Brief Introduction of Fluidized Bed Boiler

Project of energy management course

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**Abstract:** Energy management is a worldwide project nowadays and in the foreseeable future. Boilers generate steam which is then used to provide space heat, process heat, mechanical power, and possibly electricity. Since the coal is still one of the most important fuels in the world. And some other kinds of fuels like bio-fuels and wastes are developed rapidly. A fuel flexible, high efficiency and environment friendly combustion technology is needed. Till now, the best choice is fluidized bed boiler. In this paper, the fluidized bed boiler is introduced. In order to clarify the advantages of this technology, basic knowledge of fluidized bed boiler will introduced. And then the history of fluidized bed boiler is shown.

The main purpose of this paper is to discuss the research direction of fluidized bed boiler technology to improve its performance. The fluidized bed boiler technology is considered as a mature technology, so that less support from government and attention from researchers are paid on this project in the last decade than before. However, energy saving of 1% will be a very great saving in the world. Furthermore, there are so many problems in this project that need to be fixed up. Such as fuels flexibility, combustion-supporting gas, emission control, agglomeration and corrosion control and some other aspects. Fuels flexibility is an advantage of this technology, but the design and operation of different fuels are not the same. For example, bio-fuels are easier to cause agglomeration and corrosion problems. Combustion-supporting gas is changed continuously, but the optimal choice is still under discussion. Emission control will be a most important aspect in the future, since this can be a decisive advantage of fluidized bed boiler over other kinds of boilers. Agglomeration and corrosion control and other aspects are also need to be conducted. Some of researches about these problems are referred to give us a clear understanding of the research direction on this technology in the future.

**Key words:** fluidized bed boiler (FBB), bubble fluidized boiler (BFB), circulation fluidized boiler (CFB), fuels flexibility, combustion-supporting gas, emission control, agglomeration and corrosion control.
1. Basic knowledge of fluidized bed boiler

The largest use of energy in many facilities is in boilers. Boilers generate steam which is then used to provide space heat, process heat, mechanical power, and possibly electricity [1]. Fluidized bed boiler (FBB) is a latest kind of boiler, combustion happens in the FBB, and the heat will be used to produce steam. Fluidized bed combustion is widely used in power boilers due to its impressive environmental performance and also its fuel flexibility [2]. At the beginning, bubble fluidized bed combustor (BFB) was invented and industrialized. Another kind of FBB which is considered as a new generation of technology is circulated fluidized bed combustor (CFB).

1.1. BFB

Bubbling fluidized bed boilers (BFB) are often preferred in small-scale applications, with fuels having low heat value and high moisture content [3]. The whole system of BFB is shown in fig.1. It contains bubble fluidized bed boiler, fluidized air supply system, start-up burners, lower and upper overfire air supply system, fuel fill chute, sand fill chute, bubble caps (spargers), economizer and steam drum.

At the beginning, fluidized air should be send into boiler through bubble caps, and the sands, limestone and fuels should also be filled into boiler. Limestone added to the bed is to eliminate sulphur and/or chlorine. The velocity of fluidized air in the boiler should be between the minimum fluidization velocity and the entrainment velocity on which the bed particles would be dragged by the passing gas, being usually 1,2 m/s (4ft/s) at full load. Particle diameter should be less than 50mm. As the start-up burners igniting the fire, lower and upper overfire air should be supplied into the boiler to enhance staged combustion. The heat produced by the boiler can be used to help producing steam, and preheating the feed water by economizer. Combustion temperature is typically between 800 and 950 °C (1472-1742 °F), being 850 °C (1562ºF) a usual bed temperature.
The core of the BFB boiler system is the combustion boiler (shown in fig.2). It features water-cooled walls and bottom. The bottom has a full refractory lining and the lower portion of the water wall is also refractory lined, since the temperature in the lower portion and bottom is extremely high for the steel cover.

The fluidization of particles provides a larger contact area than other kinds of boilers. And the temperature of the BFB is more homogenous. These drive the BFB to excel other non-fluidized technologies in terms of fuel flexibility, efficiency, emissions and lower capital and maintenance costs. Only CFB has better performance.

Fig. 1, Bottom-Supported Towerpak® BFB Boiler from the Babcock & Wilcox Company [4].
1.2. CFB

Circulating Fluidized Bed (CFB) boilers using fossil and renewable energy sources have been successful in operation for the last two decades and have become popular due to their impressive environmental performance as well as their fuel flexibility [6]. The particle density of CFB is lower than BFB, and the fluidization is also better.

The schematic representation of a coal-fired CFB plant is shown in fig.3. CFB system comprises 1-19 parts. Coal needs to be added into coal bunker, limestone needs to be added to limestone bunker. Coal crusher receives the feed of coal from coal bunker, and crushes it into small particles with diameter less than 25mm. Coal particles and limestone should be fed to boiler at the beginning. Primary air should be sent into boiler from blast caps at a velocity of 2-10 times of minimum fluidization velocity. As the start-
up burners igniting the fire, secondary air should be supplied into the boiler to enhance staged combustion. At the same time, steam will be generated by the heat of combustion in the boiler. The flue gas will be sent into stack after electrostatic filter.

The difference between CFB and BFB is the fluidization statement. The Model of a combustion boiler (CFB) from Kvaerner Power is shown in fig. 4. Compare fig. 2 and fig. 4, we can find that the fluidization height in fig. 2 is less than 1/5 of boiler height, while the fluidization height in fig. 4 is approximately the height of boiler. Furthermore, there is a cyclone in fig. 4, the particles in the cyclone are also fluidized. At the bottom of the cyclone, there is a pipe connects the bottom outlet of cyclone and boiler. The coil particles are combusted into smaller particles, and once their gravity force is lower than the buoyancy force of the passing gas, they will be dragged into the cyclone by the passing gas. Since the cyclone can separate the particles from gas with the efficiency of over 95%, most big particles will sink in the bottom of the cyclone, and be sent back into boiler. This process improves combustion efficiency dramatically.

The design parameters of BFB and CFB are shown in table 1.

<table>
<thead>
<tr>
<th>Combustion temperature</th>
<th>BFB</th>
<th>CFB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion temperature (1C)</td>
<td>760-800</td>
<td>800-900</td>
</tr>
<tr>
<td>Fuel particle size (mm)</td>
<td>0-50</td>
<td>0-25</td>
</tr>
<tr>
<td>Fluidization velocities (m/s)</td>
<td>1-3</td>
<td>3-10</td>
</tr>
<tr>
<td>Solids circulation</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Particle concentration</td>
<td>High in bottom, low in freeboard</td>
<td>Gradually decreasing along furnace</td>
</tr>
<tr>
<td>Limestone particle size (mm)</td>
<td>0.3-0.5</td>
<td>0.1-0.2</td>
</tr>
<tr>
<td>Average steam parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam flow (kg/s) (range)</td>
<td>36 (13–139)</td>
<td>60 (12–360)</td>
</tr>
<tr>
<td>Steam temperature (1C) (range)</td>
<td>466 (150–543)</td>
<td>506 (180–580)</td>
</tr>
<tr>
<td>Steam pressure (bar) (range)</td>
<td>72 (10–160)</td>
<td>103 (10–275)</td>
</tr>
</tbody>
</table>
Fig. 3, Schematic representation of a coal-fired CFB plant (courtesy Doosen Lentjes) [7].

Fig. 4, Model of a combustion boiler (CFB) from Kvaerner Power [5].
2. History of fluidized bed boiler

In the 20th century, fluidized bed boiler (FBB) was one of the most activity subjects in the world. From the time it was invented to commercialization and diffusion, only took less than 70 years. As a human being, we have a life line. As a new technology, FBB also has its own life line. Born as a baby, is a start of human beings’ life. Then we become infants, passing the golden childhood, to the immature teenage, as time goes on, we become adolescences, and then we are mature, then we are youth... This period of grow up also happens on FBB. The born stage of FBB is the invention of fluidized bed combustor. The infant period means no independent show. For the FBB, it is realization time. After realization, there should be some equipments manufactured, and the experiments implemented. During experiment period, an innovation time should also take place, just as the childhood and teenage of human beings. Before maturity, there is another stage for FBB, which is commercialization, and it is regarded as a flourishing stage. Till now, the FBB just steps into its maturity stage, as a youth of human beings. Curve depicting the development of FBB technology is shown in fig.5.

![Curve depicting the development of FBB technology.](image)
2.1. Invention

On Dec 16, 1921 a new chapter opened in the history of energy and power industries. To gasification the lignite, Fritz Winkler from German invented the first fluidized bed combustor [8]. And it is a prototype of FBB. The original idea came from a occasional opportunity that Fritz Winkler saw the mass of particles lifted by the drag of gas to look like a boiling liquid. This experiment led to a new process in engineering which is called fluidization. And the equipment of the process is called fluidized bed.

There are some other ideas about the first discovery of fluidization and use of it. For example, in the ancient China, they invented a machine to separate the unhusked rice to get rid of unfilled rice. But this kind of machine only had the idea of using gas flow to drag the particles, not as a concept of the fluidization. Fritz Winkler is the inventor of the fluidized bed, and his fluidized bed combustor is considered as the born of FBB.

2.2. Realization

In 1965, the first bubble fluidized bed combustion test facility was commissioned. And this is the end of realization of FBB technology. During 1921 and 1965, there are over 40 years. Even the idea of burning instead of gasifying coal in a bubbling fluidized bed has been pursued and promoted most vigorously by Douglas Elliott since the early 1960s [9].

The coal combustion is the most popular project for researchers in the first half of 19th century. The pulverized coal fired boiler was first implemented in 1911. And in 1938, Warren Lewis and Edwin Gilliland invented the fast fluidized bed process, which dramatically is the same fluidized bed for gasification invented by Fritz Winkler 17 years ago [10].

2.3. Experiment and innovation

In early 1965, a hardware program to prove that fluidization could be applied to coal burning was started. With funding that year from the United States Government, Michael Pope and his group
designed and built in Alexandria, Virginia, the first atmospheric pressure fluidized bed boiler. Tests operated at temperatures around 1600 °F, with gas velocities in the four to twelve feet per second range. Tests have also demonstrated a capability of burning low-grade fuels, and transferring heat at average rates several times those expected in conventional boilers [11].

The atmospheric fluidized bed combustion (FBC) program also started in the USA in 1965. In 1970, the USA founded the Environmental Protection Agency (EPA), and they stipulated lower emissions of coal combustion, which gave FBC technology an advantage over conventional coal combustion technologies. At the same time, other countries like UK, Finland, Germany, China and Japan also started the program to develop the technology of FBC. During this period, the USA and Germany led the technical development, and the research and development budgets for coal technologies were rising in the period between mid-1970s and early 1980s.

The first circulated fluidized bed combustor CFB boiler, designed exclusively for the supply of steam and heat, was built in the Vereingte Aluminum Werke at Luenen, Germany in 1982. This plant generated 84 MW total (9 MW electricity, 31 MW process steam, 44 MW molten salt melt) by burning low-grade coal washery residues in the presence of limestone.

2.4. Commercialization

BFB installations (<100MWe) are used in the aluminium and paper manufacturing industry since 1970. Several pilot and demonstration plants have been built by various manufacturers in the power segment in the period 1976 – 1986. The first application of the BFB technology in the utility (>100MWe) segment was in 1986, when a 117MWe net demonstration plant started in Burnsville 5 (USA) [7].

Some of researchers considered the first commercially successful fluidized bed as the industrial-size atmospheric unit (equivalent to a 10-megawatt combustor) built with federal funds on the campus of
Georgetown University in Washington, D.C., in 1979. While the Georgetown unit currently still operates today.

There is a figure (fig. 6) presented by Joris Koornneef, etc. (2007) [7]. It shows the cumulative installed boilers from 1976 to 2006. The CFB is circulated fluidized bed combustor, while the BFB is bubble fluidized bed combustor. From fig. 6, we can see that cumulative amount of installed boilers used in the world in 2006 is over 500.

![Fig 6, Diffusion of FBC technology by variant [7]](image)

2.5. Maturity stage

The FBB technology is developed to a maturity stage nowadays. The improvement areas for FBB used in industrial applications are emission control, heat exchanging perfection, fuel researching, fluidization optimization, agglomeration and corrosion control etc. Some equipment manufacturers such as Kvaerner Power, Alstom, Doosan Lentjes and Foster Wheeler are playing a very important part in the technology development.
Kvaerner Power can provide the solution for bioenergy, which is a FBB process. They have both BFB and CFB. The BFB production is HYBEX®, with a capacity of 20-300 MWth. Over 150 HYBEX® boilers are provided by Kvaerner Power since 1979. The CFB production is CYMIC®, with a capacity of 50-600 MWth. Over 60 CYMIC® boilers are provided by Kvaerner Power since 1980.

Alstom Power is considered as the number one supplier of boilers worldwide. About 30% of the world boilers use Alstom technology. Alstom entered the CFB market in the 1980s, and they don’t have the technology of BFB. The Three Bay Arrangement is the common design to meet most technical requirements within the 100 – 300 MW range. The Dual Grate Arrangement up to 350 MW has been in successful operation in the United States, France and China for more than 20 years. The Ultra-supercritical CFB can offer a proven firing system for 660 MW class and higher.

In 2011, AE&E Lentjes GmbH was acquisition by Doosan Power System, and became Doosan Lentjes. They have already delivered over 100 CFBs all over the world. Their products have a proven track record of up to almost 300MWe (~700MWth). They don’t have the BFB technology.

Foster Wheeler’s CFBs first reached small-scale utility application in 1987 on the 110 MWe Tri-State Nucla power project in the U.S., then went on to the medium utility scale in 2001 with the 2 x 300 MWe units for the Jacksonville Energy Authority. During the past 30 years Foster Wheeler has booked over 360 CFB boilers ranging from 7 to nearly 1000 MWth. Of these, over 50 are designed for biomass (or bio-mix) and nearly 50 for waste (or waste-mix) containing biodegradable fractions [12]. Furthermore, Foster Wheeler has supplied more that 130 BFB boilers, mainly for industrial site.
3. Outlook of technology development

As a mature technology, it is very hard to improve the performance of Fluidized bed boiler (FBB). BFB technology is replaced by CFB step by step. It may not disappear, but the market of BFB will be narrower and narrower. Considering this situation, in this part, only CFB will be taken into discussion. The performance of CFB technology is decided by every detail of the whole system, some aspects will be listed as the project to discuss. They are fuels flexibility, combustion-supporting gas, emission control and agglomeration and corrosion control.

3.1. Fuels flexibility

The fuel used in CFB technology was diversified in the beginning of the industrialization stage. First, main fuel types used (in MWe net installed capacity) were lignite and bituminous coals. Later, also anthracite, sub-bituminous coal, petroleum coke, biomass and waste were used.

Fuel range applicable for fluidized bed combustion is shown in fig. 7. At the right fuels that can be used with standard boiler design, moving to the left the fuel characteristics causes more challenge for multi-fuel operation and boiler design [13].

The challenges of fuels preparation and adaption need to be considered. They are:

- Preparation of particles: the diameter of fuels used in CFB should be less than 25mm. The more homogenous, the better. Some big particles may be stayed at the bottom of the boiler, and the high temperature may cause them to be adhered to the inner wall of lining in the boiler.
- Filling fuels and limestone (or other additives): the filling process is very important to the whole system. It contains two different types, the first one is continuous filling, and the second one is intermittent filling. If the system is very big, intermittent filling may affect the fluidization in the boiler. On the contrary, continuous filling for the very small system may be waste of energy and operation costs.
- Preventing agglomeration: the agglomeration of particles in the boiler depends on the fuel used. If agglomeration occurs it can cover the nozzles, which provide the air for fluidization, cover the furnace wall or affect homogeneous fluidization. These problems affect the combustion process and heat transfer, and reduce the efficiency of the CFB system.

- Alkali removal to prevent corrosion of the furnace wall.

- Emission affect: When a solid fuel, such as coal, biomass or a mixture of these fuels, enters a hot fluidized bed, the volatile carbon and nitrogen compounds are released, while some nitrogen and carbon remains in the solid char. Volatile nitrogen can form reactive species such as NH3, HCN and tar-nitrogen that can react in the presence of oxygen to NO (and some N2O) [14].

![Fuel range applicable for fluidized bed combustion](image)

In these years, agricultural residues from food production and energy crops have been seen as an optional fuel of CFB. Some researching jobs are already done on this project. In Poland, the Energy Law
specifies a “green certificate” system for implementing the European Union’s directive on electricity purchased from renewable sources (2001/77/EC). That requires increasing the contribution of energy crops or other material of agricultural origin; these must account for at least 20% of electricity production (by wet mass) at the end of 2012. The proportion then will be gradually increased until 2017.

The properties of agricultural residues fuels entail many challenges for the combustion process. Nitrogen, phosphorous, potassium, magnesium, and chlorine content are usually higher in comparison to woody biomass, due to the use of fertilizers. Potassium and chlorine vaporize easily and are known to have an important role in bed agglomeration, fouling, slagging, and high-temperature corrosion-related processes. Phosphorus takes part in bed-agglomeration, fouling, and slagging-related phenomena. An increase in nitrogen content may elevate NOx emissions [15].

The influence of the agricultural residues fuels to the CFB was researched by E. C. Zabetta etc. (2013) from Foster Wheeler [16]. Experiments were implemented to find out the relationship between fuels and agglomeration, fouling and corrosion probabilities. The properties of selected fuels are shown in table 2. And the relationship between fuels and agglomeration, fouling and corrosion probabilities are shown in fig. 8- fig. 10.

Agglomeration of bed material may occur during combustion of some biomass fuels, and it is more intense with most agricultural residues -biomass than with wood-derived biomass. The reactions between alkali from fuel and quartz particles from the bed material have been identified as key events in formation of sticky alkali-silicate coating layers that lead to agglomeration. Compared to woody biomass, fouling during combustion of agricultural residues can be high and form deposits more enriched in alkali halides, which makes them more difficult to soot-blow. Chlorine-induced mechanism is the main reason for corrosion of agricultural residues.
Table 2, properties of selected fuels [16]

<table>
<thead>
<tr>
<th>Fuels</th>
<th>Wood</th>
<th>Straw A</th>
<th>Straw B</th>
<th>Olive</th>
<th>Sun-flower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>4.5</td>
<td>10.0</td>
<td>8.6</td>
<td>12.2</td>
<td>9.8</td>
</tr>
<tr>
<td>Volatile</td>
<td>83.7</td>
<td>77.0</td>
<td>77.9</td>
<td>72.6</td>
<td>76.0</td>
</tr>
<tr>
<td>Ash$^a$</td>
<td>0.8</td>
<td>4.5</td>
<td>4.3</td>
<td>8.4</td>
<td>3.0</td>
</tr>
<tr>
<td>LHV</td>
<td>18.96</td>
<td>15.51</td>
<td>16.05</td>
<td>15.94</td>
<td>16.63</td>
</tr>
<tr>
<td>C</td>
<td>50.6</td>
<td>47.1</td>
<td>47.1</td>
<td>48.5</td>
<td>50.2</td>
</tr>
<tr>
<td>H</td>
<td>6.4</td>
<td>6.2</td>
<td>6.2</td>
<td>6.0</td>
<td>5.9</td>
</tr>
<tr>
<td>N</td>
<td>0.13</td>
<td>0.46</td>
<td>1.75</td>
<td>1.23</td>
<td>0.68</td>
</tr>
<tr>
<td>S</td>
<td>34</td>
<td>1400</td>
<td>1900</td>
<td>1600</td>
<td>1700</td>
</tr>
<tr>
<td>Cl</td>
<td>30</td>
<td>1700</td>
<td>1200</td>
<td>2200</td>
<td>630</td>
</tr>
<tr>
<td>Na</td>
<td>140</td>
<td>82</td>
<td>32</td>
<td>200</td>
<td>25</td>
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<tr>
<td>K</td>
<td>680</td>
<td>10000</td>
<td>12200</td>
<td>34100</td>
<td>10500</td>
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<td>Ca</td>
<td>1400</td>
<td>4200</td>
<td>1800</td>
<td>10900</td>
<td>3600</td>
</tr>
<tr>
<td>Mg</td>
<td>310</td>
<td>530</td>
<td>2300</td>
<td>1600</td>
<td>1800</td>
</tr>
<tr>
<td>Fe</td>
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<td>200</td>
<td>160</td>
<td>980</td>
<td>100</td>
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<tr>
<td>Al</td>
<td>320</td>
<td>120</td>
<td>110</td>
<td>440</td>
<td>60</td>
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<td>Si</td>
<td>790</td>
<td>7900</td>
<td>2100</td>
<td>3400</td>
<td>280</td>
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<tr>
<td>Ti</td>
<td>28</td>
<td>9.5</td>
<td>9</td>
<td>83</td>
<td>3</td>
</tr>
<tr>
<td>P</td>
<td>67</td>
<td>470</td>
<td>6100</td>
<td>1900</td>
<td>620</td>
</tr>
<tr>
<td>Mn</td>
<td>110</td>
<td>48</td>
<td>79</td>
<td>19</td>
<td>8</td>
</tr>
</tbody>
</table>

$^a$ Ashing at 550 °C.

Fig. 8, relationship between fuels and agglomeration probabilities [16].
From the explanation above, we can see that good fuels flexibility is an advantage of CFB, on the other hand, there are plenty of researches should be done on different fuels before designing a CFB system for them. Otherwise, some problems such as agglomeration, fouling, corrosion and some other incognizant impacts may occur.
3.2. **Combustion-supporting gas**

Air combustion used to be the main process of CFB systems. From 1990th, considering CO₂, SO₂ and NOₓ discharge of the system, and the requirement of environmental protection, oxy-fuel combustion process was invented. Oxy-fuel combustion in fluidized beds has revealed as an attractive and feasible option to reach the concept of clean-coal technology. It gathers the environmental advantages of both technologies: SO₂ and NOₓ control inherent to fluidized bed combustion and the oxy-fuel capability of generating a flue gas stream suitable for efficient CO₂ capture. In addition, the fuel flexibility characterizing fluidized bed units represents the possibility to implement oxy-fuel boilers for bio-energy with carbon capture and storage for negative CO₂ emissions [17].

The effect of the combustion type on the radiative heat transfer of the back pass channel has also been studied, and it was found that the oxygen-fired combustion may increase the average radiative heat flux on the solid walls by 33.4%, while the local values may increase up to 40% compared to the air-fired case [18].

Air Liquide has developed an ASU (Air Separation Unit) and CPU (Cryogenic Purification Unit) for the Oxy-fuel CFB system, which gains very high performances as follows [19]:

- Cost effective CO₂ recovery above 95%
- CO₂ purity greater than 99.99%
- Low water usage
- Near Zero Air emissions and in particular zero chemicals emissions
- Very limited liquid and solid wastes
- Its flexibility in design and operation including potential for energy storage through cryogenic liquids
- A “Non chemical” route
The input excess oxygen to the plant (the global stoichiometric ratio) can be lowered compared to that of a corresponding air-fired plant. Because of gas recirculation, the excess oxygen to the furnace (the internal stoichiometric ratio) can be maintained at a conventional level for a CFB boiler while the global stoichiometric ratio is smaller [20].

Some researchers are also focus on the external heat exchangers used in Oxy-fuel CFB system. In any case, the higher the O2 concentration in oxy-fuel combustion, the more important is the heat exchange in an EHE and the higher the need is of increasing elutriated solids, Gs, for controlling temperature. Heat transferred in EHE becomes very important for O2 combustion ratios higher than 30% [21].

An oxy-fuel CFB system simplified block diagram is shown in fig. 11 [22]. Four subsystems are included in this system. They are Air separation unit, Boiler / Gas Quality Control Systems, CO2 Purification Unit and Steam power cycle. The gas sent into the boiler is the mixture gas of oxygen and fuel gas. And the CO2 in the fuel gas is purified and stored as a product.

![Image of an oxy-fuel CFB system simplified block diagram](image-url)

Fig. 11, an oxy-fuel CFB system simplified block diagram [22].
Oxy-fuel CFB system has a lot of advantages over the air combustion CFB system. It is the direction of the technical development. Since there are some problems of the Oxy-fuel CFB system, such as oxygen density choice, heat efficiency improvement and fluidization optimal, more researches should be implemented on this project.

3.3. Emission control

Greenhouse gases are becoming a more and more important problem for not only environmental protection agencies, but also every human being on the world. Carbon dioxide gas has been recognized as one of the major contributors to the build-up of greenhouse gases. Carbon dioxide enters the atmosphere through burning fossil fuels (coal, natural gas and oil), solid waste, trees and wood products, and also as a result of certain chemical reactions (e.g., manufacture of cement) [23]. The composition of U.S. greenhouse gas emissions in 2012 is shown in fig. 12. In which Carbon dioxide takes 82% part of all greenhouse gases.

Human activities are responsible for almost all of the increase in greenhouse gases in the atmosphere over the last 150 years. The largest source of greenhouse gas emissions from human activities in the United States is from burning fossil fuels for electricity, heat, and transportation [24]. The total U.S. greenhouse gas emission by economic sectors in 2012 is shown in fig. 13. Reducing the greenhouse gases in burning fossil fuels is really urgent.

The FBB process, as described in the former chapters, is becoming one of the most popular technologies in combustion area. CO₂, SO₂, NOₓ are pollutant gases emission of FBB. CO₂ gas has been recognized as one of the major contributors to the build-up of greenhouse gases and, on the other hand, sulfur and nitrogen content in coal are oxidized to SO₂ and NOₓ respectively, which contribute to acid rain formation [25]. A lot of researches were focus on this topic from the birth of FBB, but there are also
some new technologies appeared in the recent years. The improvement on this aspect should be continuously.

Carbon Capture and Storage (CCS) technologies are one of the options to mitigate the CO2 released into the atmosphere. CIUDEN’s 30 MWth CFB boiler, supplied by Foster Wheeler and located at the Technology Development Centre for CO2 Capture and Transport (es.CO2) in Spain [26]. In their research, some useful conclusions were reached, which is very helpful for pollutant emission gas control of FBB.
• Sulphur capture efficiency (%) was higher in oxy-combustion compared to air-combustion in a 30 MW thermal CFB boiler using anthracite and limestone as sulphur sorbent.

• For a Ca/S molar ratio higher than 2.6 there was barely any improvement on sulphur capture efficiency for both air-combustion and oxy-combustion conditions in a 30 MW thermal CFB boiler using anthracite and limestone as sulphur sorbent.

• Optimum temperature for sulphur capture at a fixed Ca/S molar ratio is around 880-890 °C under oxy-combustion conditions and for anthracite coal with limestone as sorbent in a 30 MW thermal CFB boiler.

Dynamic soft sensors were developed by some other researchers [27]. Soft sensor is a common name for software where several measurements are processed together. There may be dozens or even hundreds of measurements. It can be used for fault diagnosis, control applications and emission estimation. According to M. Liukkonen etc (2012), NOx concentration estimated by soft sensor they developed and measured in experiment are almost the same.

![Fig. 14, A period of 50 h showing the measured and estimated NOx concentration using the linear soft sensor [27].](image)

In 1970s, lower CO2 in emission gases was a vital advantage of FBB, so that it could be improved so rapidly. In the future, reduction of pollutant emission gases will also be an indispensable advantage of
FBB. Upgrading technology by experiment or soft sensor estimation or any other ways will be a tendency in the future.

3.4. **Agglomeration and corrosion control**

Agglomeration and corrosion are two types of harmful phenomenon in the FBB system during operation. Agglomeration is formed by particles nearby each other melted and combined together. It happens in the corner, on the inner wall and in the bottom of FBB, and sometimes it can also happen during the fluidization. Corrosion can happen on blast caps, uncovered wall and uncovered bottom. Most of area which is easy to be corroded in the boiler has the lining. Corrosion is mainly caused by halogen, such as Cl⁻ and Br⁻. In bio-mass fuels, Cl and Br are abundant. Such as listed in table 2, around 2200 mg/kg Cl is in olive. Except for the chemical corrosion, mechanical corrosion is also a very important one in the boiler. Fluidized particles in FBB may hit on the inner wall or some other parts of the boiler, and cause the mechanical corrosion. In the CFB, because of the higher velocity of particles, corrosion is worse than BFB.

A lot of research jobs are done on the preventing of agglomeration and corrosion in the boiler. According to E. C. Zabetta etc. (2013), Kaolin retards agglomeration and fouling. Besides the alleged chemical reactions by kaolinite, its effect may also include dilution and “dry powdering” effects. Kaolin contributes to increase fly ash whose composition, however, is less fouling and less corrosion. Added sulfur can decrease agglomeration and corrosion, producing more compact and harder deposits. Limestone can control agglomeration by a well-known dual mechanism. The representation of mechanisms observed between fuel ash, bed materials, and additives is shown in fig. 15.

The high-temperature corrosion-resistant materials (CRMs) and the corrosion-resistant coatings (CRCs) are considered to be a very good choice to replace linings in the boiler to pretest the corrosion, since the performance (including such as the suppression of pollutants, high electric power generation efficiency, material recycling, etc.) of CRMs and CRCs is much better than lining. Deterioration process of spray coating layer and reduce in bonding strength in severe corrosion environment is shown in fig. 16 [28].
Fig. 15, Schematic representation of mechanisms observed between fuel ash, bed materials, and additives [16].

Fig. 16, Deterioration process of spray coating layer and reduce in bonding strength in severe corrosion environment [28].
Replacing conventional fuels with biomass or waste often results in severe ash related problems such as slagging, fouling and high temperature corrosion [29]. Dealing with these problems will bring us a considerable profit, so plenty of jobs are done on this project. However, the direction of preventing agglomeration and corrosion should be material used to build boilers, uniform size particle preparing technology and additives added to the boiler during combustion.
4. Conclusion

Fluidized bed boiler represents the new combustion technology, even though it is almost 100 years old. It has a very big advantage over other processes. Fluidized particles move like liquid, and have biggest contact area with gas. As a result, the combustion efficiency is optimal. The fluidization inside the boiler also provides a relatively homogenous particle distribution in the bed, which leads to a uniform heat distribution. Furthermore, the circulating fluidized bed boiler has the ability to reuse the unburned particles. The efficiency of combustion increases dramatically. The property of fluidization also enables FBB to burn fuels at lower temperature. And also be flexible for different kind of fuels. It is considered to be the first option for biomass combustion.

The technology is invented in 1921 by Fritz Winkler of Germany. The innovation time lasted for more than 40 years, and in 1965, the first experimental setup was built by Michael Pope and his group in United States. Since 1965 to 1972, a plenty of experiment in atmosphere pressure were carried out, and they found that this technology has a critical advantage which is lower pollutant emission gases. In 1970, The USA founded the Environmental Protection Agency (EPA), and they stipulated lower emissions of coal combustion, which gave FBB technology an advantage over conventional coal combustion technologies. From then on, the FBB technology became more and more popular, with the fund supported by US government, FBB grew up to a mature technology before 1990s. It finished commercialization and industrialization before 2000.

Because the growth velocity of FBB market slowed down these years, and the technology is considered to be a mature technology. Less attention is paid on this technology now. Considering energy consumption in the world is a tremendous amount, and increasing day by day, a 0.1% of efficiency improvement in FBB process will benefit the world a lot. From fuels to operation, there are some areas that can be taken into discussion for further research. They are fuels flexibility, combustion-supporting gas, emission control and agglomeration and corrosion control.
Fuels flexibility is an advantage of FBB. Biomass, garbage, wastes and even sludge can be burned in FBB, and gain energy for human beings. Some researchers found that some problems may follow up with the use of a new kind of fuel. For some of them, it is better to burn with other fuels. Limestone and some other additives are discovered to be helpful for solving some problems like agglomeration and high pollutant emission.

Oxy-fuel is one of the directions for FBB development. Oxy-fuel CFB system has a lot of advantages over the air combustion CFB system. On the other hand, there are also some problems of the Oxy-fuel CFB system, such as oxygen density choice, heat efficiency improvement and fluidization optimal, more researches should be implemented on this project.

Emission control is related to the future of this technology. Minimize the emission of CO$_2$, SO$_2$ and NO$_x$ will bring this mature technology to a new broad way. More and more market occupied by other process will be replaced by FBB, for the target of this technology is to lead our planet to a clean and clear future.

Agglomeration and corrosion control is the key to keep our system running efficiently. New fuels and new kinds of material for boilers may cause more tendency of facing the problem of agglomeration and corrosion. Some experiments have already been implemented on this subject. And some soft sensors to estimate this kind of problems are developed in the resent years.

In a word, FBB is considered as an advanced technology with a lot of advantages over others in combustion area. No good things ever died. More research should be taken on this subject, to find out a more efficient, more fuel flexible and cleaner combustion process, to realize a bright future for human beings and our descendants.
5. References:


[16] E.C. Zabetta, V. Barisic, etc. Advanced technology to co-fire large shares of agricultural residues with biomass in utility CFBs. Fuel Processing Technology 105 (2013) 2–10


