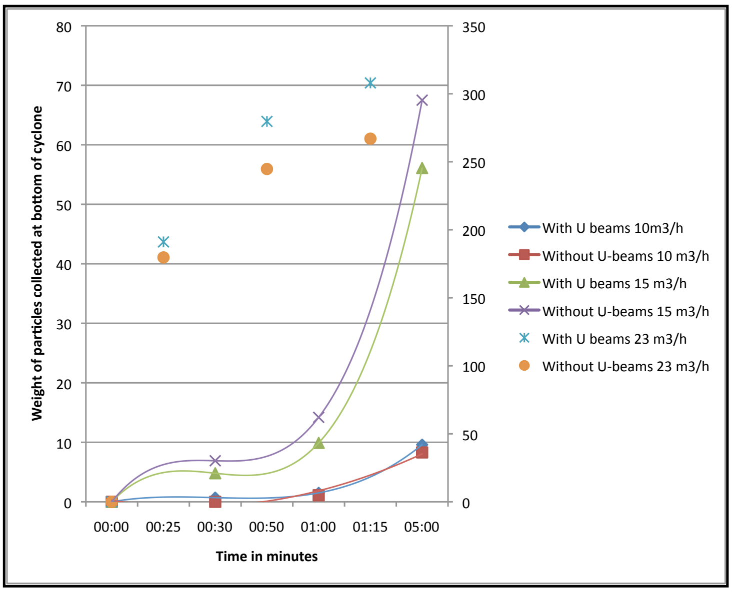


Figure 28: Comparison of particle collection with and without U-beams (one cyclone)

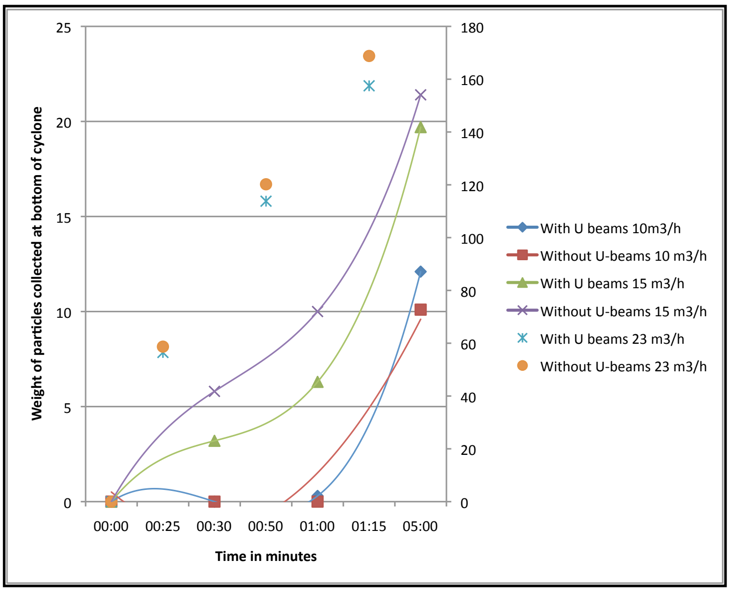


Figure 29: Comparison of particle collection with and without U-beams (two cyclones)

3.3. Discussion

Figures 25 and 26 show that the addition of a second cyclone is very efficient in reducing the amount of particles collected at the bottom of those cyclones. However, this is mainly due to the pressure drop that is caused by the addition of the second cyclone. Indeed, when adding the second cyclone, the latter only collects very few particles: not more than one gram out of 300g, as shown in Figure 30.

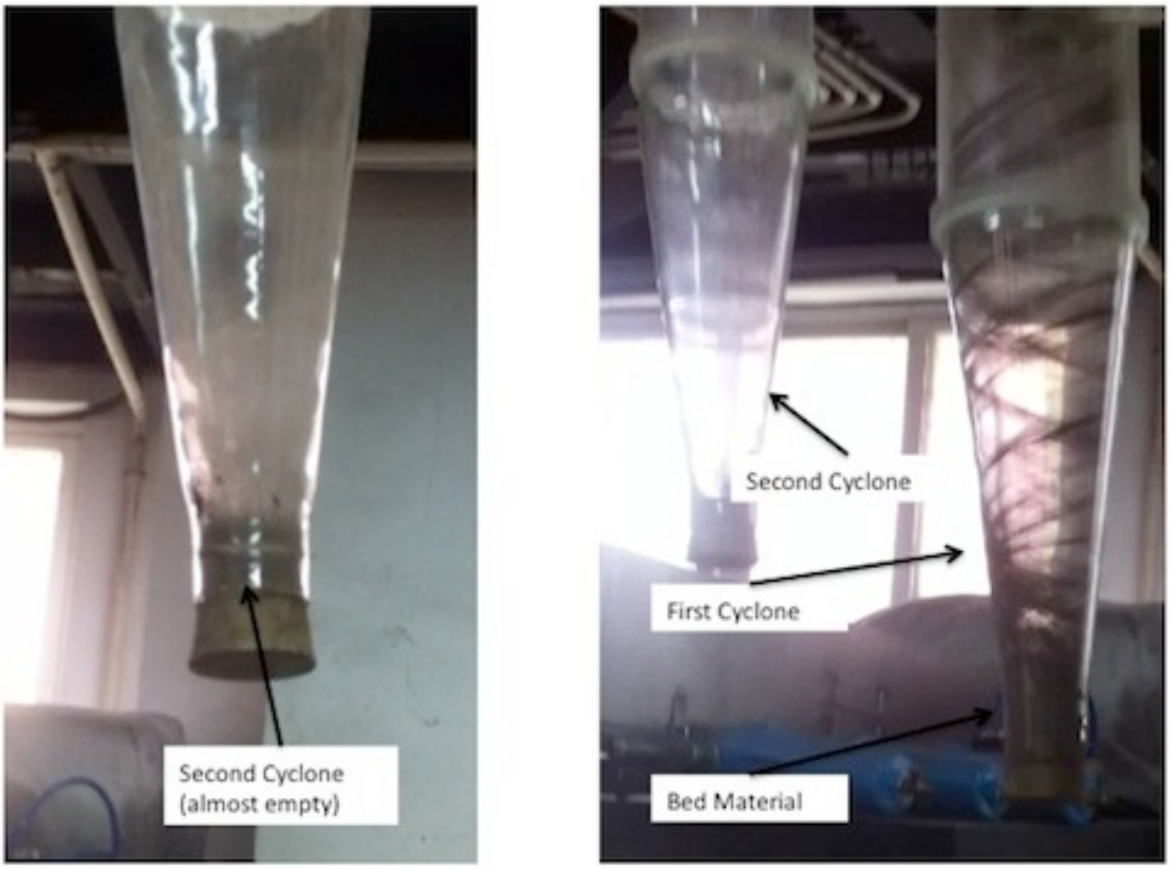


Figure 30: Photos of cyclone separators during experiments

What can be concluded from this experiment is that the second cyclone is efficient in reducing the particle amounts that go to the APC only because it reduces the pressure in the exit ducts. However, when looking only at the second cyclone performance, it seems inefficient and only collects a maximum of 2% - on average 1% - of the particles collected in the first cyclone. However, this amount is consistent with the first cyclone efficiency of 98.5%, and this additional collection can make a big difference in the fly ash generation of an actual industrial plant: even if the second cyclone collects 1% of what the first cyclone collects, the amount of fly ash will undergo a threefold reduction - from 1.5% to 0.5% of incoming particles. Of course, the presence of a second cyclone will increase the pressure drop of the system and electricity consumption but this may be justified by generating less fly ash.

The test results presented in Figures 28 and 29 display a decrease in particle collection at the bottom of cyclones for most of the airflows. At 15m^3/h, this decrease was observed in all tests and ranged from 8% to 45%. For 10m^3/h, it is less clear but the very low quantities of particles collected may be responsible for imprecise results.

The 23m^3/h results are harder to interpret since with one cyclone the presence of U-beams increased the particle collection while with two cyclones the U-beams had the opposite effect. This may be due to the fact that with one cyclone the pressure and airflows were so high that the effect of the U-beams was masked.

Overall it seams that U-beams are efficient in reducing particle amounts downstream of the duct connecting the furnace and the cyclone, and therefore in reducing fly ash amounts, for medium airflows - that is not too small and not too large. Additionally, this device doesn't incur a very large pressure drop and therefore should reduce fan power requirement.

Conclusions

This thesis has explored the combustion of municipal solid waste in waste-to-energy power plants and has included a comparative assessment of the two main WTE technologies used in the world: Moving Grate and Circulating Fluidized Bed reactors. A specific advantage of the CFB technology is its ability to burn high-moisture waste efficiently and, also, the very high heat flux per square meter of combustion chamber cross section. A CFB disadvantage is that it produces a large amount of fly ash (about 12% of the weight of MSW processed), in comparison to the moving grate systems (about 3% of the MSW) . However, it is believed that the CFB fly ash can be reduced by altering the cyclone configuration after the combustion chamber. Some preliminary experiments on reducing the fly ash generated in the Zhejiang University 10 ton/day CFB pilot system were carried out by the author in collaboration with Prof; Qunxing Huang of Zhejiang University and the results are presented in this report. The addition of a second cyclone was proven to be efficient in capturing the remaining fraction passing through the first cyclone, but at the cost of increased pressure drop a relatively high pressure drop cost. The U-beam system, on the other hand, has been shown to be an efficient system, which requires less additional power requirements than adding a second cyclone. Several solutions are proposed that may overcome this drawback, along with an estimate of their costs and benefits. This part also includes the description of experiments that were conducted by the author at Zhejiang University to evaluate the proposed solutions for reducing the fly ash fraction of CFB.

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Appendix : Environmental assessment

This part paves the path for an environmental assessment of both MG and FB technologies. It is not totally complete but presents several interesting results, articles and figures.

1. Literature review

1.1. Comparison of combustion to other waste management options

In terms of comparing combustion to other types of waste management, many studies have been published over the years. In 2009, J. Cleary conducted the most recent comprehensive review of LCA studies of solid waste management (SWM) scenarios (Cleary, 2009), analyzing 23 papers in 11 different peer-reviewed journals. This study dates back to 2009 and some new research papers have been published since, adding to the existing stock of SWM publications. Most of these are listed below.

- M.D. Bovea, V. Ibáñez-Forés, A. Gallardo, F.J. Colomer-Mendoza, Environmental assessment of alternative municipal solid waste management strategies. A Spanish case study, Volume 30, Issue 11, November 2010, Pages 2383–2395, 2010
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- H. Khoo, Life cycle impact assessment of various waste conversion technologies, Life cycle impact assessment of various waste conversion technologies, 2009
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- M. Banar, Z. Cokaygil, A. Ozkan, Life cycle assessment of solid waste management options for Eskisehir, Turkey, Volume 29, Issue 1, January 2009, Pages 54–62, 2008
- Massarutto, A. de Carli, M. Graffi, Material and energy recovery in integrated waste management systems: A life-cycle costing approach, Volume 31, Issues 9–10, September–October 2011, Pages 2102–2111, 2011

- S. Batool, M. Chuadhry, The impact of municipal solid waste treatment methods on greenhouse gas emissions in Lahore, Pakistan, Volume 29, Issue 1, January 2009, Pages 63–69, 2008
- G. De Feo, C. Malvano, The use of LCA in selecting the best MSW management system, Volume 29, Issue 6, June 2009, Pages 1901–1915, 2009

These studies, not analyzed in J. Cleary' paper, compare different scenarios, study different areas and scale, have different functional units, data sources, boundaries, goals for the analysis, and finally, present different results. In order to do a comprehensive review of these studies, one has to take into account these dissimilarities, and try to compare them on an even scale.

Let's look at the scenarios the studies are comparing.

Table 8: Scenario analyzed by each paper[1]

Paper authors	Scenarios analyzed in the LCA
M.D. Bovea et al.	Bs, Bs + different selective collection efficiencies + Biological treatment + LF
TC. Chen et al.	RE, ICR, LF, CPST, Swine feeding
J. Hong et al.	ICR, LF, CPST & ICR, CPST & LF
W. Zhao et al.	Bs, Bs + LFgas use, ICR, Bs + RE, Bs + CPST, Bs + anAD, Integrated system
H. Khoo et al.	Py + GF, Py, Thermal cracking GF, Combined GF + Py +oxidation, CFB GF, Steam GF, GF of RDF, GF of shredded tyres
F. Cherubini et al.	LF, LFgas use, Sorting RDF + AD, ICR
F. Cherubini et al.	Bs, Bs + source separation w/o CPST, Bs + source separation w CPST, Bs + source separation w ICR, ICR only
M. Banar et al.	LF, LF w gas collection, Sorting + LF, ICR
A. Massarutto et al.	Scenarios with different selective collection efficiencies
S. Batool et al.	Biowaste collection +CSPT, BioGF, RE with "bring system", RE, RE + biowaste collection, RE + BioGF
G. De Feo et al.	Different selective collection efficiencies + LF / ICR

One can see from Table 8 that these studies focus on very different solid waste management methods but have some points in common:

- either the comparison of landfilling to incineration,
- or baseline scenarios with several possible improvements and their implications on CO_2 emissions, amount of waste landfilled etc.

In conclusion, there seems to be room for a review paper of LCA analyses since J. Cleary's paper (Cleary, 2009).

2.1. Comparison of MG to FB

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[1] Note: ICR: incineration, RE: recycling, LF: landfilling, CPST: composting, Bs: baseline, (an)AD: (an)aerobic digestion, Py: pyrolisis, GF: gasification

Comparison of MG to FB is much less analyzed in the literature than comparison of combustion to other SWM options. Actually, the author only found two studies in recent literature that compare FB and MG technologies across an LCA metric.

In the first study (Consonni 2005), the comparison was not the main point of the article, but some elements could be useful for comparison. Two scenarios were compared in this study. Both of them include a Material Recovery Facility (MRF) upstream, which is assumed to recycle 35% of the waste, independently of the chosen downstream scenario. In the first scenario, the MRF residue is combusted "as is" in a moving grate furnace. In the second scenario, the MRF residue is bio-stabilized to produce RDF. Then the waste is sifted before being sent to a fluidized bed combustor.

The results of the study show a significant advantage to the grate combustion of the MRF residue across all metrics: GWP, Human Toxicity Potential (HTP), Acidification Potential (AP), Photochemical Ozone Creation Potential (POCP), Landfill Volume (LV).

However, a big assumption was made in this study: identical emissions at the stack for all strategies in terms of dry gas. According to the authors of the article, the reason for such an assumption is that regulations are the same for all types of plants and that feedstock composition doesn't influence stack emissions.

The difference of life-cycle emissions was then due to emissions occurring during bio-stabilization of the waste, to RDF production (that uses a lot of energy), and to the less important share of initial material being turned into energy in the end. This study could contain useful information when conducting an LCA, but comparing MG to FB is not the point of the article and no simple conclusion can be inferred since the two compared scenarios have other differences than just using MG or FB - bio stabilization is not used with MG.

The second study (Chen, 2010) presents an LCA comparison of both MG combustors and FB combustors, with low energetic value of waste, in a Chinese context. This study used the EASEWASTE software for the LCA analysis (an LCA model for waste management, developed by one of the authors of the paper).

They analyzed several scenarios, including very low heating value (4.45MJ/kg) and higher heating value fuels (6.05MJ/kg), with or without co-combustion of coal or diesel oil, and with different leachate disposal methods.

The results of this study showed that, without co-combustion of coal or oil, fluidized bed incineration (FBI) was more efficient when considering almost all categories except global warming potential and bulky and hazardous waste avoidance. In these categories, moving grate incineration (MGI) was slightly more environmentally friendly.

Need of further research

The fact that so few studies exist in the literature and that one of them, assumed identical stack emissions is in favor of pushing the analysis further on this topic. This means that a new analysis, would not be redundant with existing published research, and would contribute to advancing research on this cutting edge topic.

2. Process maps

In order to do a thorough LCA, one needs to list all stages, inputs and outputs present in the process to be analyzed. A good way to show these elements is a detailed process map. Any LCA process usually comprises a detailed process map that is useful to clearly determine the boundaries of the system. Figure 31 represents a process map of the Fluidized Bed Incineration process.

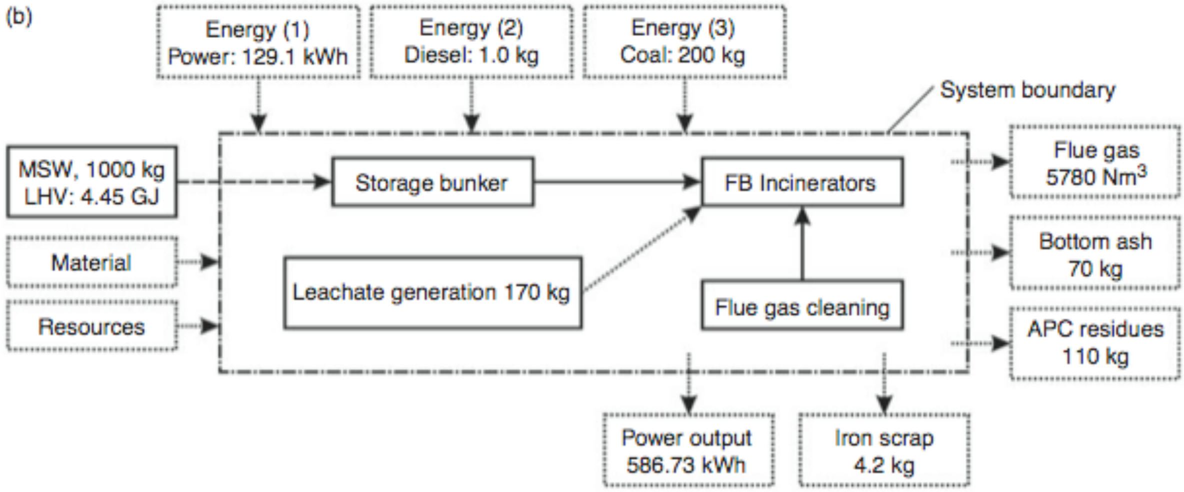

Figure 31: Process map of the FB technology (Chen, 2010)

Figures 32 and 33 present Mass and Energy balances of the Cixi plant (FB), using a process map approach, and using data from Zhejiang University on the Cixi plant.

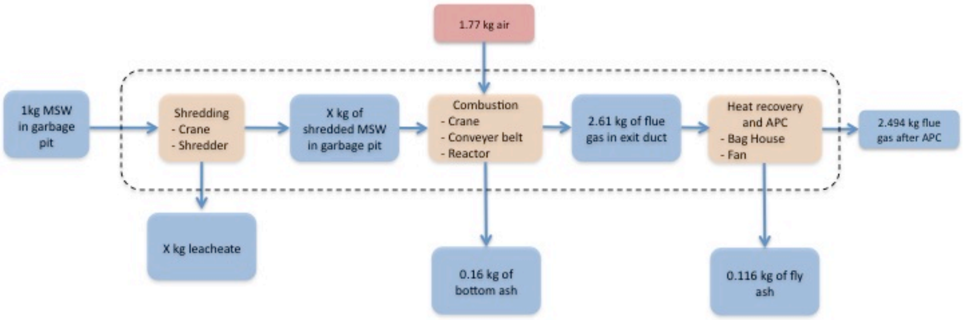

Figure 32: CFB system process map - mass balance

3. Life cycle inventory

In order to do a full life-cycle analysis, very precise data is needed. Table 10 lists the data needed, most of which is still unknown from the author.

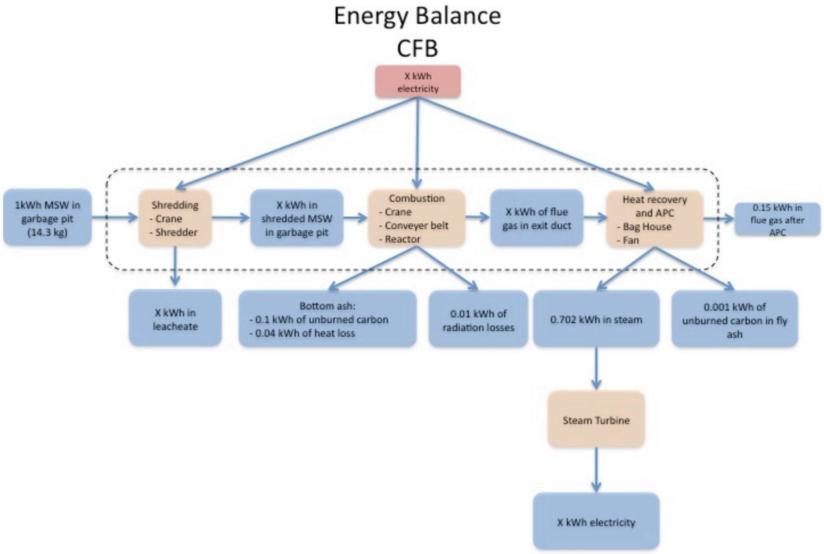

Figure 33: CFB combustion system energy balance

Table 9: Data needs in order to conduct the LCA analysis

Part of CFB	Data needs	Answer / Unit
General plant	Materials and energy used to build the plant	(If available) Ton cement, kWh electricity, etc.
General plant	Heating Value of the waste	3970 kJ/kg
Roller bag breaker	Power consumption	kWh
Conveyer	Power consumption	kWh
Shredder	Power consumption	kWh
Crane	Power consumption	kWh
Magnetic iron separator	Power consumption	kWh
Pit	Leachate disposal method	
Incinerator	Diesel, coal use (for startup?)	MJ
Incinerator	Fly ash and bottom ash production and use /disposal method	Fly ash: 3838 kg/h Bottom ash: 5327 kg/h Disposal method?
Heat recovery	Power output of the plant / efficiency	kWh
APC	Flue gas emissions	g/m3
APC	Materials used for APC (filter bags, Ca(OH), activated carbon, water)	Number of bags per hour, kg, kg, liter
Fans	Power consumption	kWh
General plant	Material recovered during the process (iron, aluminum)	kg

A thorough LCA comparing FB and MG was not the purpose of this section. It could be the subject of a whole thesis by itself. Here the author wanted to pave the path for such an LCA, and to present the conclusions that are available in the literature.

Overall, the only environmental assessment comparing on a LCA basis MG and FB concludes in a close advantage of FB incineration over MG incineration, except in the greenhouse gas category.