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Designing a Bubbling Fluidized Bed (BFB) Boiler for Research Purposes

Daniel Castiella Franco

Bachelor's Thesis

"What we know is a drop of water;
what we ignore is an ocean"

Isaac Newton

"I hear and I forget,
I see and I remember,
I do and I understand"

Confucius

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<p>Abstract</p> <p>This project is part of the efforts made by Savonia University of Applied Sciences to plan the future EU-funded combustion research laboratory that will be located on Varkaus Campus.</p> <p>The main objective of the present thesis was to carry out an optimal design, in technical, environmental and economical terms, of a small-sized bubbling fluidized bed (BFB) boiler, which will be used mainly for research purposes.</p> <p>This design takes as a reference a former BFB boiler that was located at Lappeenranta University of Technology. The efforts have been focused mainly on adapting this reference design to be used for research activities and bringing construction and operating costs down.</p> <p>All the drawings and virtual three-dimensional models of the components have been executed using SolidWorks, a computer-aided design program.</p> <p>The result of the design process is an efficient and environmentally friendly boiler that is going to enable numerous testing services and lines of research.</p>			
Keywords Bubbling fluidized bed, BFB, boiler, design, SolidWorks			
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1 INTRODUCTION

The progress and industrial development have improved the standard of living in the entire world. However, this evolution and growth has also caused an alarming increase of the environmental risks.

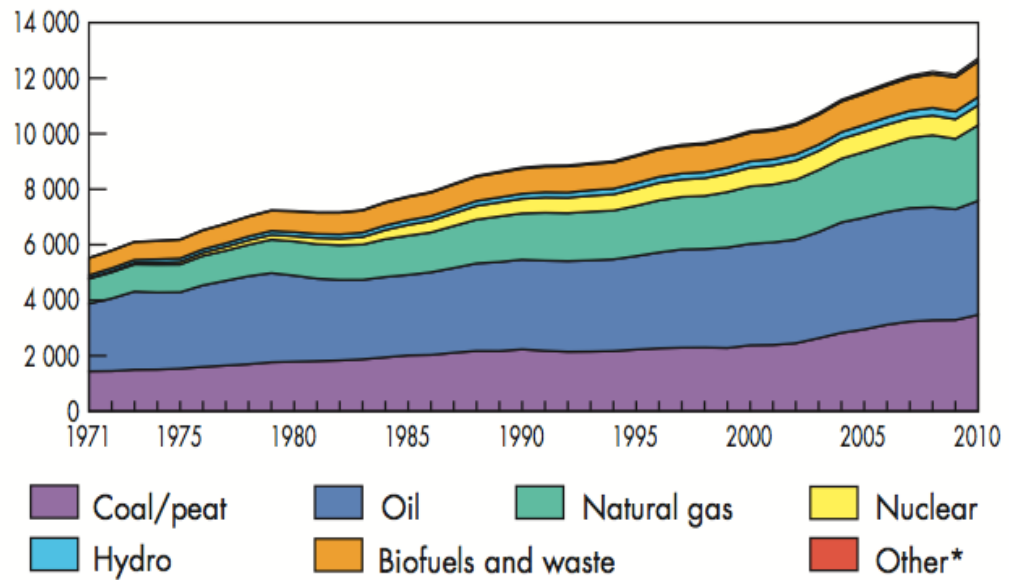
The environmental policy, which began in the United Nations Conference on the Human Environment (Stockholm, 1972), has become one of the most important in the European Union. (Prieto 2013,1.)

In the framework of this policy, community legislation on atmospheric emissions has the following objectives:

- Reducing the amount of pollutants emission: Human activity has increased the proportion of greenhouse gases, such as carbon dioxide and methane, in the atmosphere and, as a consequence, the mean global temperature is currently growing faster than at any time over the last 10.000 years. Furthermore, the emission of nitrogen oxides and sulphur dioxide is causing acid rain. Other restrictions are stated of CFCs, ozone (O₃), hydrocarbons and other photochemical oxidants, as well as limitations of volatile organic compounds and ammonia. In order to reduce the amount of pollutants released into the atmosphere, it is necessary to lessen not only the emission of the substances cited above but also the emission of ash particles. (Honkanen 2012, 6; Fossil-fuel power station Wikipedia 2013; Air pollution Wikipedia 2013.)
- Using the energy in a more efficient way: Earth's supplies are limited and, therefore, the challenge is to use them in a rational manner. (Prieto 2013,1.)

The sources of pollution are very varied: agricultural and domestic uses, transport, industry in general, forest fires, etc. However, the efforts to reduce the pollutants emission has been focused mainly on thermal power stations due to their relative ease of identification, volume and growth. (Prieto 2013,1.)

World population growth and high levels of human development entail an increase in global energy consumption as can be seen from Figure 1. The world is demanding more and more energy but it has to be supplied in a way that ensures energy security, geopolitical balance and a minimization of environmental damages.



*Other includes geothermal, solar, wind, etc.

FIGURE 1. World's total primary energy supply (Mtoe) from 1971 to 2010 by fuel.
(International Energy Agency 2012)

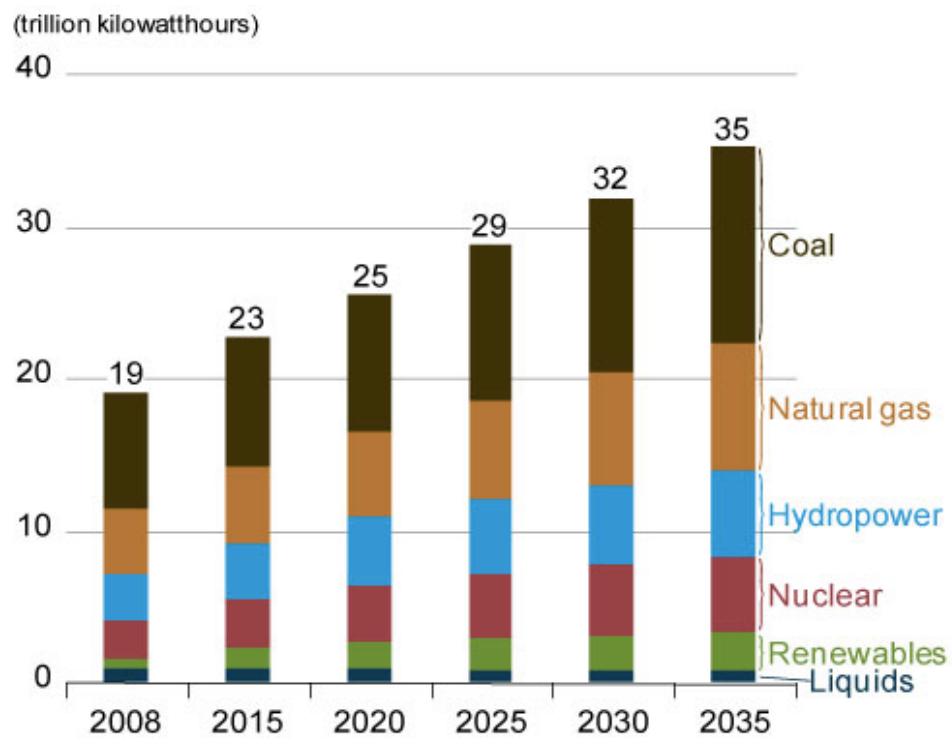


FIGURE 2. World net electricity generation from 2008 to 2035 by fuel type.
(U.S. Energy Information Administration. International Energy Outlook 2011)

A decade ago, hydroelectricity was the only renewable energy affordable compared to other energy sources. However, continued research has reduced the cost of renewable energy technologies, especially of wind turbines, which is permitting them to compete with conventional generation sources in some countries. This is an important step in the fundamental transition of the world's energy mix towards renewable sources. Nevertheless, greater social and political will is required to change the current energy model and reduce dependence on fossil fuels. (Cost of electricity by source Wikipedia 2013; Renewable energy commercialization Wikipedia 2013.)

According to IEO2011 predictions (see Figure 2), fossil fuels will remain the primary source of electricity generation worldwide for the next few decades, especially in developing countries where the power sector is highly dependent on coal (U.S. Energy Information Administration. International Energy Outlook 2011).

TABLE 1. Coal in electricity generation. (World Coal Association 2012)

South Africa 93%	Poland 87%	PR China 79%
Australia 78%	Kazakhstan 75%	India 68%
Israel 58%	Czech Rep 51%	Morocco 51%
Greece 54 %	USA 45 %	Germany 41%

The environmental impact of fossil fuels, especially coal, is a matter that concerns the International Energy Agency (IEA) and other world organizations. Global warming and acid rain are to a large extent caused by coal burning. These environmental problems are mainly ascribed to the emission of gases such as nitrogen oxides, sulphur dioxide and carbon dioxide into the air. (Fossil-fuel power station Wikipedia 2013.)

Over the last few decades, important efforts have been made to deal with the environmental challenges raised. Owing to the chemical composition of coal, the removal of impurities from the fuel prior to its combustion involves serious difficulties. Thus, the main objective of thermoelectric plants has been the improvement and development of methods to reduce the contaminants of flue gases produced by coal combustion. (Fossil-fuel power station Wikipedia 2013.)

At first, the main efforts were focused on the lessening of particles release and acid emissions (Sistemas de Generación Eléctrica 2012, 159). Within this field, different products were developed as a result of extensive research, among which some of the most representative are:

- Low NO_x burners
- Flue gas desulphurisation systems
- Electrostatic precipitators
- Filters

Thanks to these technological advances, modern day coal power plants are more environmentally friendly than older designs.

In addition to developing methods for controlling the formation of pollutants and for exhaust gas cleaning in conventional boilers, other novel methods were promoted such as fluidized bed combustion (FBC). Fluidized bed technology has numerous advantages to burn solid fuels and produce steam. This fact has made its development possible from the seventies to the present becoming a viable alternative of conventional firing systems. Low temperatures of fluidized beds contribute to high efficiency of SO_x retention and to a considerable reduction of NO_x formation. Besides, high overall system efficiency reduces fuel consumption and, consequently, pollutant emissions. Another of its major advantages is the fuel flexibility: it is possible to burn not only coal but also a large variety of fuels like biomass, petroleum coke, combustible industrial wastes, etc. This fact makes them particularly important in countries like Finland where biomass reserves are enormous. Besides, biomass is considered as a renewable energy source. (Sistemas de Generación Eléctrica 2012, 159-160; Prieto 2013, 2-3.)

Nowadays, research on clean combustion technologies is considered as an optimal solution for the natural environment. Progress made by scientific institutions from all around the world during the last years has brought about the optimization of combustion in fluidized bed boilers, resulting in improved fuel utilization and, as a consequence, economic and environmental benefits.

1.1 Context and objectives

The main objective of the present thesis is to carry out an optimal design, in technical, environmental and economical terms, of a small size bubbling fluidized bed (BFB) boiler, which will be used mainly for research purposes.

In particular, the design process has focused on the following components:

- Windbox
- Boiler tube
- Ceramic layers
- Air nozzles
- Fuel feeder
- Sorbent and inert material feeder
- Maintenance flanges
- Flue gas measurement flanges
- Pipes for pressure and temperature measurement
- Bed material removal flange
- Exhaust gases tube

This project is part of the efforts made by Savonia University of Applied Sciences to plan the future EU-funded combustion research laboratory that will be located on Varkaus Campus (see Figure 3).

The construction of this laboratory is going to enable, among others, the following testing services and lines of research:

- Fuel management
- Fuel analysis
- Fluid dynamic and thermal behaviour of the installation
- Combustion characterization
- Firing tests with different operating conditions: fuels, air speeds, temperatures, sorbents, etc.
- Exhaust gas cleaning and emissions control

The ultimate aim of the research activities is to transfer the results to companies so as they can greatly improve their technology, bring the costs down and enhance production.



FIGURE 3. Map of Varkaus Campus. (National Land Survey of Finland 2013)

L - Future research laboratory location

A, B and C - Savonia UAS buildings

It is important to mention that this laboratory will be used not only by the Research and Development (R&D) department but also by students (Hämäläinen 2012, 1). Thus, it will have both research and educational functions.

Besides, the boiler has a practical purpose because the hot water produced will be probably used to generate electricity and to heat the laboratory building and perhaps

also the building C of Varkaus Campus (Huttunen 2 May 2013). However, the research and educational functions prevail over this one and, therefore, it will be necessary to install a supplementary heating system to supply the demand when the boiler is not working. It is estimated that the boiler will be operating for one week a month on average (Hämäläinen 2012, 3). The rest of the time, the demand will be supplied by a geothermal heating system connected to the hot water container of the boiler (Hämäläinen 2012, 7-9). This seems to be the best solution because there are many economical and technical problems of obtaining the thermal energy from the district heating network of Varkauden Aluelampo Oy (Hämäläinen 2012, 4).

1.2 Thesis structure

The present thesis is divided into the following main parts:

- 1) Brief introduction of fluidized bed boilers, context of the thesis and objectives.
- 2) Theoretical background of fluidized bed technology.
- 3) Design of a small size bubbling fluidized bed boiler for research purposes
- 4) Conclusions

Appendix 1: List of all the standard components that are necessary to build the installation

Appendix 2: Installation drawings

2 THEORETICAL BACKGROUND OF FLUIDIZED BED TECHNOLOGY

Although fluidized bed properties have been known since 1921, it has been used for energy production only during the last four decades. The need to minimize pollutant emissions and reduce dependence on fossil fuels has led to the development of this technology, which is currently in full expansion. Nowadays, fluidized bed boilers are considered as an accepted technology for solid fuels combustion to generate electric power. Besides, they are also used in combined heat and power (CHP) plants. (Teir 2003, 37,155; Sistemas de Generación Eléctrica 2012, 164.)

The different types of fluidized bed combustion can be classified according to the following criteria:

- Pressure: there are two different families of fluidized bed combustion depending on the pressure at which the combustion takes place:
 - Atmospheric fluidized bed combustion (Atmospheric pressure)
 - Pressurised fluidized bed combustion (Higher pressure than the atmospheric one)
- Fluidization speed: this classification will be further explained in later chapters. Basically, fluidized bed combustion processes can be classified in two main groups according to the speed of the upward gas current that causes fluidization:
 - Bubbling fluidized bed combustion
 - Circulating fluidized bed combustion

The result is a comprehensive range of efficient and reliable boilers that can compete successfully against other combustion technologies. (Prieto 2013, 2.)

The main advantages over conventional boilers are high combustion efficiency, fuel flexibility and low atmospheric emissions. The combustion takes place in a turbulent bed with high heat transfer coefficient. These features provide more effective chemical reactions and enable enormous flexibility when it comes to using different fuels, especially those that are difficult to burn such as anthracite and petroleum coke, low quality fuels such as combustible industrial wastes and coal with high moisture and ash content, as well as fuels with highly variable heat value like biomass or mixtures

of fuels. The high gas-solid mixing along with the long residence time of fuel particles reduce the amount of unburned fuel and, consequently, the combustion efficiency is very high. Furthermore, this technology enables the combustion of solid fuels in a more efficient and environmentally friendly way. The emission of atmospheric pollutants such as SO_2 , NO_x and dust is below the permitted limits. (Fluidized bed combustion Wikipedia 2013; Prieto 2013, 14-15.)

2.1 Fluidized bed phenomenon and practical applications

Fluidized bed is the name given to a mixture of particles suspended in an upward current of gas (Prieto 2013, 4). The operating principle of a fluidized bed is shown in figure 4.

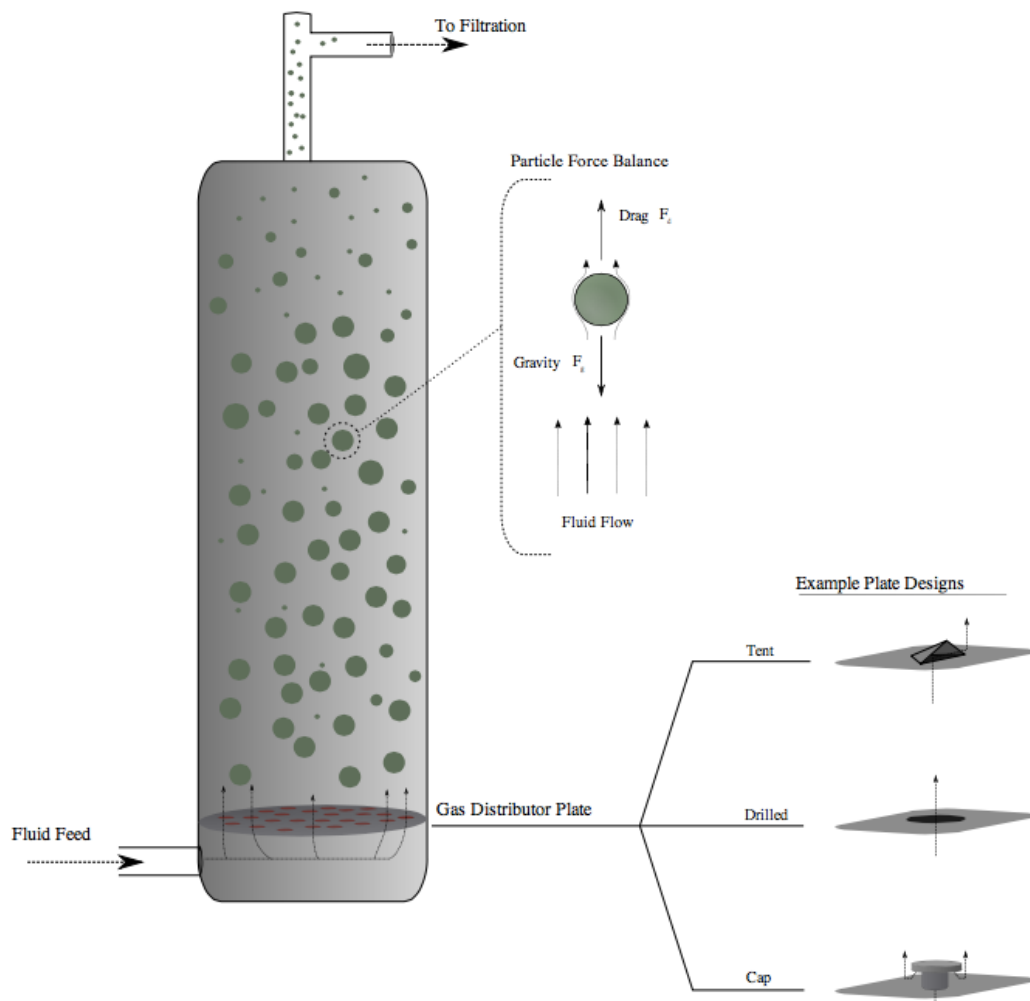


FIGURE 4. Diagram of a fluidized bed. (Fluidized bed Wikipedia 2013)

A granular material is placed in a vertical cylinder with a gas distributor plate or nozzles through which gas moves upwards in a vertical direction. The gas current moves also through the bed formed by that granular material. If the speed of the gas current is high enough, a process or phenomenon called fluidization occurs. This phenomenon consists of the contact between solids (granular material) and fluids so that the solid particles are suspended in the fluid. (Prieto 2013, 4.)

It is very important to control the speed of the upward gas stream because it can lead to different situations. The granular material contained in the cylinder is a porous media. When the speed of the fluid is very low, it only circulates through the winding channels formed by this porous media and, thus, the bed remains fixed. The gas moves from the bottom to the top through the bed without causing any significant change on it. This situation is called “fixed bed” and it is defined by the following parameters:

L = length of the fixed bed

U = speed of the fluid, measured with respect to the cross section

(Prieto 2013, 4.)

Increasing the speed little by little a new state is reached in which the particles of the bed start to vibrate and move in restricted zones. A bed with these properties is known as “expanded bed”. (Prieto 2013, 4-5.)

If the fluid speed continues to increase, all the particles are suspended in the upward flow. In this situation there is equilibrium between the weight of those particles and the drag force that the fluid exerts on those particles as can be seen in Figure 4. This is the moment when the phenomenon of fluidization starts. In this situation, the height of the bed is known as “minimum fluidization height” (L_{mf}) and the speed of the fluid as “minimum fluidization speed” (U_{mf}). The value of this speed depends on numerous factors such as particles size, gas viscosity, particles shape, particles and gas density and bed porosity. (Prieto 2013, 5; Teir 2003, 155.)

An increase of the flow causes a more violent agitation. As a consequence, the bed is a turbulent mixing of solids and gas similar to boiling lava inside a volcano. However,

the particles are held mainly in the bed, which does not expand along the boiler tube. This state is called “bubbling fluidized bed”. (Honkanen 2012, 23; Prieto 2013, 5.)

If we continue increasing the speed of the injected gas, the turbulence degree becomes greater and a large number of bed particles are drawn by the gas stream, still preserving the features of a fluidized bed. This is called “circulating fluidized bed”. The greater flow of drawn particles makes the use of recirculation devices necessary. (Prieto 2013, 5.)

If the speed is increased even more the state reached is known as “pneumatic transport” in which all the particles are drawn and go out of the boiler through the flue gas tube. (Prieto 2013, 5.)

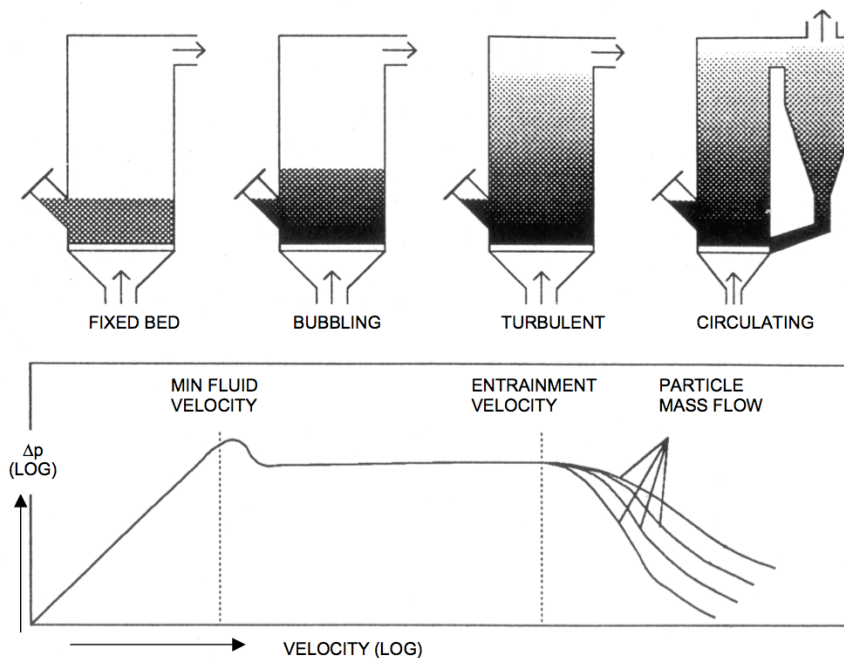


FIGURE 6. Regimes of fluidized bed systems. (Teir 2003, 156)

As can be seen from the graph of figure 6, the fluid speed and the pressure drop due to frictional losses are related.

This relation is described by the formula

$$\Delta p_f = f(U) \quad (1)$$

Where Δp_f is the pressure drop and U is the fluid speed

The function is represented in the logarithmic coordinate system. This graphic is known as fluidization curve and it enables the differentiation and classification of the various families of fluidized beds. (Prieto 2013, 6-7.)

When the fluid speed is below the minimum fluidization speed (U_{mf}) the bed is fixed and pressure loss experienced by the flow, due to the particles friction, is proportional to its speed. In other words, $\log \Delta p_f$ increases linearly with $\log U$ until the maximum porosity is reached (expanded bed). In this state the particles are still in contact. Once the gas speed exceeds the minimum fluidization limit, all the particles are suspended in the upward flow. When this happens, the pressure drop decreases slightly since the bed particles move to a position in which the pressure drop is lower. (Prieto 2013, 6.)

An increase of the flow causes an intense agitation of the bed particles but the pressure drop remains almost constant until the entrainment velocity is attained. This velocity marks the transition from a bubbling bed to a circulating bed. From here on, if the gas speed continues to rise, the pressure drop (Δp) falls suddenly on account of the loss of bed particles. In other words, the gradual loss of the bed weight brings about a decrease in gas flow resistance. (Prieto 2013, 6.)

Having explained the phenomenon of fluidization and the different types of fluidized beds, it is necessary to define some of their applications. The properties of fluidized beds can be used in many industrial activities such as fluid catalytic cracking, gasification, mineral and metallurgical processes, etc. However, fluidized bed combustion (FBC) is, without doubt, one of its most important practical applications. (Fluidization Wikipedia 2013)

Some of the main advantages of fluidized beds in order to be used in combustion processes are the following:

- As a result of the high turbulence degree of the bed, the distribution of temperatures is very homogenous, even reaching a nearly isothermal state (Prieto 2013, 5).
- High heat transfer between bed particles and gases (Prieto 2013, 5).
- Heat exchangers may be placed in the bed ensuring a high heat transfer due to the violent agitation of bed particles (Prieto 2013, 5).

- The liquid behaviour of a fluidized bed makes it easier to remove or feed solids (Prieto 2013, 5).

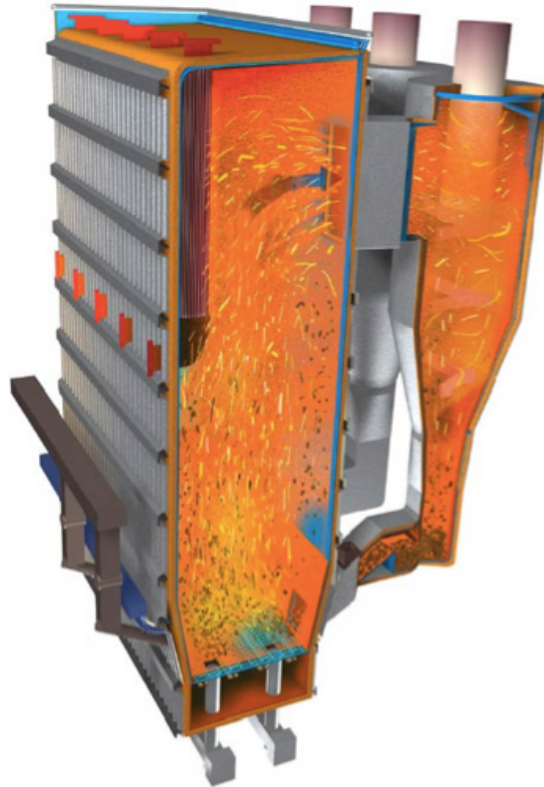


FIGURE 5. CFB boiler. (Teir 2003, 39)

There are two main kinds of fluidized bed boilers according to the fluidization speed:

- Bubbling fluidized bed (BFB) boiler
- Circulating fluidized bed (CFB) boiler

In BFB boilers fluidization speed is usually 1.2 m/s at full load, whereas in CFB boilers it is between 4.5 and 6,7 m/s. Both can work at high pressure for combined-cycle applications or at atmospheric pressure for steam generation. (Basu 2006, 7; Pascual Peña 2011, 3-4.)

As explained above, the speed of the upward gas current in CFB boilers is higher than in BFB boilers. For this reason, the number of drawn particles is also higher.

This fact brings about a cloud of suspended solids along the boiler tube, which is called “fast bed”. In this kind of boilers, a large number of drawn particles is collected by a high-temperature cyclone and recycled to the boiler (see Figure 5). Recycling increases the efficiency and maintains the bed height. Due to the high turbulence in CFB boilers, the chemical reactions are more complete. This causes a better fuel utilization and, as will be seen in later chapters of this report, a more efficient reduction of SO₂ emissions. (Teir 2003, 38; Prieto 2013, 23-24.)

2.2 Fluidized bed combustion

As already stated, fluidized bed combustion (FBC) is an important practical application of the phenomenon of fluidization. This combustion technology is used in power plants.

In fluidized bed boilers, a bed of particles is contained in the furnace chamber. This bed is preheated with an ignition system formed by one or many burners whose function is to raise the temperature of the bed and furnace chamber to 500-600 °C so as the initial ignition of the fuel is ensured. The burners heat the air that is injected into the furnace. In some boilers there are supplementary burners that preheat the upper part of the boiler and/or directly the surface of the bed. (Huttunen, 2 May 2013; Prieto 2013, 22.)

Firstly, the air speed is kept below the minimum fluidization speed until the bed temperature reaches 400-500°C. Once the minimum ignition temperature is reached, the fuel particles are fed into the furnace. The bed temperature and the amount of excess air must be monitored carefully. The fuel and air flow are increased gradually while, at the same time, the burner power is reduced and finally turned off. The fuel flow continues to grow until operating conditions are attained. Operating temperature of the bed is normally between 800 and 900 °C. (Prieto 2013, 22; Basu 2006, 6.)

On account of the chemical reactions that occur in the furnace the bed is composed of the following elements:

- Fuel particles: due to the high turbulences, the fuel is distributed evenly throughout the bed.
- Ash

- In most cases an inert additive such as sand or gravel (especially for burning low-ash fuels like woodchips)
- Sorbent: limestone or dolostone. This will be further explained in next chapter.

(Prieto 2013, 11-12; Basu 2006, 6.)

Fuel particles are constantly introduced into the combustion chamber through one or more feeders. When those particles come into contact with the hot fluidized bed they reach the ignition temperature almost immediately due to the high heat transfer typical of fluidized beds. The ash produced in the combustion process is extracted continually. Besides, the inert material and sorbent is also fed and removed continuously to avoid problems of excessive calcination. All these feedings and extractions are regulated ensuring that the weight of the bed remains approximately constant. (Prieto 2013, 7-8.)



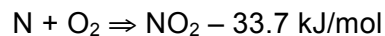
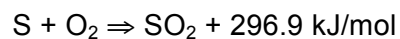
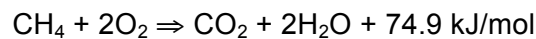
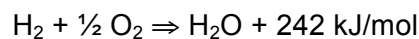
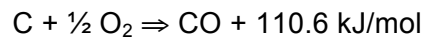
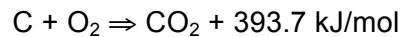
FIGURE 7. Fluidized bed combustion. (Teir 2003, 10)

The combustion process does not take place only in the fluidized bed but also in the stream of hot gases and particles above the bed. Some unburned components are generated in the upper part because of the lack of sufficient oxygen. It is important to mention that the air is injected into the furnace in different levels. Around 40% is inserted in the primary zone of fluidization through the gas distributor plate of the bottom (primary air). The rest of the air (secondary air) is inserted through numerous air

nozzles situated in the walls of the furnace. (Prieto 2013, 8; Sistemas de Generación Eléctrica 2012, 175.)

The unburned components of the bed rise through the boiler tube and react with the secondary air giving off a significant amount of energy. This phenomenon raises the temperature of the gases, which is generally higher than the temperature of the bed. This staged combustion increases the efficiency and reduces the formation of nitrogen oxides (NO_x). (Prieto 2013, 8; Basu 2006, 160)

The typical reactions that take place in the furnace are:



(Prieto 2013, 8.)

2.3 Reduction of pollutant emissions

2.3.1 Sulphur dioxide

Ever-tighter regulations on atmospheric emissions exclude important fuel resources due to their high sulphur content. The fluidized bed combustion of solid fuels is an alternative that has risen strongly worldwide in recent years.

In combustion processes, the sulphur contained in the fuel is oxidised producing sulphur dioxide (SO₂). The release of this polluting gas into the atmosphere is one of the main causes of acid rain. In conventional boilers, flue gas desulphurisation systems are indispensable in order to remove the SO₂ produced (Prieto 2013, 3).

One of the highlights of the fluidized bed boilers is the high sulphur retention in the bed. A sorbent, which is normally limestone, is fed into the furnace chamber. At atmospheric pressure, limestone particles are calcined by producing calcium oxide (CaO). This chemical compound reacts with the sulphur dioxide and produces gypsum (CaSO_4) that is removed with the ash. The desulphurization efficiency of this process is around 90 %. As a result, in this kind of boilers is not necessary to add a flue gas desulphurisation system to comply with the legislation of gas emissions. (Sistemas de Generación Eléctrica 2012, 173; Prieto 2013, 8-9.)

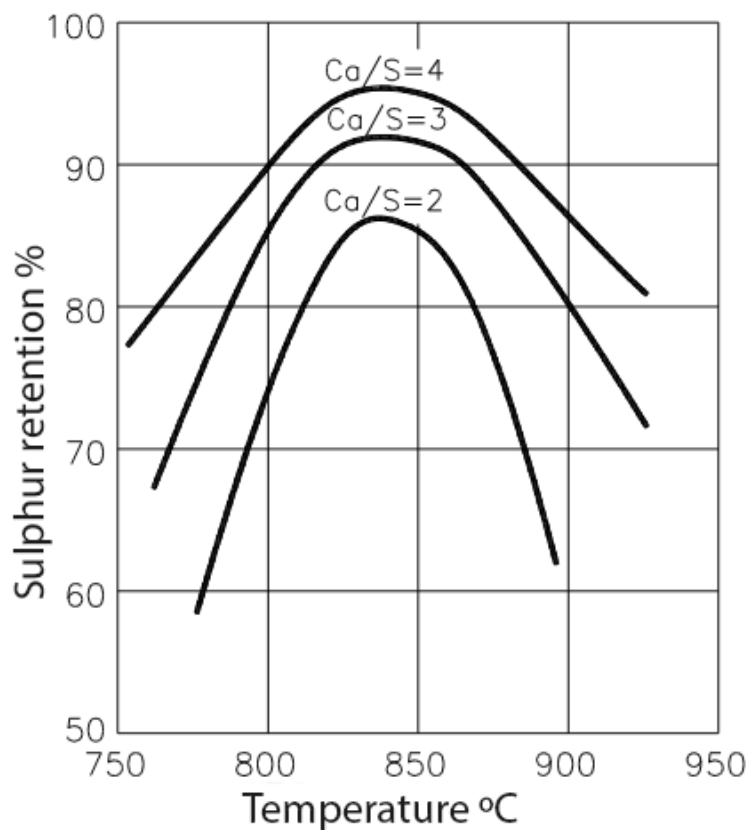


FIGURE 8. Relationship between bed temperature and sulphur retention percentage for different Ca/S ratios. (Prieto 2013, 10)

The efficiency of sulphur retention depends mainly on the following factors:

- Temperature of the bed: the optimal temperature is around 800 - 850 °C (see Figure 8). A temperature above the optimal range would cause a growth of the sulfation rate, plugging the pores of the CaO and, consequently, restricting the reaction with the sulphur dioxide. Furthermore, a higher temperature

would lead to the decomposition of gypsum. On the other hand, a temperature below the optimal range may cause a low calcination of limestone, which would cause inadequate sulphur retention. (Basu 2006, 151.)

- Ca/S ratio: The greater the ratio the greater the sulphur retention as can be seen in Figure 8 (Prieto 2013, 9).
- Residence time: A higher residence time of bed particles and gases results in a raise of desulphurization reactions (Prieto 2013, 9).
- Sorbent particle size: The efficiency of sulphur retention is higher when sorbent particles are smaller. This is due to the high contact surface between sulphur dioxide and calcium oxide. Small sorbent particles leave finer unreacted cores after sulfation. (Basu 2006, 155).
- Sorbent reactivity has a positive influence on sulphur retention (Prieto 2013, 9).

2.3.2 Nitrogen oxides

NO_x pollution is also considered as an important threat to the environment. A high concentration of these gases in the atmosphere (above 0.5 ppm) may cause acid rain, which has adverse effects on vegetation, water and aquatic species, buildings, etc. It can also affect human health and, in this sense, it is even more dangerous than sulphur dioxide. (U. S. Environmental Protection Agency 2012; Prieto 2013, 10)

NO_x may come from the oxidation of nitrogen from the air (giving thermal NO_x) or organic nitrogen from the fuel (giving fuel NO_x) (Energy Tech 2003). Formation of nitrogen oxides depends mainly on the following factors:

- Amount of Fuel-bound nitrogen: a high nitrogen proportion in the fuel increases the formation of nitrogen oxides (Prieto 2013, 10).
- Excess air ratio and combustion temperature (Basu 2006, 160). This relation can be seen in Figure 9.

Other methods to suppress efficiently the formation of nitrogen oxides are staged combustion as explained in chapter 2.2, as well as injecting ammonia (NH₃) into the cyclone or the higher part of the furnace (Basu 2006, 160-161).

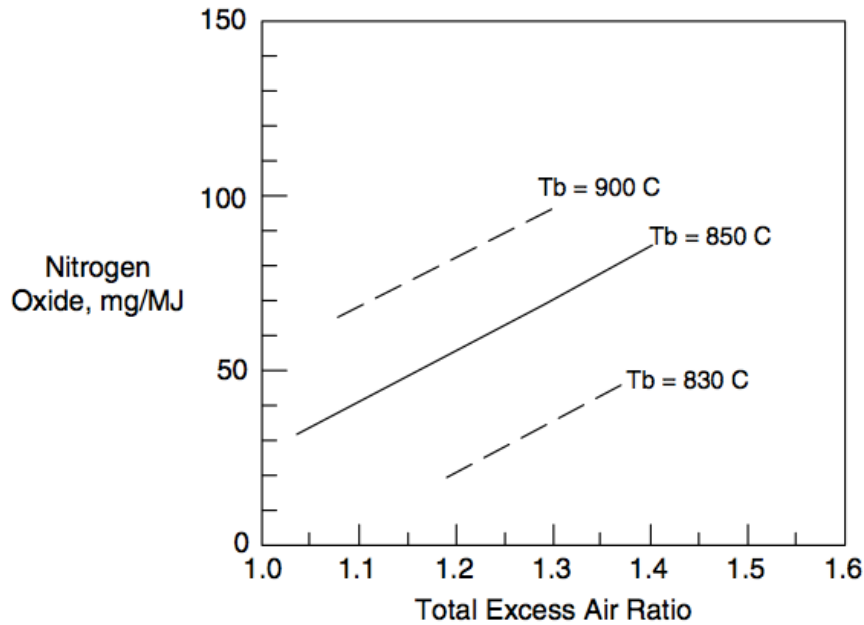


FIGURE 9. NO_x formation increases with combustion temperature and with excess air ratio. (Basu 2006, 160)

2.3.3 Particles

Fundamentally, the particles that are removed from the bed are composed of the ash contained in the fuel, gypsum produced by the reaction of calcium oxide with sulphur dioxide, inert material of the bed (only if it is necessary to feed it) and the amount of limestone that does not react. It is very important to reduce the emission of those particles into the atmosphere, mainly the smallest ones, because it has been linked to numerous respiratory and cardiac problems. (Clean Air Task Force 2004; Sistemas de Generación Eléctrica 2012, 176-177.)

These particles are taken out by means of the following systems:

- Bed drainage system: the major part is drained from the bed (bottom ash)
- Flue gas cleaning system: the rest is called fly ash and it leaves the furnace through the flue gas tube. It is collected by particulate collection equipment such as cyclones, electrostatic precipitators and filters.

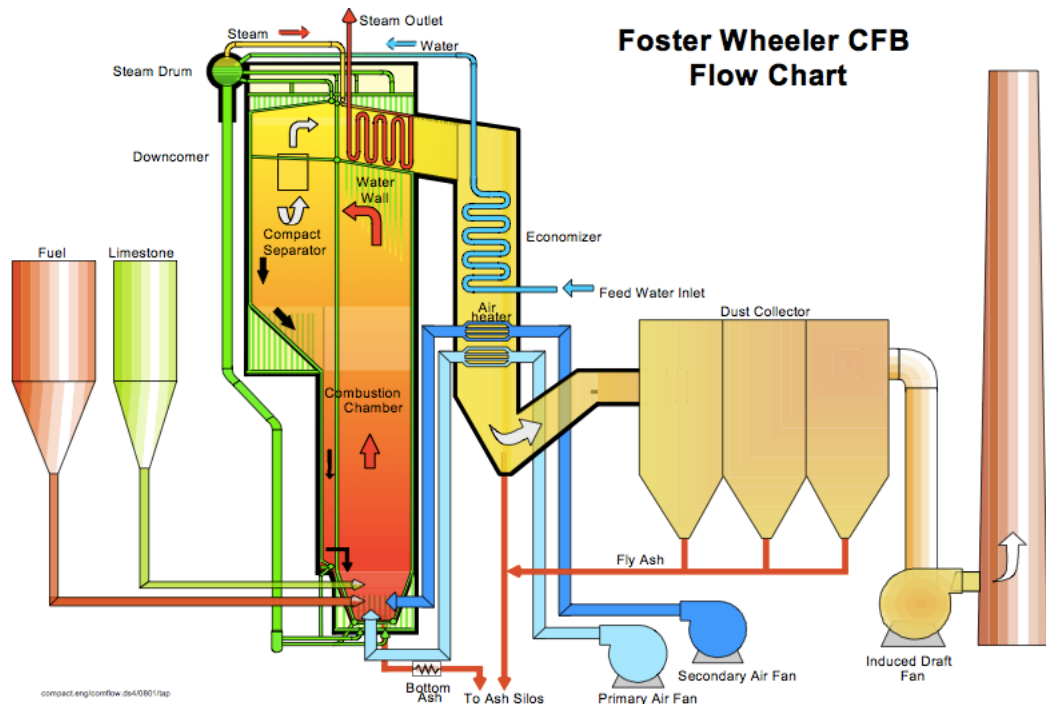


FIGURE 10. Structure of a CFB boiler with flue gas treatment facilities. (Teir 2003, 143)

2.4 Bed temperature

In fluidized bed boilers the combustion takes place in a low temperature bed. The furnace temperature of conventional boilers, such as grate furnace and pulverized coal fired (PCF) boilers, is much higher. Low temperature combustion is an advantage because the ash melts at higher temperatures and therefore there are no problems of slag formation in the furnace. Furthermore, as already explained, this relatively low combustion temperature reduces the formation of nitrogen oxides (NO_x). (Prieto 2013, 2.)

The most common temperature range of the bed is from 750 °C to 950°C. However, it is more appropriate to maintain the temperature between 800 °C and 900 °C in order to reduce the amount of SO_2 released. A higher temperature should not be reached because the ash would melt causing agglomeration. On the other hand, a lower temperature would result in a large amount of non-combusted components reducing the efficiency of the combustion process. Thus, due to the environmental and technical risks of reaching extreme temperatures it is recommended to keep the bed at a tem-

perature as close as possible to 850°C, which is considered the optimal operating temperature. (Prieto 2013, 9-11.)

2.5 Depth of the bed

Accepted values for the depth of the bed are usually from 15-20 cm (superficial bed) to 0,8-1m or more (deep bed). The choice depends on the desulphurization requirements. On the one hand, the combustion of fuels with high sulphur content requires a deep bed with a sorbent in order to comply with international regulations on atmospheric emissions. On the other hand, very low-sulphur fuels are commonly burned in superficial beds. In this case, the emissions of SO₂ are low so the bed does not have to be composed of limestone or dolostone to meet the requirements. It is possible to use an inert material such as sand only to achieve the phenomenon of fluidization. (Prieto 2013, 12.)

Furthermore, it is very important to take into account the ash content of the fuel. As mentioned above, the bed is also composed of the ash produced by the burning of the fuels and, consequently, the use of fuels with high ash content increases the depth of the bed (keeping the fluidization speed constant). (Prieto 2013, 12.)

2.6 Combustion efficiency

Combustion efficiency of a CFB boiler is normally between 97.5 and 99.5%. The efficiency of a BFB boiler is commonly lower, from 90 to 98%. (Basu 2006, 11.)

Combustion efficiency depends mainly on the following factors:

- High excess air reduces the amount of unburned components in the exhaust gases. Thus, excess air has a positive influence on the combustion efficiency. However, this improvement is less notable when the percentage of excess air is above 20 %. BFB boilers may need a slightly higher proportion of excess air than CFB boilers. (Basu 2006, 119).
- More reactive fuels have higher combustion efficiency (Prieto 2013, 13).

- Normally, the higher the temperature of the bed the higher the combustion efficiency (Basu 2006, 119). However, it should be kept around 850 °C to reduce the environmental and technical problems already explained.
- A deep bed provides longer residence time of fuel particles resulting in a reduction of total non-combusted components (Basu 2006, 121).
- A high density of fuel feeders has a positive influence on combustion efficiency (Prieto 2013, 13).
- High fluidization speed intensifies entainment of unburned particles reducing combustion efficiency. However, combustion efficiency improves with a high recirculation rate of fly ash. (Basu 2006, 119-121).
- Staged combustion increases combustion efficiency, especially in BFB boilers (Basu 2006, 121).

2.7 Advantages of fluidized bed boilers

Fluidized bed boilers have numerous significant advantages over conventional combustion technology:

- Enormous fuel flexibility: It is possible to burn a large variety of fuels like petroleum coke, biomass, combustible industrial wastes, low-grade coal, among others (Fluidized bed combustion Wikipedia 2013).
- This technology enables the disposal of combustible wastes providing significant cost saving (Prieto 2013, 14).
- It enables the combustion of low-grade fuels with high ash content (Prieto 2013, 14). This represents a major advantage over conventional boilers.
- The fuel particle size may be varied. It is not necessary to pulverize the fuel particles like in other technologies. (Prieto 2013, 14.)
- The ash does not melt on account of the low combustion temperature. Therefore, there are fewer problems of slag formation compared to conventional boilers resulting in a reduction of maintenance costs. (Prieto 2013, 14.)
- Heat exchangers may be placed in the bed or in the furnace walls ensuring a high heat transfer due to the violent agitation of bed particles (Prieto 2013, 14).
- High efficiency compared with conventional units. The efficiency (over lower heating value) of a BFB boiler is normally above 90 %. The efficiency of a

CFB boiler is commonly higher (up to 95%) on account of the high heat transfer and large internal solid recirculation. (Pascual Peña 2011, 3- 4.)

- High reduction of sulphur and nitrogen oxides emission (Sistemas de Generación Eléctrica 2012, 173).
- There are fewer corrosion problems (Prieto 2013, 14).
- Effective response to all the needs of energy. An increase of the load demand is satisfied relatively quickly (Prieto 2013, 14).
- Low combustion temperature reduces dangerous thermal shocks (Prieto 2013, 14).
- Less risk of breakdown because the furnace temperature is lower and there are fewer moving parts (Prieto 2013, 14).

A refined design is required to maintain the benefits for the whole power range, from small size boilers to 500-600 MWe or even more, and for a wide variety of fuels. ((Prieto 2013, 4; Jäntti, Nuortimo, Ruuskanen, & Kalenius 2012, abstract)

3 DESIGNING A SMALL-SIZED BFB BOILER FOR RESEARCH PURPOSES

3.1 Introduction to the design process

Once the main features of fluidized bed combustion have been explained, this section proceeds with the design process of the future combustion research laboratory that will be situated on Varkaus Campus.

The present thesis concentrates on the design of a small size bubbling fluidized bed (BFB) boiler, which will be used mainly for research purposes. The nominal power of this boiler will be between 250 kW and 300 kW in a normal bubbling fluidized bed regime (Huttunen 14 May 2013). However, it will be possible to reach a maximum power of up to 500 kW by reducing bed particles size and increasing the injected air speed (Huttunen 14 May 2013). Even so, a power of 500 kW is still relatively low compared with commercial size boilers (Jäntti et al. 2012, abstract). Fundamentally, a low power boiler has the following advantages:

- Reduced costs of construction, operation and maintenance
- The small size bed will permit to perform short-duration research tests
- It will not be necessary to use large quantities of fuel to perform experiments

However, it also has some disadvantages compared to bigger units:

- Changes in moisture occur fast
- A small size bed does not have enough heat capacity and, therefore, the bed behaviour changes easily
- The bed of particles may change quickly from balanced to unstable mode during tests
- A detailed simulation and calculation is necessary in order to extrapolate the results to large size boilers

The main reasons for designing a BFB boiler instead of a CFB boiler are basically economical and technical. The recirculation system of a CFB boiler entails increased investment costs as well as a most sophisticated design that would not mean significant advantages for the new lines of research that Savonia UAS R&D department wants to develop. (Huttunen 2 May 2013.)

In particular, the design process has focused on the following components:

- Windbox
- Boiler tube
- Ceramic layers
- Air nozzles
- Fuel feeder
- Sorbent and inert material feeder
- Maintenance flanges
- Flue gas measurement flanges
- Pipes for pressure and temperature measurement
- Bed material removal flange
- Exhaust gases tube

It is important to mention that the principal aim of this thesis was to carry out a preliminary graphic design of these components. Afterwards, an advanced heat and fluid dynamic simulation as well as a stress analysis should be done so as to ensure the reliability and proper operation of the installation. This means that the drawings of some components will probably be slightly modified in future stages of the design process.

All the drawings have been executed using SolidWorks, a computer-aided design program. Among many other things, this software enables the creation of a virtual three-dimensional model that can be easily modified. Thanks to this three-dimensional solution it is possible to make a detailed observation of the model to identify and correct any defect before it is approved for construction. Besides, this software enables a powerful simulation that will be necessary in further working stages. Therefore, the use of this kind of programs is almost indispensable for designing a complex installation such as this one.

The virtual model generated with this software is included in the CD attached to this document. Furthermore, the drawings created from this model can be seen in Appendix 2. These documents should be considered as the principal aim of this thesis.

In addition to the components listed above, the installation has more elements that form part of the following systems:

- Ignition system
- Bed drainage system
- Temperature control system
- Ammonia injection system
- Flue gas cleaning system

Some of the decisions about these systems that have been taken together with the supervisor of this thesis, Jukka Huttunen (14 May 2013), are included in the chapter 3.7. However, this report does not include the drawings of many components that form part of these systems because it is the task of other students that are also working on the design of this combustion laboratory.

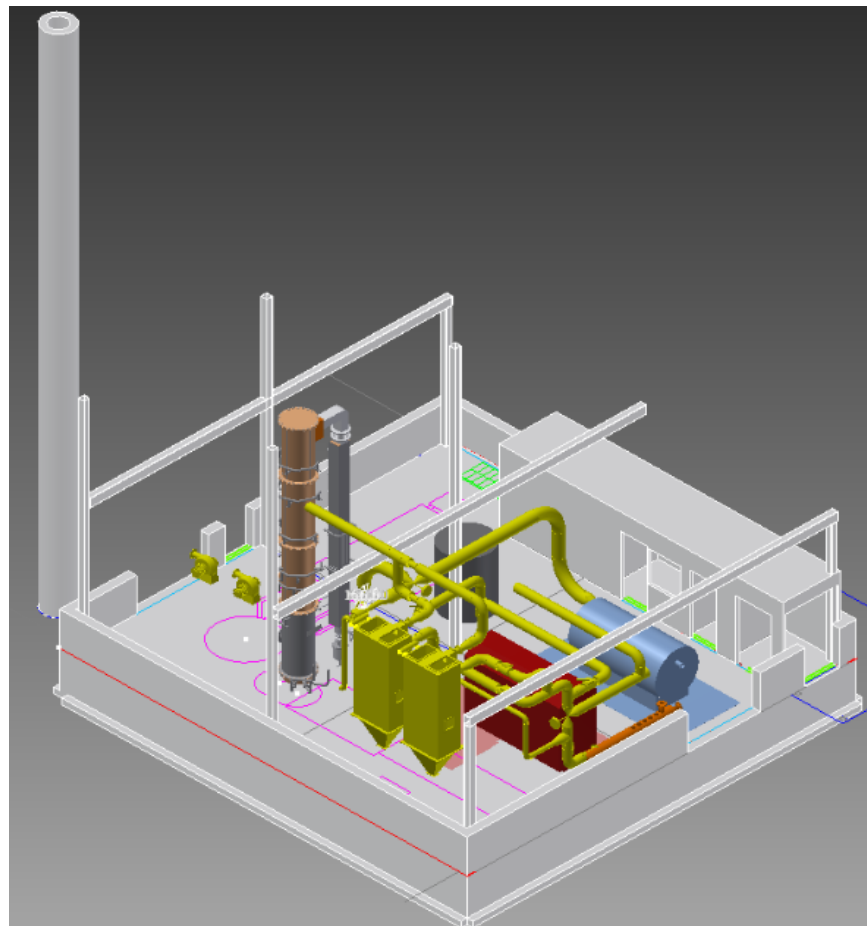


FIGURE 11. Preliminary laboratory layout (Savonia UAS 2013)

3.2 Reference design

The design process takes as a reference a BFB boiler built by the former company IVO (now part of Fortum Corporation). This small size boiler was sold to Kvaernev Power (now part of Metso) and then transferred to Lappeenranta University of Technology (LUT). Finally, it was disassembled due to the space requirements of a new nuclear power laboratory. (Huttunen 14 May 2013.) A three-dimensional representation of this model can be seen in Figure 12.

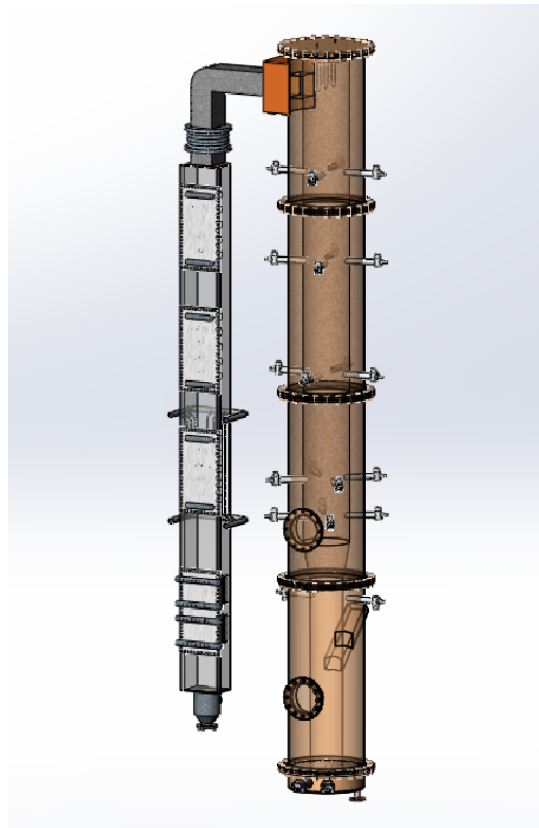


FIGURE 12. Reference design

All the efforts have been mainly directed towards improving the design of this boiler in technical and economical terms and adapting it to be used for research purposes. Firstly, it was observed that the reference design has many parts that are difficult and expensive to build. To solve this problem, these parts have been replaced by others that can be easily manufactured from standard components resulting in a considerable cost reduction. Besides, many tubes and components have been added to enable collecting data for research and control purposes throughout the entire boiler tube.

3.3 Final design: components of the assembly and identification numbers

As a result of the design process, almost all the components of the reference model have been entirely or partially modified. Figure 13 shows a graphic representation of the final design.

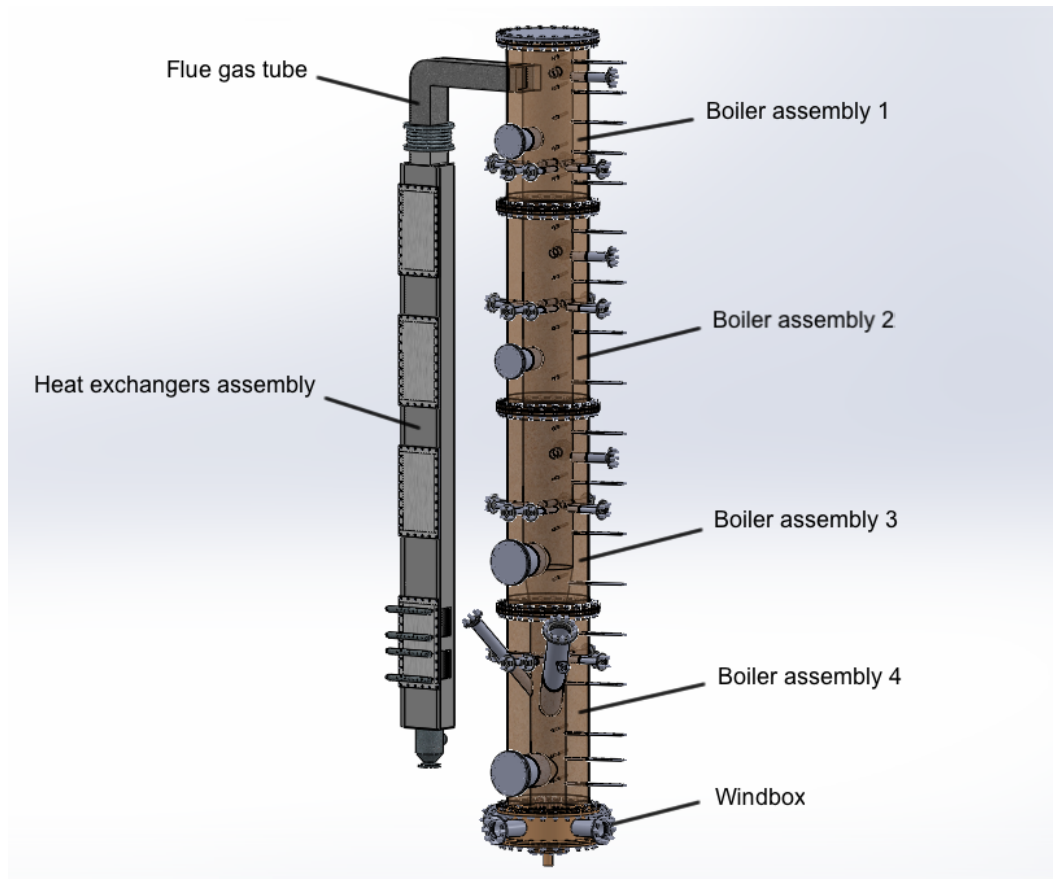


FIGURE 13. Final design

The three-dimensional model is divided into the following seven main assemblies. Each of them has its identification number in brackets:

- Boiler assembly 1 (1.01)
- Boiler assembly 2 (1.02)
- Boiler assembly 3 (1.03)
- Boiler assembly 4 (1.04)
- Windbox (1.05)
- Flue gas tube (1.06)

- Heat exchangers assembly (1.07)

The identification numbers permit to identify clearly each part or assembly and its corresponding drawing. These numbers are included in the title block situated on the lower right-hand corner of each drawing (see Appendix 2). The standards do not specify rules to assign these numbers, so each company or institution assigns them according to its own criterion. The criterion used in this thesis is based on the idea that identification numbers should provide information about the structure of the installation. The identification numbers are composed of different fields, each of them explained below. (Auria Apilluelo, Ibáñez Carabantes & Ubieto 2000, 15-16.)

From the last to the first, the fields are the following:

- 1) The last digit refers to a specific component of a subassembly
- 2) Subassembly to which the component belongs
- ...) Upper units
- n) Project number

(Auria Apilluelo, Ibáñez Carabantes & Ubieto 2000, 16.)



FIGURE 14. Identification numbers criterion. (Auria Apilluelo, Ibáñez Carabantes & Ubieto 2000, 16)

Therefore, the component whose identification number is, for instance, 1.05.01 belongs to the subassembly “Windbox” (1.05), which in turn is part of the general assembly “Boiler, flue gas tube and heat exchangers” (1.00) shown in Figure 13.

Table 2 shows a list of all the parts or subassemblies that form part of the general assembly with their corresponding identification number. Furthermore, the quantity of each component per assembly is also indicated.

TABLE 2. Parts and Subassemblies. Count per assembly

Id. Num.	Designation	Quantity per assembly
1.01	<i>Boiler assembly 1</i>	
1.01.01	Boiler tube 1	1
1.01.02	Ceramic layer 1	1
0.01	Short pipe for P and T measurement	10
0.02	Short air nozzle	8
0.03	Flue gas measurement flange	2
0.04	Maintenance flange DN 200	1
1.02	<i>Boiler assembly 2</i>	
1.02.01	Boiler tube 2	1
1.02.02	Ceramic layer 2	1
0.01	Short pipe for P and T measurement	8
0.02	Short air nozzle	8
0.03	Flue gas measurement flange	2
0.04	Maintenance flange DN 200	1
1.03	<i>Boiler assembly 3</i>	
1.03.01	Boiler tube 3	1
1.03.02	Ceramic layer 3	1
1.03.03	Short maintenance flange DN 300	1
0.01	Short pipe for P and T measurement	6
1.03.04	Pipe for P and T measurement - connection	2
0.02	Short air nozzle	8
0.03	Flue gas measurement flange	2
1.04	<i>Boiler assembly 4</i>	
1.04.01	Boiler tube 4	1
1.04.02	Ceramic layer 4	1
1.04.03	Fuel feeder-Air nozzle	1
1.04.03.01	Fuel feeder	1x1=1
1.04.03.02	Air nozzle of the fuel feeder	1x1=1
1.04.04	Sand feeder	1
1.04.05	Long maintenance flange DN 300	1
1.04.06	Long pipe for P and T measurement	10
0.02	Short air nozzle	4
1.04.07	Long air nozzle	4
1.05	<i>Windbox</i>	
1.05.01	Windbox bottom frame	1
1.05.02	Windbox air nozzle	4
1.05.03	Sump	1
1.05.04	Sand and ash removal flange	1
1.05.05	Windbox upper frame	1
1.06	<i>Flue gas tube</i>	
1.06.01	"Boiler-bellows" tube	1
1.06.02	"Bellows-heat exchangers assembly" connection	1
1.07	<i>Heat exchangers assembly</i>	
1.07.01	Tube for heat exchangers	1
1.07.01.01	Tube	1x1=1
1.07.01.02	Short bar	1x8=8
1.07.01.03	Long bar	1x8=8
1.07.02	Cover	4
1.07.03	Outflow pipes	1

In order to make machinist's work easier, the table below shows a list with all the components that appear in the Table 2 but, this time, the right column shows the quantity of each component needed to build the general assembly.

TABLE 3. Parts and subassemblies. General count

Id. Num	Designation	Total Quantity
0.01	Short pipe for P and T measurement	24
0.02	Short air nozzle	28
0.03	Flue gas measurement flange	6
0.04	Maintenance flange DN 200	2
1.01.01	Boiler tube 1	1
1.01.02	Ceramic layer 1	1
1.02.01	Boiler tube 2	1
1.02.02	Ceramic layer 2	1
1.03.01	Boiler tube 3	1
1.03.02	Ceramic layer 3	1
1.03.03	Short maintenance flange DN 300	1
1.03.04	Pipe for P and T measurement - connection	2
1.04.01	Boiler tube 4	1
1.04.02	Ceramic layer 4	1
1.04.03	Fuel feeder-Air nozzle	1
1.04.03.01	Fuel feeder	1x1=1
1.04.03.02	Air nozzle of the fuel feeder	1x1=1
1.04.04	Sand feeder	1
1.04.05	Long maintenance flange DN 300	1
1.04.06	Long pipe for P and T measurement	10
1.04.07	Long air nozzle	4
1.05.01	Windbox bottom frame	1
1.05.02	Windbox air nozzle	4
1.05.03	Sump	1
1.05.04	Sand and ash removal flange	1
1.05.05	Windbox upper frame	1
1.06.01	"Boiler-bellows" tube	1
1.06.02	"Bellows-heat exchangers assembly" connection	1
1.07.01	Tube for heat exchangers	1
1.07.01.01	Tube	1x1=1
1.07.01.02	Short bar	1x8=8
1.07.01.03	Long bar	1x8=8
1.07.02	Cover	4
1.07.03	Outflow pipes	1

As can be seen in Table 2 and Table 3, the criterion used in the following components is different to the one explained above:

- “Short pipe for P and T measurement” (0.01)
- “Short air nozzle” (0.02)
- “Flue gas measurement flange” (0.03)
- “Maintenance flange DN 200” (0.04)

The reason for this new criterion is that these components belong to different assemblies. In other words, they are repeated in different constructional units and, consequently, they cannot be defined as part of only one of them. The group 0 has been created to identify these common components. On the other hand, the rest of the components belong to only one assembly and, therefore, the quantity per assembly and the total quantity are the same.

3.4 Documentation of selected solutions and decisions

The aim of this chapter is to describe the function of the main components as well as to explain the selected solutions and decisions in order to design this installation.

3.4.1 Windbox

As already explained, the upward movement of the air bubbles through the bed causes turbulences similar to a boiling liquid (Prieto 2013, 17). This phenomenon is the reason why it is called bubbling fluidized bed boiler. The device that injects the primary air into the furnace is called windbox.

An image of the windbox can be seen in Figure 15. However, a clearer representation of this unit can be seen in the drawing 1.05 included in Appendix 2.

This assembly consists of the following main elements:

- Windbox bottom frame (1.05.01)
- Windbox air nozzle (1.05.02)
- Sump (1.05.03)
- Sand and ash removal flange (1.05.04)

- Windbox upper frame (1.05.05)

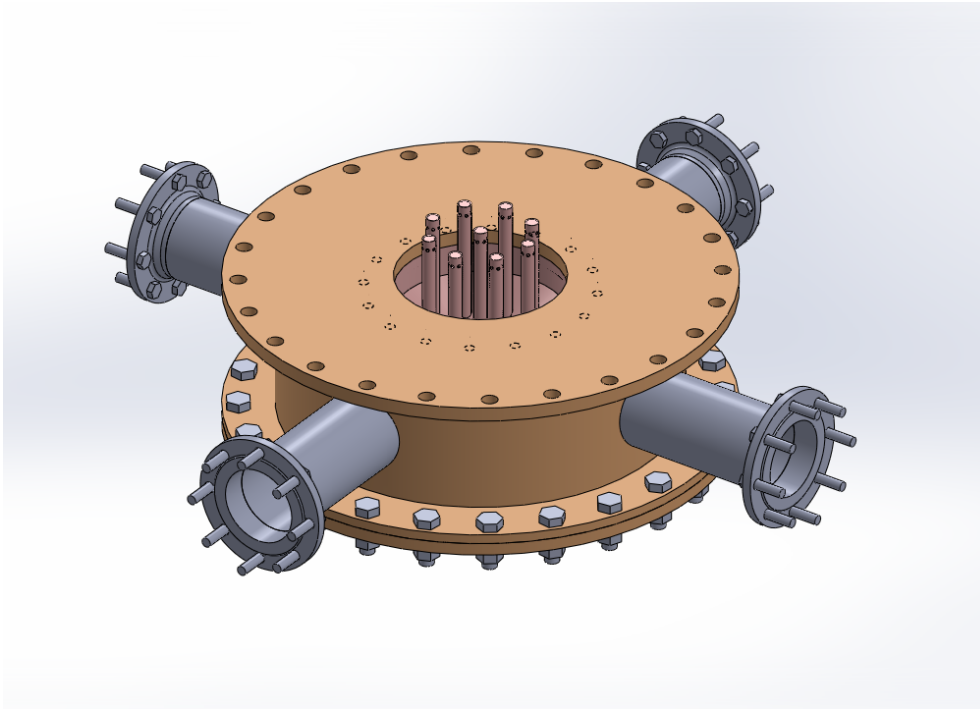


FIGURE 15. Windbox

Particular attention has been paid during the design process to ensure that the assembly and disassembly of all the components can be done without difficulty.

Figure 16 shows a section of the windbox in which the bed material drainage and primary air flow are graphically represented.

Under normal operating conditions, the primary air is preheated in heat exchangers situated in the flue gases tube. After that, it is injected into the windbox chamber through the “windbox air nozzles” (1.05.02). Afterwards, the air goes upwards through the air nozzles of the “sump” (1.05.03) and enters into the furnace causing the fluidization of the bed (only if the air speed is above the minimum fluidization speed).

Furthermore, the windbox assembly has another function. The greater part of the ash produced in the combustion process (bottom ash) goes downwards through the “sump” (1.05.03) and the “sand and ash removal flange” (1.05.04) as can be seen in Figure 16. This process is called bed material drainage. A brief summary about the system that enables this process is included in chapter 3.7.2.

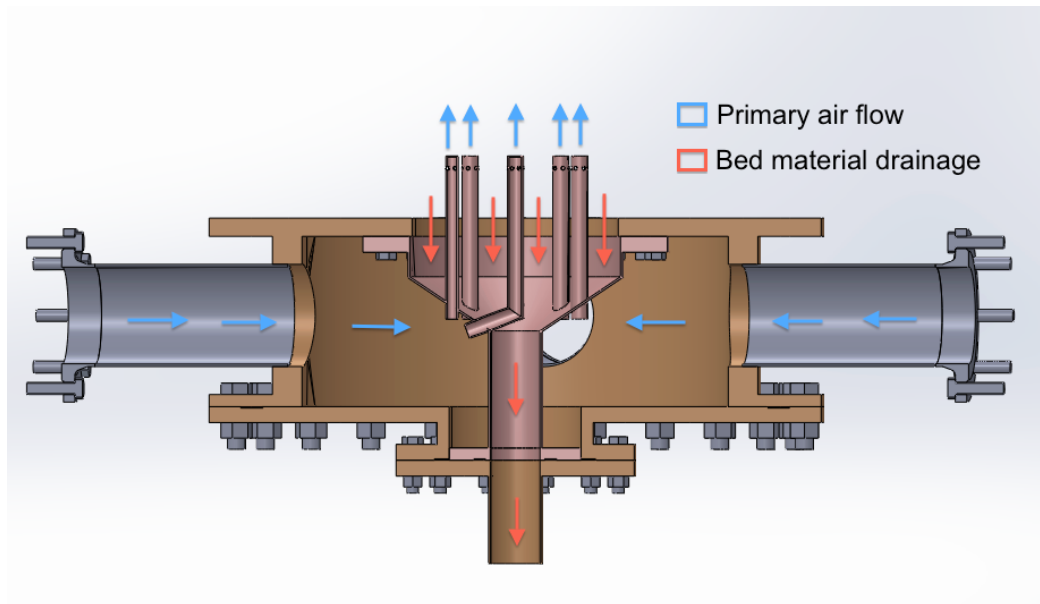


FIGURE 16. Windbox section. Bed material drainage and primary air flow

The figure below shows a detailed view of the air nozzles through which the fluidized air is injected into the furnace. A cap covers the upper part of each tube and the orifices are drilled in the lateral surface so as to reduce significantly the amount of bed material that enters into the pressurized air chamber. However, in spite of this design some particles of the granular material may go downwards through the nozzles. Besides, the ignition system (see chapter 3.7.1) injects flue gases into the pressurized chamber that may cause slag formation on the walls. To solve these problems the bottom part of the windbox can be easily taken apart enabling maintenance operations.

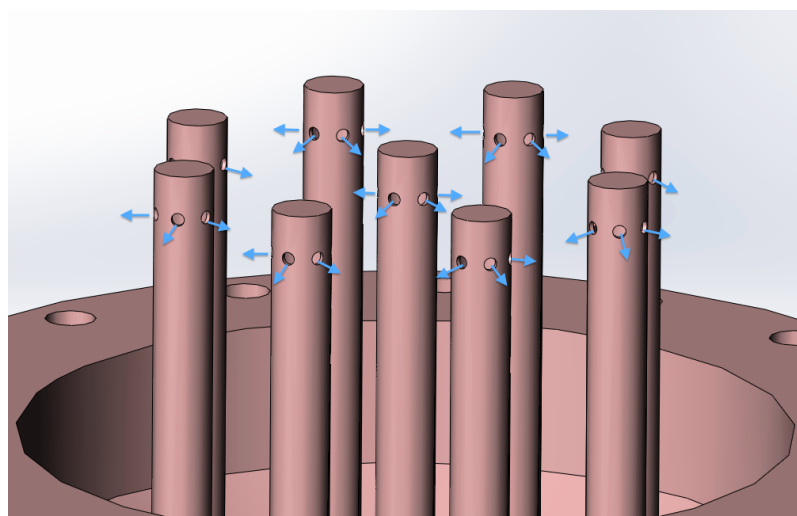


FIGURE 17. Sump air nozzles

3.4.2 Furnace

The furnace is the chamber where the combustion takes place. The figure below shows a representation of this device along with all the peripheral pipes and flanges that enable data collection as well as bed material, fuel and air feeding. The size of this device is large enough to simulate the real behaviour of a commercial scale furnace.

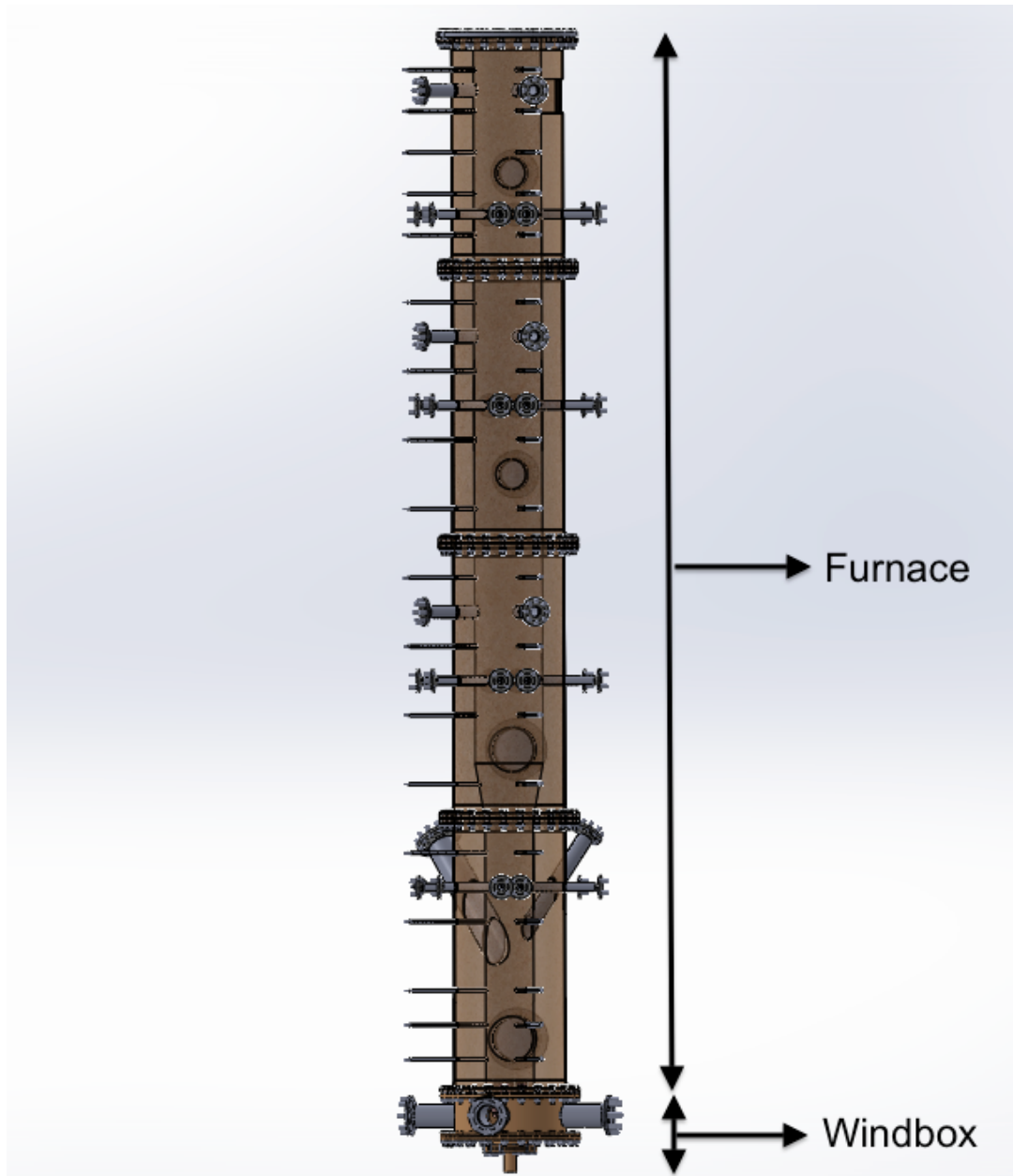


FIGURE 18. Furnace and windbox

In order to simplify the design, the furnace is divided into the following four assemblies (see Figure 13).

- Boiler assembly 1
- Boiler assembly 2
- Boiler assembly 3
- Boiler assembly 4

The bed of particles is contained in the bottom part of the furnace (Boiler assembly 4). The operating temperature of the bed will normally be between 820 °C and 860 °C (Huttunen 2 May 2013). It is very important to operate in this range of temperatures in order to comply with international regulations on atmospheric emissions and avoid problems of slag formation.

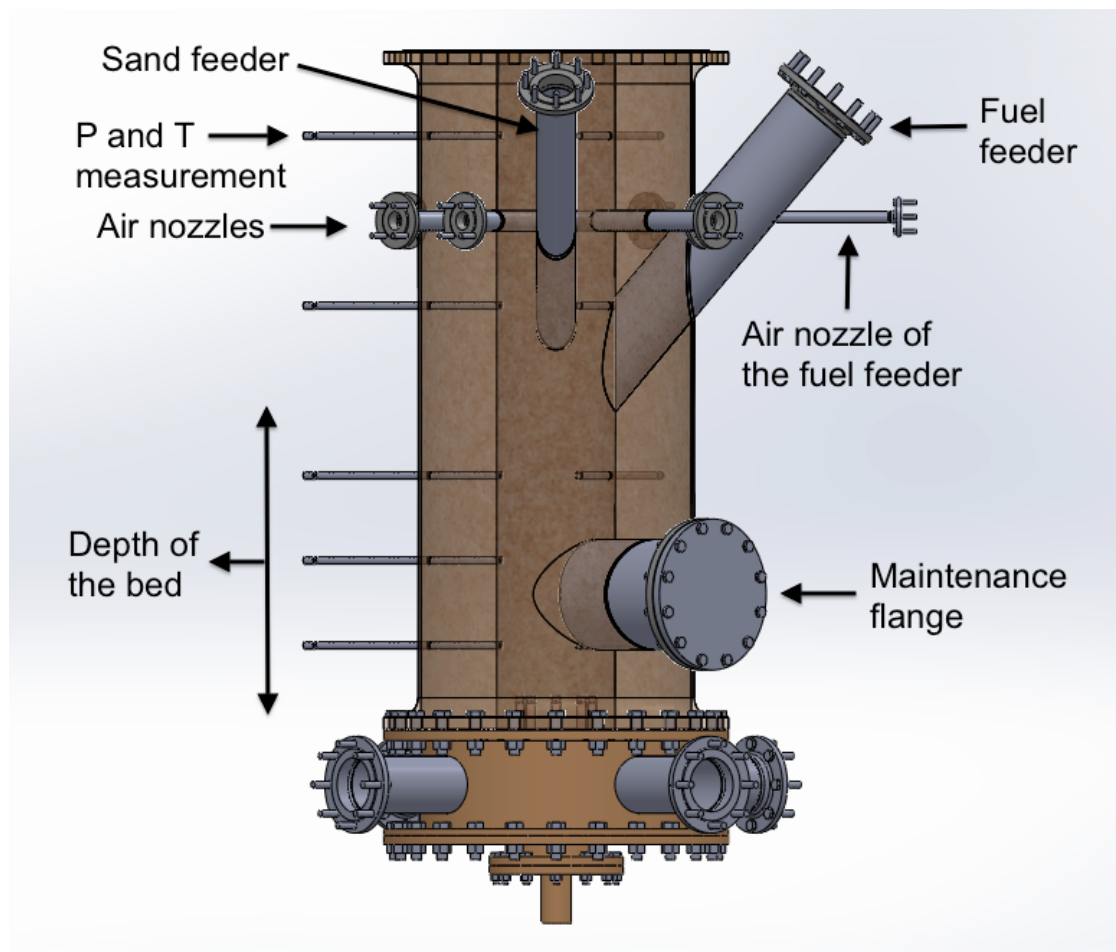


FIGURE 19. Boiler assembly 4

Figure 19 shows a three dimensional representation of the bottom part where the bed is contained. Both the outer boiler tube (1.04.01) and the inner ceramic layer (1.04.02) are represented with a high transparency degree in order to show the combustion chamber. Ceramic materials are strong, non-conductors of heat and chemically inert (Ceramic materials Wikipedia 2013). Besides, they can withstand high temperatures (Ceramic materials Wikipedia 2013). These features make them a perfect material to be used in the walls of combustion chambers.

In addition to the ceramic layer and boiler tube, an outer insulating layer is necessary to reduce heat losses and improve the overall efficiency (this layer is not represented in the figures).

As already explained in the theoretical background of this report, one of the main advantages of commercial size fluidized bed boilers is that heat exchangers can be placed in the bed or in the furnace walls increasing heat transfer due to the high turbulence degree of the granular material and gases (Prieto 2013, 14). However, placing heat exchangers inside of a small size furnace would cause a significant reduction of combustion temperature (Huttunen 14 May 2013). This would decrease combustion efficiency and pollutant gases retention. Besides, research data collected in this boiler could not be extrapolated to large size boilers if combustion temperature is different.

It is important to mention that the depth of the bed will be around 1.2 m (deep bed) (Huttunen 15 February 2013). The choice depends mainly on desulphurization requirements (Prieto 2013, 12). The combustion of fuels with high sulphur content requires a deep bed with a high proportion of sorbent. In this case, the sorbent will be limestone due to its high sulphur retention at low pressures (Prieto 2013, 9). The combustion process takes place at a pressure slightly lower than the atmospheric one (around -40 mbar) in order to reduce the risk of flue gas leakage (Huttunen 2 May 2013).

Limestone particles along with inert material enter into the furnace through the “sand feeder” (1.04.04). This feeding is typically done by gravity (Prieto 2013, 20). The material is stored in a silo and it goes downwards through a pipe (Prieto 2013, 20). In some cases, a rotary valve controls the amount of material that enters the furnace (Prieto 2013, 20). Simultaneously, fuel particles are introduced constantly into the combustion chamber through the “fuel feeder” (1.04.03.01). The function of the lateral pipe called “air nozzle of the fuel feeder” (1.04.03.02) is injecting air in order to loosen

the fuel particles, especially when their moisture content is high (Huttunen 13 April 2013).

The combustion process takes place both in the fluidized bed and in the stream of hot gases and particles above the bed. Secondary air is injected in four different levels along the boiler tube. This staged combustion increases the efficiency and suppresses efficiently the formation of nitrogen oxides (Basu 2006, 160).

The air nozzles are arranged around the boiler tube as can be seen in Figure 20. The main purpose of this particular disposition is increasing the turbulence degree so as to ensure a high fuel-air mixing. The air flow rotates spirally along the furnace and reacts with unburned components that rise from the fluidized bed giving off a significant amount of energy.

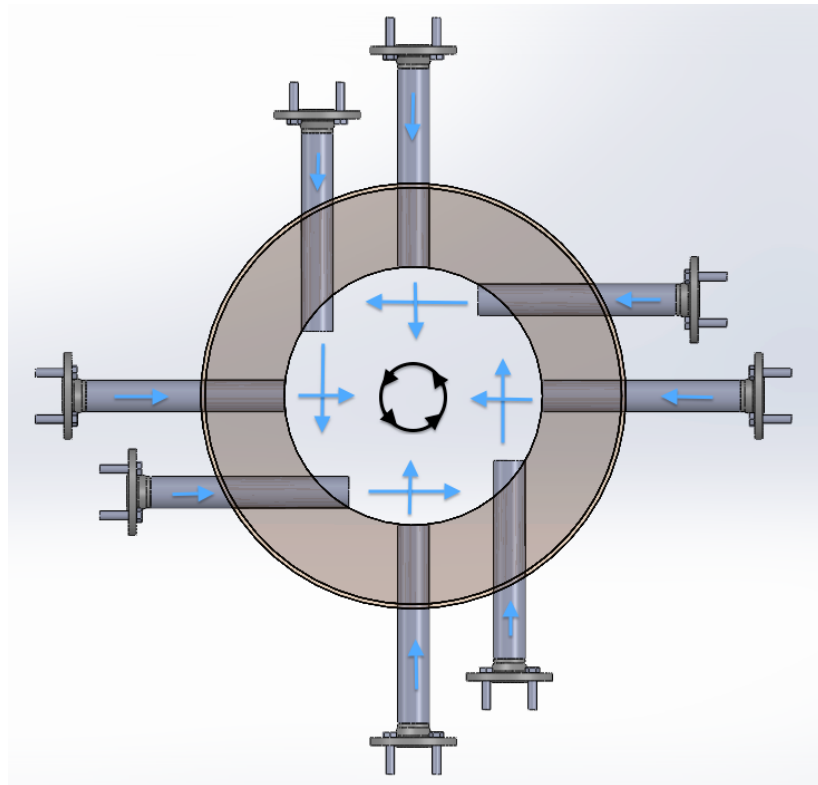


FIGURE 20. Secondary air injection

In commercial size boilers this phenomenon raises the temperature of the gases, which is generally higher than the temperature of the bed. However, on account of the high surface-to-volume ratio of this research boiler, the heat transfer through the furnace walls is very high and therefore, the gas temperature would be lower than in

commercial size boilers. Obviously, the validity of the collected research data depends on achieving similar combustion conditions as in commercial scale boilers. In order to solve this serious problem, an additional system to control the gas temperature is being designed (see chapter 3.7.3). (Huttunen 14 May 2013.)

In addition to maintenance flanges (see figure 19) and feeders, there are other elements throughout the boiler tube whose purpose is collecting research and control data:

- Flue gas measurement flanges: Their function is analysing the exhaust gas released in the combustion process and carrying out corrosion probes. These flanges are located at three different levels in order to know the proportion of pollutants and unburned components in different parts of the boiler. Thus, these flanges along with the correspondent measurement devices will enable the comparison of combustion efficiency and emissions with different operating conditions: fuels, air speeds, temperatures, sorbents, etc.

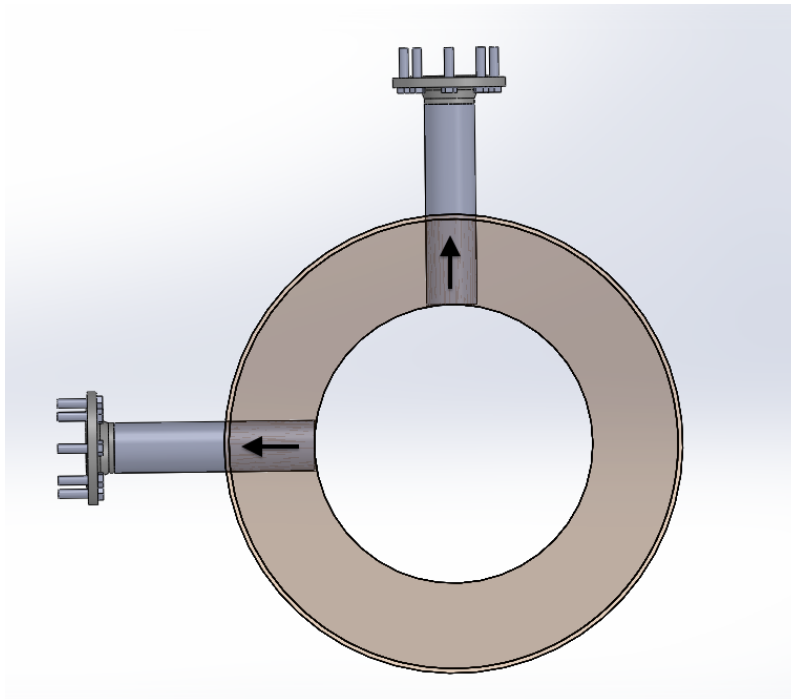


FIGURE 21. Flue gas measurement flanges

- Pressure and temperature measurement pipes: They are located along the entire boiler tube. Basically, they will enable the analysis of the fluid dynamic and thermal behaviour of the installation. The density of these pipes is higher in the bottom part of the furnace due to the particular importance of monitoring the combustion conditions of the fluidized bed.

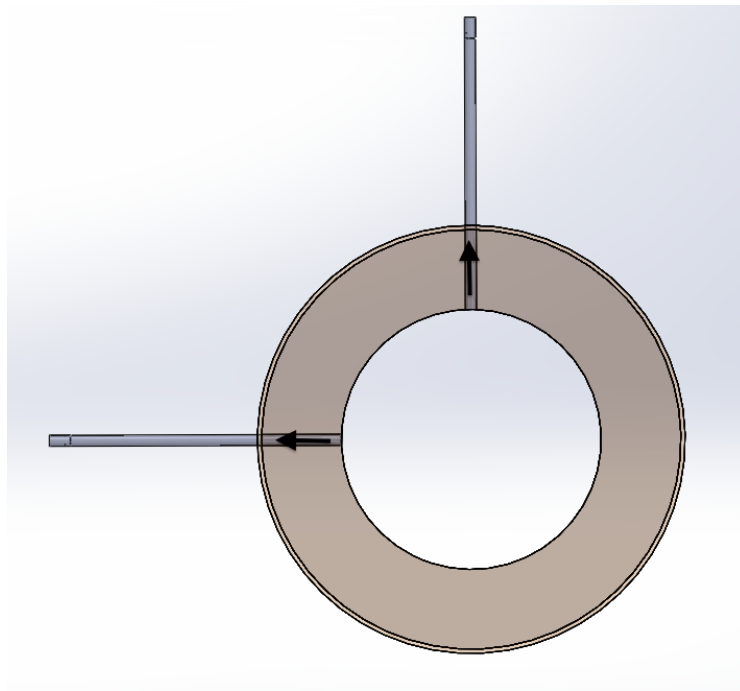


FIGURE 22. Pressure and temperature measurement pipes.

3.4.3 Exhaust gas tube

The exhaust gas tube has been divided into the following two assemblies (see figure 13) on account of its large size:

- Flue gas tube (1.06)
- Heat exchangers assembly (1.07)

The hot flue gases rise to the top of the furnace and go out through the “flue gas tube”. Afterwards, they come into contact with the heat exchangers pipes in the “heat exchangers assembly”.

The drawings of these elements can be seen in Appendix 2. The detailed view below shows the top part of the “heat exchangers assembly”.

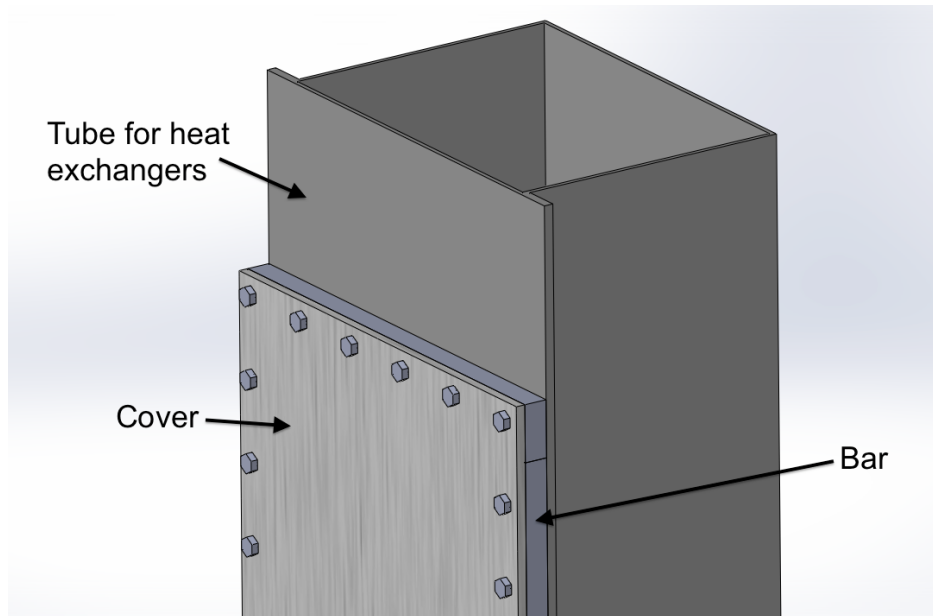


FIGURE 23. Detailed view of the “heat exchangers assembly”

As can be seen in the figure, the frontal plate of the “tube for heat exchangers” (1.07.01) is too thin to support the bolts of the cover. To avoid this problem, welded bars have been added to the design.

Besides, three more covers have been placed along the exhaust gas tube. The function of these covers is to enable the assembly of heat exchangers inside the tube. In the current design only two heat exchangers have been assembled below one of the covers. These heat exchangers will be used to preheat the primary and secondary air before it enters the combustion chamber. The function of the rest of the covers is to enable a possible future assembly of the following devices:

- Superheater: superheats the saturated steam
- Economizer: preheats the water up to the boiling point

However, the budget for the construction of this laboratory is limited and therefore, there is little prospect of buying these expensive heat exchangers, at least in the short term (Huttunen 14 May 2013). Furthermore, an evaporator would be required to

produce steam resulting in, as already explained, technical problems to maintain the suitable combustion temperature in the furnace (Huttunen 14 May 2013). It should not be forgotten that this boiler will be used mainly for research purposes.

Once the flue gas leaves this tube it goes through fly ash cleaning devices (see chapter 3.7.5) and enters an Organic Rankine Cycle (ORC) heat recovery boiler where water is heated. The stream of hot gases leaves this device at a temperature of approximately 180 °C. (Huttunen 14 May 2013.)

3.5 Standard components

Almost all the parts and assemblies that make up this unit can be manufactured from the following standard components:

- Flanges
- Spades
- Pipes
- Bolts
- Nuts
- Muffs
- Pipe reducers
- Bellows

The tables in Appendix 1 show a complete list of all these components along with the identification number of the drawing in which they are included.

3.6 Connecting elements and welds

Basically, there are two different connections between the structural elements of this installation:

- Permanent joints.
 - 1) Gas tungsten arc welding, also known as tungsten inert gas (TIG).
 - 2) Shielded metal arc welding
- Detachable joints: bolts and nuts.

Furthermore, graphite sealing and ceramic material will be necessary in all the flanges to reduce leakage risks.

All the connecting components and welds of the installation can be seen in the drawings of Appendix 2.

3.7 Additional systems

The design process of this thesis has focused on the elements that have been explained in previous chapters. However, there are more systems that form part of this installation.

Due to the large scale of this project, only the main features of the most important systems are explained below.

3.7.1 Ignition system

The function of the ignition system is to raise the temperature of the bed and boiler so as the initial ignition of the fuel is ensured. This is accomplished by two kinds of burners (Huttunen 14 May 2013):

- An external wood pellets burner: the hot flue gases released in the pellets combustion are injected into the windbox and, immediately afterwards, these gases go upwards through the nozzles of the “sump” (1.05.03) entering the furnace (Huttunen 14 May 2013).
- Oil burners placed in different parts of the furnace and flue gas tube (Huttunen 2 May 2013).

These burners preheat the temperature of the bed and boiler to 500 °C (sometimes as high as 600 °C) before solid fuel feeding sequence is started. The fuel and air flows are increased gradually while, at the same time, the power of the burners is reduced. (Huttunen 2 May 2013.)

Normally, the fuel feeding sequence is the following (the range of temperatures for each fuel appears in brackets):

- 1) Wood pellets (500-700 °C)
- 2) Wood chips (700-850°C)
- 3) Waste fuels (once the operating conditions are reached)

(Huttunen 2 May 2013.)

3.7.2 Bed drainage system

The greater part of the ash produced in the combustion process (bottom ash) goes downwards through the “sump” (1.05.03) and the “sand and ash removal flange” (1.05.04) as can be seen in Figure 15. This process is called bed material drainage. This extraction has to be regulated to ensure that the weight of the bed remains approximately constant.

In addition to these components, the bed drainage system includes:

- Extraction tube
- Cooling system to reduce the ash temperature
- Rotary valve
- Cooled screw feeder
- Screen
- Ash tray

(Huttunen 14 May 2013.)

3.7.3 Temperature control system

Research data collected in this boiler cannot be extrapolated to large size boilers if combustion temperature is different. Due to the high surface-to-volume ratio of this research boiler, the heat transfer through the furnace walls is very high and, therefore, a supplementary heating system is necessary in order to operate at suitable temperature conditions along the entire boiler tube. Besides, when wastes are burned it is necessary to reach a temperature of 1100 °C in the flue gas tube for at least two seconds in order to comply with environmental regulations. (Huttunen 14 May 2013; Marín, Monné. & Uche 2007, 32)

This is achieved by the same burners used during the ignition process (see 3.7.1):

- An external wood pellets burner
- Oil burners placed in different parts of the furnace and flue gas tube

(Huttunen 14 May 2013.)

The only difference is that the hot flue gases released in the pellets combustion are not injected into the windbox. This time those gases go through spiral pipes placed in the ceramic layers of the furnace. Thus, heat is exchanged directly with the boiler tube without injecting flue gases into the furnace. Those pipes can also be used as a cooling system when the combustion conditions require it. (Huttunen 14 May 2013.)

3.7.4 Ammonia injection system

Ammonia (NH_3) injection into the upper part of the furnace is a method to suppress efficiently the formation of nitrogen oxides. Normally, one part of this component is mixed with three parts of water. The injection of this aqueous solution in the flue gas causes chemical reactions that convert the nitrogen oxides to free nitrogen and water. (Huttunen 2 May 2013.)

3.7.5 Flue gas cleaning system

The fly ash that leaves the furnace through the flue gas tube is collected in a very high proportion with the flue gas cleaning system, which is installed downstream after the boiler. Basically, this system consists of the following components:

- Ceramic bag filters
- Flue gas scrubber
- Cyclon
- Electrostatic precipitator

(Huttunen 14 May 2013.)

4 CONCLUSIONS

The objective set in the beginning of this thesis, carrying out an optimal design in technical, environmental and economical terms of a small size BFB boiler, has been fully achieved. The design process has focused on adapting the reference design provided by Lappeenranta University of Technology to be used for research purposes and bringing construction and operating costs down. As a consequence of this process, almost all the components of the reference model have been entirely or partially modified. The result is an efficient and environmentally friendly boiler that is going to enable numerous testing services and lines of research.

Furthermore, active participation in the design of other systems that form part of this combustion facility has been crucial to ensure an optimum connection between all components and a better understanding of the general installation. In this regard, the lecturer Jukka Huttunen has played an essential role in the coordination of the teams involved in the design process.

This thesis is without doubt an important step towards the construction of the future combustion research laboratory of Varkaus Campus and I am extremely proud of having contributed to such an important project.

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