Modelling of Biomass Combustor
Final assignment Energy from Biomass

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Summary

In this study a 1.1 MW fluidized bed combustor is modeled. A literature study is performed on aspects which determine the characteristics of the combustor. A model is set up and calculations for the design of the Fluidized Bed Combustor (FBC) are performed. Characteristics are calculated for the Fluidized Bed (FB) and Freeboard Zone (FBZ). Matlab is used to perform simulations and generate specific parameters for the design of the FBC.

The report starts with an introduction on the FBC, from the sustainable and technological point of view. In Chapter 1 a short overview of the history of biomass is given, from where the link to the FBC design is made. The general aspects of a FBC are stated.

Chapter 2 shows the results of the literature study. In particular attention is paid to the formation of greenhouse gasses, which play an important role in power generation and thus in FBC’s. Possibilities to reduce these pollutants are mentioned. It is explained why the formation of thermal $NO_X$ is primarily dependent on the temperature and stoichiometry. In the model the formation of thermal $NO_X$ is neglected, since the reaction temperature is too low to generate significant amounts of $NO_X$. Fuel $NO_X$ seems to contribute in a larger amount to the $NO_X$ formation, but the contribution is still insignificant in the model. The formation of Carbon Monoxide (CO) plays a more important role. This formation is directly related to the mixing of fuel and air at sufficient temperature. To reduce the CO formation, an optimal air to fuel ratio and a greater residence time are suggested.

In Chapter 3 the design of the model is presented. This chapter starts with the outcome of the literature study, where the principles of the FBC are described. After that, a list of assumptions is presented. The overview of the assumptions is specified and worked out for the different reactor zones in the FBC: the Fluidized Bed, the Splashing Zone and the Freeboard Zone.

Chapter 4 elaborates on the air speed in the FBC. The air speed affects important running characteristics such as the behavior of the sand particles in the bed, the burning efficiency and the formation of greenhouse gasses. It is also an important parameter for the determination of the dimensions of the FB and FBZ. This chapter concludes with a section including numeric values and results of the calculations are presented, which in turn are used for the calculations on the combustor model.

The complete model is presented in Chapter 5. Detailed calculations on the model are explained, starting with the combustion reactions. This model description includes molar ratio’s, caloric values and mass flows. Furthermore specific energy balances are shown for each section of the combustor. Finally, the wall losses are defined.

A summary of the results can be found in Chapter 6. Results of energy balances and efficiency are presented and a clarification of the temperature profile is given. This document concludes with a discussion on the obtained results and the limitations of the model.
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Chapter 1

Introduction

Almost all studies and literature on biomass refer to the reduction or migration of greenhouse emissions [16], [17], [18]. This nowadays is a hot topic on different levels; globally and locally, from political point of view all the way down to companies and individuals. The increasing energy demand together with the depletion of fossil fuels cause a rising oil price and these are strong motivators in the research for alternative energy sources [2]. Biomass is one of humanity’s earliest energy sources since the ability to control fire. In recent years biomass utilization has been attracted the attention again due to the above described motivations.

This causes an energy shift from fossil fuels, which have been dominating the world’s energy supplies for decades, to renewable energy sources including biomass. Today bio-energy represents about 14% of the world’s primary energy supply. About 25% of the usage is in industrialized countries and the other 75% is being used in developing countries [19]. It should be noted that a large part of the biomass usage in developing countries is noncommercial and used for cooking and space heating generally by the poorer part of the population.

The use of biomass in power plants is primarily done in industrialized countries where technology and finances are available. There are a number of technological options available to make use of a wide variety of biomass types. Conversion technologies may release the energy directly, in the form of heat or electricity, or may convert it to another form, such as liquid biofuel or combustible biogas. In this document the research is limited to the thermal conversion process of biomass into electric energy particularly in a Fluidized Bed Combustor (FBC).

Fluidized bed combustion has many advantages over other methods of (bio)energy production. FBC is indicated as one of the most promising techniques, because of its flexibility, high combustion efficiency and low environmental impact [20]. The FBC plants can be fired on different fuels such as coals and a variety of biomass products.

In a FBC solid fuels particles float on upward-blowing jets of air during the combustion process. This results in a turbulent mixing of gas and solids. The tumbling action, much like a bubbling fluid, provides more effective chemical reactions and heat transfer.

The specific researched and modeled combustor is a combined heat and power system for woody fuel. This reactor is developed in a joint effort of TU Delft and Crone in cooperation with Tri-O-Gen. The electricity is produced by an organic Rankine turbine of 800 kW thermal.

In figure 1.1, a general overview of a FBC reactor is shown. The combustion air is injected at the bottom of the reactor and the fuel enters from the top. In the beginning the biofuels float on top of the fluidized bed and get dispersed on top of the bed. The fuel is being mixed in the FB and in the meantime heat up, dry and volatiles are released. During this they loose weight and finally start to flow upwards. Finally the fuel particles reach their terminal velocity and rise up in the air and leave the boiler as flue gas (FG). From the fuel side of view the reactor is assumed to be a perfectly stirred-tank
reactor (PSR). This is true because the residence time is larger than the mixing time.

In the Fluidized Bed (FB) the injected air flows upwards to the Freeboard Zone (FBZ). It is assumed that the complete reaction of fuel and air takes place in the FB. The temperature at the FB is assumed to be constant during the operation of the reactor. At the FBZ, the temperature decreases since the particles dissociate from the FB, where the combustion take place. The FBZ is assumed to behave like a plug flow model for the flue gas and only flue gas is going upwards in this section of the reactor.
Chapter 2

The formation of $NO_x$ and fuel burnout/CO

Nitrogen oxides ($NO_x$) in the ambient air consist primarily of nitric oxide (NO) and nitrogen dioxide ($NO_2$). These two forms of gaseous nitrogen oxides are highly toxic and play an important role in the atmospheric reactions that create pollutants in the lower atmosphere. These nitrogen oxides create harmful particulate matter, ground-level ozone and acid rain. Another form of nitrogen oxide is nitrous oxide ($N_2O$), which is a greenhouse gas. CO formation is another important issue which has to be taken into account. Carbon Monoxide (CO) emission is an important issue which has to be taken into account. CO formation is the result of incomplete combustion. The above mentioned pollutants will be explained, starting which the $NO_x$ formation.

The three primary sources of $NO_x$ formation in combustion processes are:

- **Thermal $NO_x$:**
  $NO_x$ formed through high temperature oxidation (usually above 1500°C) when the nitrogen atoms ($N_2$) and oxygen atoms ($O_2$), combine in the combustion air supply [1].

- **Fuel $NO_x$:**
  $NO_x$ which is formed when nitrogen in the fuel combines with the excess oxygen in the combustion air. During combustion the nitrogen bound in the fuel is released as a free radical and ultimately forms free $N_2$. This usually is only a problem with oils containing fuel-bound nitrogen. In case of gaseous fuels it is rarely a problem [5].

- **Prompt $NO_x$:**
  $NO_x$ formed during the early, low temperature states of combustion from in a rapid reaction of atmospheric nitrogen with hydrocarbon radicals. Prompt $NO_x$ is generally minor compared to the overall quantity of $NO_x$ generated from combustion.

### 2.1 Thermal $NO_x$

From several sources of literature we found that the formation of thermal $NO_x$ in fluidized bed combustors is unlikely or negligible [1], [6]. In our Fluidized Bed Combustor (FBC) the operating temperature is aimed at 850°C. Thermal $NO_x$ is significant in systems with relatively high stoichiometric ratios (1,1 - 1,3) and high temperatures (above 1500°C). At these high temperatures the nitrogen ($N_2$) in the air is oxidized with oxygen ($O_2$). The nitrogen and oxygen dissociate and recombine in the form $NO_x$. These elements will participate in a series of reactions. Above the mentioned temperature, the rate of $NO_x$ formation increases exponentially.

At temperatures below 750°C, the generation of $NO_x$ is generated in a much lower concentration or not at all [7]. This makes thermal $NO_x$, with a contribution of less than 10 %, a minor contributor.
to the NOX formation in fluidized bed combustors [3].

\( \text{N}_2 \) is a highly stable molecule with the two nitrogen atoms attached by a triple bond. These bonds can be broken by the use of extreme heat which leads to reaction with elemental oxygen as follows (Zeldovich mechanism) [8]:

\[
\begin{align*}
\text{N}_2 + \text{O} & \rightarrow \text{NO} + \text{N} \\
\text{N} + \text{O}_2 & \rightarrow \text{NO} + \text{O} \\
\text{N} + \text{OH} & \rightarrow \text{NO} + \text{H}
\end{align*}
\]

The formation rate is primarily a function of temperature and to a lesser extent oxygen dependent. The residence time of nitrogen at that temperature determines the amount of NO molecules that are formed.

![N2 molecule](image)

Figure 2.1: \( \text{N}_2 \) molecule

Nitrogen’s abundance in the atmosphere is 78%. This means that the air which is introduced into the combustor consists mainly of nitrogen, which can form thermal NOX. Despite it’s high abundance, due to the relatively low temperature, the formation of NOX is neglected in our model. Nevertheless we will describe some methods to control and reduce the formation of thermal NOX.

### 2.1.1 Reducing Thermal NOX

The typical approach to reduce the formation of thermal NOX is by reducing the peak and average flame temperature [9]. According to the author of “Combustion and Gasification in Fluidized beds” the formation of fuel NOX decreases with temperature.

When staged combustion is used a part of the combustion air goes in through the bottom of the furnace. Another part of air is added separately at a section further downstream the furnace to complete the combustion process. This results in a lower peak and average flame temperature and thereby a reduction of thermal NOX production. According to the author of “Guide to Low-Emission Boiler and Combustion Equipment Selection” and “Combustion and Gasification in Fluidized beds” this as an effective way to control NOX formation. For staged combustion it is essential to have an accurate process control to ensure the proper air ratio required in the different zones of the combusting process.

Flue Gas Recirculation (FGR) is a technique in which some of the relatively cool flue gas recirculates and is mixed with the combustion air. The mixture is introduced in the combustion process again due to which the total gas weight in the reactor (that must be heated) increases. This causes a reduction of the peak flame temperature. As mentioned a reduction of the flame temperature results in a reduction of thermal NOX. The mixture is introduced as a supplement to the regular air-input, through a separate inlet higher in the reactor. When instead of this mixture fresh and cool air would be used to reduce the flame temperature it would also unbalance the stoichiometry in the reactor. Of course this is an unwanted effect.

### 2.2 Fuel NOX

Fuel NOX is formed by the reaction of the fuel-bound nitrogen with oxygen in the combustion air. Nitrogen found in fuels is typically bound to the fuel as part of organic compounds. During combustion the nitrogen bound in the fuel is released as a free radical and ultimately forms NO or \( \text{N}_2 \). The NO is the leading element while the \( \text{NO}_2 \) concentration generally is less than 5%. According to
"Guide to Low-Emission Boiler and Combustion Equipment Selection" fuel NO\textsubscript{X} is a major factor in NO\textsubscript{X} emission. Though only 20\% to 30\% of the fuel-bound-nitrogen converts to NO.

In opposition to thermal NO\textsubscript{X} Fuel NO\textsubscript{X} is relatively independent on temperature [9]. Rather it is strongly dependent on fuel-air proportions, the percentage nitrogen in the fuel, the reactivity of the fuel and stoichiometry in the combustion process.

In several sources the nitrogen content of specific wood species is stated. The nitrogen content of Finnish wood is between 0,1\% and 0,8\% [11] while wood species from the Amazonia contains on average between 0,03\% and 0,5\% nitrogen [12]. When the different results from the literature are taken into account an average is taken: wood contains approximately 0,3\% nitrogen. This small amount of fuel-bound nitrogen is neglected in the modeled design of the FBC.

2.2.1 Reducing Fuel NO\textsubscript{X}

To reduce the emission of fuel NO\textsubscript{X} techniques such as controlled fuel-air mixing and staged combustion can be applied. By these techniques a reduction of the oxygen supply during the initial stages of combustion is feasible.

Also the injection of Ammonia (NH\textsubscript{3}) is described to be an efficient way to reduce the NO\textsubscript{X} emission. Ammonia is injected in the upper selection of the furnace. The following reaction takes place:

\[2NO + 4NH_3 + 2O_2 + 2H_2O \rightarrow 3N_2 + 8H_2O\]  

(2.4)

In this reaction the temperature again influences the reaction (conversion) rate. Also NH\textsubscript{3}/NO\textsubscript{X} molar ratio and the number and location of the ammonia injection nozzles influence the NO\textsubscript{X} conversion rate [13]. The injection of ammonia reduces the NO\textsubscript{X} emission but it increases N\textsubscript{2}O formation. Also the danger of NH\textsubscript{3} escaping into the solid waste or flue gas has to be taken into account, with the possibility of Ammonium Chloride (NH\textsubscript{4}CL) emission.

Also fuel NO\textsubscript{X} emission could be prevented by using a fuel with a lower NO\textsubscript{X} content. Off course all other parameters have to be taken into account to make sure not to shift the NO\textsubscript{X} emission problem to another (emission related) issue. The use of wood in general reduces the emission of several unwanted species. Wood contains virtually no sulfur, no mercury and has a low nitrogen content. This results in a lower pollutants production compared to coal.

The dominant source of NO\textsubscript{X} (and N\textsubscript{2}O) is originating from volatiles in the woody fuel. Biomass itself has a high volatile content but low nitrogen content. This can explain why a higher N concentration in the biomass fuel not necessarily leads to a higher NO formation [1].

Figure 2.2: CO molecule

2.3 Formation of Carbon Monoxide

The emission of CO also plays an important role in the Fluidized Bed Combustor. The formation of CO is directly related to the mixing of the fuel and air at sufficient temperatures. CO emissions are the result of incomplete combustion. Roughly stated: a better fuel distribution in the combustion process and together with better mixing of fuel and air gives a lower CO emission level [14]. In general, the
combustion of CO may be considered as an indication of the efficiency of the combustion [1].

The Bed Temperature (BT) strongly influences the formation of CO. A higher temperature results in a more complete combustion of the biomass fuel, which lead to a reduction of CO formation. Furthermore the fluidization velocity affects CO formation. This comes back to residence time; to which the fluidization velocity is inversely proportional. A lower fluidization velocity, which means a longer residence time, gives a reduction of the CO formation [2].

As earlier mentioned biomass contains high levels of volatiles. This is the reason why the CO concentration emitted from biomass fuels can be higher compared to these from coal. Combustion of liquid and gaseous fuels commonly produces the least amount of CO. The loss due to unburned carbon from wood can be controlled to below 0.5% of the burnt fuel [15].

2.3.1 Reducing CO emission

The reduction of CO emission can be achieved by adjusting the fuel and air ratio, to obtain a complete combustion. A good fuel distribution over the combustion process and a stoichiometric mixture with air is desirable to realize a complete combustion [14]. Also the fuel fineness and particle size can be optimized to ensure a lower CO emission. It has been reported that a larger particle size and high ash content contribute to high CO levels. Furthermore longer freeboards are recommended. These increase the residence time and increase thereby the amount of complete combusted particles. Also excess air improves the combustion process.
Chapter 3

Description of combustor

This chapter describes the Fluidized Bed Combustor (FBC). The introduction explains how the FBC is divided and which mass and energy flows are present. The second section will elaborate on the assumptions that were made.

3.1 Model introduction

The FBC is divided into two sections; the Fluidized Bed (FB) and the Free Board Zone (FBZ), which includes the Splashing zone (SPZ). For each zone a different mass and energy balances is created. An overview of the complete system can be seen in figure 3.1.

![Figure 3.1: FBC system overview](image)

The FB has the following mass flows: biomass (in), air (in) and flue gas (out). The biomass flow consists of demolition wood and moisture. The air is considered to be dry and thus consists of only oxygen and nitrogen. The flue gas contains: reaction gases, unburnt fuel and unoxidized air.

The energy content is calculated for each of these flows which is used in the energy balances. In these energy balances it is calculated how much energy the FB heat exchanger (HE1) needs to extract from the FB to maintain the ideal bed temperature. The heat extracted by HE1 is dependent on the
temperatures of the bed and the thermal oil used in the heat exchanger.

The FBZ is used to extract the remaining combustion heat from the flue gasses. The flue gas is the only mass flow present in the FBZ. The flue gas is linearly cooled down from the bed temperature to the exit temperature, which should be as low as possible to obtain a high system efficiency. The FBZ heat exchanger (HE2) receives cold thermal oil from the Toluene heat exchanger and passes the heated oil on to the FB heat exchanger. The energy extracted in this zone is primarily depending on the temperature difference between the flue gas and the thermal oil.

3.2 Model assumptions

3.2.1 General assumptions

During the creation of the model assumptions were made, this section explains these assumptions. This first list shows the assumptions that were made to simplify the model.

- The energy flow of ash is neglected
- The radiation energy (between FB and FBZ) is neglected
- The sulfur reactions are neglected
- \( \text{N}_2 \) does not react to \( \text{NO}_x \) products
- \( \text{H}_2 \) reacts to \( \text{H}_2\text{O} \) only
- \( \text{C} \) reacts to \( \text{CO}_2 \) only
- All reactions take place in the FB
- No reactions take place in the FBZ
- The airspeed through the bed is constant

Some of the assumptions were made after running the simulation model, since they had only a minor influence and could thus be neglected.

The second list below shows the assumptions that were used as input for the calculations. Some came from the assignment and others where found in literature. These assumptions are easily changed and were varied to check the working of our model.

- The energy content of the flow of demolition woods is 1.1 MW
- The composition of dry demolition wood is \( \text{C}_{0.51} \text{O}_{0.30} \text{H}_{0.84} \text{N}_{0.01} \)
- The moisture content of the demolition wood is 9.1%
- The heat exchangers extracts the amount of energy that is calculate by the model
- The heat exchangers are designed such that they can extract the calculated energy
- 90% of the inserted fuel reacts
- The stoichiometric ratio is 1.2
- The FBC cross section area is 1.1 m\(^2\)
- The bed temperature is 850°C
- The FB bed mass is 480 kg [1] (p.83)
- The sand density is 2650 kg \( \cdot \) m\(^{-3}\) [3] (p.30)
- The FB voidage is 0.5
- The mean sand diameter is 650 \( \mu \text{m} \)
3.2.2 Fluidized bed

The fluidized bed is assumed to work as a perfectly stirred reactor (PSR). The biomass (dropped in from above) is assumed to be equally spread through the bed. The temperature of the bed is therefore also uniform ($850^\circ$C). The air that is flowing through the bed is assumed to have a speed that is equal to the average of the insert speed and the exit (FBZ) speed. The air is assumed to have the same temperature as the bed material, which means that it directly heats up when it enters the bed. The heat exchanger (HE1) is designed such that it can extract the energy required energy to keep the bed temperature steady. The heat flow from the bed (sand) to the oil is assumed to be a function of the temperature difference, which will be explained in more detail in section 5.3.2. Section 4.2.3 will explain how the height of the bed is determined.

The FB sand mass is assumed to be 480kg, which is a typical sand mass used in 1.1MW FBCs according to Khan [1] (p.83). According to several sources, but especially Basu [3], p.30 it was assumed that the sand density was 2.65$kg/m^3$.

3.2.3 Splashing zone

The splashing zone is assumed to be very small and to be part of the FBZ. Therefore the convection losses of this zone are not calculated, but assumed to be part of the FBZ convection losses. As was explained in the previous section, no reactions occur outside the FB. Therefore no NO$_x$ or CO$_x$ is formed in the SPZ. Since radiation losses are also neglected, the energy inflow is equal to the energy outflow in the SPZ. No (mass or energy) balances are therefore made for the SPZ. It is assumed that the temperature is constant and equal to the FB temperature.

3.2.4 Freeboard zone

The free board zone is the second and last zone on the FBC. The FBZ starts with the splashing zone, which is assumed to be very small as explained in the previous section. The heat exchanger is positioned just above the SPZ. It is assumed that the amount of bed material is very small above the SPZ. The FBZ heat exchanger (HE2) is designed such that it is capable of extracting the required energy from the flue gas to cool it down to the exit temperature. In this zone it is assumed that the temperature of the flue gas decreases linearly, because the heat exchanger will extract the energy as a function of the average temperature difference between the flue gas and the oil in the heat exchanger. It is therefore also assumed that the temperature of the oil increases linearly. Section 5.3.2 describes the working of the heat exchanger (HE2) in more detail. Section 4.2.2 explains how the height of the FBZ is determined. It is assumed that the height of the FBZ is equal to the Transport Disengagement Height (TDH).
Chapter 4

Combustor design

The first section of this chapter elaborates on the air speed limitations and explains how to calculate the minimum and maximum fluidization velocity. The second section explains how the air speed influences the dimensions of the Fluidized Bed (FB) and Free Board Zone (FBZ). At the end of this chapter all the numeric values and results are presented.

4.1 Air speed limitations

The mean air speed in the Bubbling Fluidized Bed (BFB) is an important design parameter for the behavior of the sand particles in the bed and it influences for example the burning efficiency and formation of emissions. The lower boundary is formed by the minimum speed required for the fluidization of the bed and the upper boundary is posed by elutriation; the outflow of particles through the exhaust. When burning efficiency and emissions are taken into account, a decision can be made to determine the final mean air speed.

4.1.1 Minimum Fluidization

Fluidization is defined as the operation through which fine solids are transformed into a fluidlike state by contact with a gas or liquid [3]. In this state certain objects with a higher density will sink in the "fluid" and objects with lower density will float. Furthermore it is assumed that the bed will keep an uniform temperature.

The formulas used to calculate the minimum fluidization velocity $U_{mf}$ are the following:

$$U_{mf} = \frac{Re_{mf} \cdot \mu}{d_p \cdot \rho_g}$$

(4.1)

$$Re_{mf} = \left[ C_1^2 + C_2 Ar \right]^{0.5} - C_1$$

(4.2)

$$Ar = \frac{\rho_g \cdot (p_p - \rho_g) \cdot g \cdot d_p^3}{\mu^2}$$

(4.3)

The average size of the sand and their density the particles used in the bed belong to Group B particles, according to Basu. This means that their $U_{mf}$ equals the $U_{mb}$ which is the minimum bubbling velocity. This in turn is the minimum velocity the incoming air should have.

The calculated limit for the lower velocity is 0.037 m/s as can be seen in table 4.1.

4.1.2 Maximum Fluidization

The upper limit of fluidization is where the particles are reaching the state of turbulent fluidization. This limit is posed by the terminal velocity; the limit at which the bed particles are starting to float and eventually elutriate out to the exhaust. With the Reynolds number calculated by equation (4.2), one determines which equation to use to determine the Terminal Velocity ($U_t$).
For $0.4 < \text{Re} < 500$:

$$\frac{d_p U \rho_g}{\mu} = \left[ \frac{\text{Ar}}{7.7} \right]^{2/3}$$

The calculated limit for the upper velocity is 2.725 m/s as can be seen in table 4.1.

With these lower and upper boundary one can delve deeper into the working of the BFB to determine the appropriate speed of air. These are determined by burning efficiency and emission control. The air speed is chosen in chapter 5.

### 4.1.3 Bubbles

Another factor being influenced by the speed of air through the bed are air bubbles formation. Bubbles are important because they can disrupt the boiler by passing through the bed as a slug. Since the boiler considered in this text has heat exchanger tubes in the bed it is assumed that the formation of slugs is being disrupted by these tubes, therefore slugging is not considered in the determination of the mean air speed.

The bubble size at a certain height is determined by the following formula:

$$d_b = 0.54 \left( U - U_{mf} \right)^{0.4} \left( Z + 4 \sqrt{A_0} \right)^{0.8} g^{-0.2}$$

This value has a large influence on the Transport Disengagement Height (TDH), which will be used in section 4.2.2 to determine the FBZ height.

### 4.2 Combustor sizing

#### 4.2.1 Transport Disengagement Height

The Transport Disengagement Height is the height at which the elutriation of particles through the exhaust is disengaged. According to Basu the following equation can be used to calculate the TDH:

$$\text{TDH} = 4.47d_{eq,s}^{0.5} m$$

The mechanism behind the elutriation of particles is based on the bubbling of the bed. The bubbles cause an eruption at the bed surface which forces the particles up in the TDH. Therefore the volume diameter of a bubble at the bed surface ($d_{eq,s}$) is the only parameter in the TDH equation.

#### 4.2.2 Free board zone dimensions

The height of the FBZ needs to be at least equal to the TDH to prevent that bed material flows out of the combustor. The TDH is high enough to fit the FBZ heat exchanger, as will be shown in later. This is why the height of the FBZ is chosen to be equal to the TDH.

#### 4.2.3 Fluidized bed dimensions

Since the cross sectional area of the reactor was given in the assignment as $1.1m^2$, the height of the unfluidized bed can be calculated by equations 4.7 and 4.8.

$$V_{sand} = \frac{m_{sand}}{\rho_{sand}}$$

$$h_{sand\text{(not fluidized)}} = \frac{V_{sand}}{A_{cross}}$$

The bed expansion can be calculated by equation 4.9.
\[ h_{FB} = \frac{h_{sand\,(not\,fluidized)}}{\epsilon_{mf}} \]  

(4.9)

where:

\[ \epsilon_{mf} = \text{Bed voidage} \]

According to Khan [1] (p.102), a high voidage is beneficial in terms of gaseous emissions, since it increases the FB height and thus the residence time for combustion air. Though, a higher voidage also increases the fan power requirement Basu [3] (p.121). A voidage of 0.5 is therefore chosen as a compromise between high FBC efficiency and high polluter concentrations in the emissions.

### 4.3 Numerical values and results

The input for and the results from equations (4.1) to (4.6) are given in table 4.1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Name</th>
<th>Value (Unit)</th>
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<td>mean air speed</td>
<td>0.44 (m/s)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Name</th>
<th>Value (Unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Re_{mf})</td>
<td>Reynolds number for minimum fluidization</td>
<td>0.83 -</td>
</tr>
<tr>
<td>(Ar)</td>
<td>Archimedes</td>
<td>1120</td>
</tr>
<tr>
<td>(U_{mf})</td>
<td>minimum fluidization velocity</td>
<td>0.18 (m/s)</td>
</tr>
<tr>
<td>(U_t)</td>
<td>terminal velocity</td>
<td>6.13 (m/s)</td>
</tr>
<tr>
<td>(d_b)</td>
<td>bubble diameter</td>
<td>0.086 (m)</td>
</tr>
<tr>
<td>(TDH)</td>
<td>Transport Disengagement Height</td>
<td>1.31 (m)</td>
</tr>
</tbody>
</table>

Table 4.1: Air speed and TDH input and results

The input for and the results from equations (4.7) to (4.9) are given in table 4.2.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Name</th>
<th>Value (Unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m_{sand})</td>
<td>Sand mass</td>
<td>480 (kg)</td>
</tr>
<tr>
<td>(\rho_{sand})</td>
<td>Sand density</td>
<td>2650 (kg/m^3)</td>
</tr>
<tr>
<td>(\epsilon_{mf})</td>
<td>Bed voidage</td>
<td>0.5 -</td>
</tr>
<tr>
<td>(V_{sand})</td>
<td>Sand volume</td>
<td>0.18 (m^3)</td>
</tr>
<tr>
<td>(h_{FB})</td>
<td>Fluidized bed height</td>
<td>0.33 (m)</td>
</tr>
</tbody>
</table>

Table 4.2: FB height input and results

The total height of the FBC is 1.64\(m\).
Chapter 5

Combustor model

5.1 Combustion

In order to model the FBC and the energy flows concerned with it, the combustion process needs to be modelled. In order to do this some assumptions need to be made and properties need to be determined. The reaction will be modelled according to the molar chemical equations using Conversion \((X)\), Selectivity \((S)\) and Yield \((Y)\): \(Y = S \cdot X\). In order to use these parameters additional information is needed.

First of all the composition of the fuel needs to be determined. According to Kahn [1], the weight fractions \(w\) of the used biomass are listed in table 5.1. Using the molar mass of the elements, a molar ratio \(x\) can be calculated.

In order to calculate the molar ratio the molar mass of the fuel should be determined. The molar mass of the fuel \((M_{\text{fuel}})\) is calculated using the weight fractions of table 5.1.

\[
M_{\text{fuel}} = \sum_j (w_j \cdot M_j) \quad \text{[kg/kmol]} \quad (5.1)
\]

\[
x_j = \frac{w_j}{M_j} \cdot M_{\text{fuel}} \quad \text{[kmol/kmol]} \quad (5.2)
\]

where:

\(j = C, H, O, S, N, Cl, ash, H_2O\)

<table>
<thead>
<tr>
<th>Element (j)</th>
<th>Weight fraction (w_j)</th>
<th>Molar ratio (x_j)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.457</td>
<td>0.509</td>
</tr>
<tr>
<td>H</td>
<td>0.0630</td>
<td>0.8420</td>
</tr>
<tr>
<td>O</td>
<td>0.3620</td>
<td>0.3024</td>
</tr>
<tr>
<td>S</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>N</td>
<td>0.0090</td>
<td>0.0086</td>
</tr>
<tr>
<td>Cl</td>
<td>0.001</td>
<td>0.0004</td>
</tr>
<tr>
<td>ash</td>
<td>0.0170</td>
<td>0.0170</td>
</tr>
<tr>
<td>H_2O</td>
<td>0.0910</td>
<td>0.0676</td>
</tr>
</tbody>
</table>

Table 5.1: Fuel weight ratios
With the molar ratio the composition of a standard ‘fuel molecule’ can be determined. The fuel molecule used can be written as $\text{C}_{0.509}\text{H}_{0.842}\text{O}_{0.302}\text{N}_{0.009}(\text{H}_2\text{O})_{0.068}$.

The conversion factor ($X$) of the fuel is the amount of present fuel that is being converted into flue gas. In order to determine the selectivity ($S$) (the number of moles reaction product created per mol fuel reacted) a certain ratio for combustion products is assumed. For instance with a C atom certain molecules can be formed, like $\text{C}$, $\text{CO}$, $\text{CO}_2$. These ratios are defined like $r_{\text{C},\text{C}}$, $r_{\text{C},\text{CO}}$, $r_{\text{C},\text{CO}_2}$, which give the ratio of C atoms that are formed into $\text{C}$, $\text{CO}$, $\text{CO}_2$. Therefore, the values in table 5.2 are assumed.

<table>
<thead>
<tr>
<th>Element $j$</th>
<th>Product $i$</th>
<th>Ratio $r_{j,i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>C</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>$\text{CO}$</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>$\text{CO}_2$</td>
<td>1.00</td>
</tr>
<tr>
<td>H</td>
<td>$\text{H}_2$</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>$\text{H}_2\text{O}$</td>
<td>1.00</td>
</tr>
<tr>
<td>O</td>
<td>$\text{O}_2$</td>
<td>1.00</td>
</tr>
<tr>
<td>S</td>
<td>S</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>$\text{SO}$</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>$\text{SO}_2$</td>
<td>0.00</td>
</tr>
<tr>
<td>N</td>
<td>$\text{N}_2$</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>$\text{NO}$</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>$\text{NO}_2$</td>
<td>0.00</td>
</tr>
<tr>
<td>Cl</td>
<td>Cl</td>
<td>1.00</td>
</tr>
<tr>
<td>ash</td>
<td>ash</td>
<td>1.00</td>
</tr>
<tr>
<td>$\text{H}_2\text{O}$</td>
<td>1.00</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2: Reaction product ratios

Using these ratios the partial yields ($Y_i$) can be determined for the reaction (combustion) products. For the part of the fuel that did not react ($1 - X$), the selectivity ($S_{u,j}$) is equal to the molar ratio.

\[
S_i = r_{j,i} \cdot x_j \quad (5.3)
\]
\[
Y_i = S_i \cdot X \quad (5.4)
\]
\[
S_{u,j} = x_j \quad (5.5)
\]
\[
Y_{u,j} = S_{u,j} \cdot (1 - X) \quad (5.6)
\]

where:

\[
j = \text{C}, \text{H}, \text{O}, \text{S}, \text{N}, \text{Cl}, \text{ash}, \text{H}_2\text{O}
\]
\[
i = \text{C}, \text{CO}, \text{CO}_2, \text{N}_2, \text{etc}
\]

In case of the yield of O, a different approach is used. Since this element is also consumed during the formation of reaction products, the total balance of the reaction should be given. If this balance appears to be negative (which is to be expected), it means that additional oxygen is needed in order for the reaction to take place. This is to be expected with a combustion reaction.
\[ S_O = \sum_j (n \cdot S_{jO}) \]  
\[ Y_O = S_O \cdot X \]  

where:
\[ j = C, H, O, S, N, Cl, ash, H_2O \]

Equation (5.8) determines the stoichiometric rate of combustion, in moles \((S_O)\). The total yield \((Y_i)\) consists of unreacted and reacted fuel components. In this yield, a negative component for oxygen is present. When the total yield is combined with the air flow in the bed the flue gas mixture is known. (Steady state system with no accumulation is assumed, so \(\dot{m}_{in} = \dot{m}_{out}\)). To emphasize the oxygen in- and outflow, consider formula (5.9), where \(Y_{O, reaction}\) is a negative value as explained above. The nitrogen content of the air inflow is considered to behave inert and outflow equals inflow.

\[ Y_{O, flue \ gas} = Y_{O,in \ flow} + Y_{O, reaction} \]  

In order to calculate actual flows, the main input parameter is the required mass flow of fuel. To determine this the energy content of the fuel needs to be calculated. The procedure for this is to calculate the gross calorific value \((GCV)\) (5.10), followed by the net calorific value, dry based, \((NCV^{db})\) (5.11) and finally the net calorific value, wet based, \((NCV^{wb})\) (5.12) [4]. The last value takes into account the hydrogen and moisture content of the fuel. The calculations are based on the fuel content in table 5.1.

\[ GCV = 34.91w_C + 117.83w_H + 10.05w_S - 1.51w_N - 10.34w_O - 2.11w_{ash} \]  
\[ [MJ/kg] \]  
\[ (5.10) \]

\[ NCV^{db} = GCV - 2.4 \times 8.9 w_H \]  
\[ [MJ/kg] \]  
\[ (5.11) \]

\[ NCV^{wb} = NCV^{db}(1 - w_{H_2O}) - 2.4 w_{H_2O} \]  
\[ [MJ/kg] \]  
\[ (5.12) \]

The required thermal power determines the fuel mass flow \((\dot{m}_{fuel})\), based on the \(NCV^{wb}\). Using the molar mass of the fuel \((M_{fuel})\) the molar flow of fuel \((\dot{n}_{fuel})\) can be determined, which can be used with the molar yield calculated before.

\[ \dot{m}_{fuel} = \frac{P_{th}}{NCV^{wb}} \]  
\[ [kg/s] \]  
\[ (5.13) \]

\[ \dot{n}_{fuel} = \frac{\dot{m}_{fuel}}{M_{fuel}} \]  
\[ [kmol/s] \]  
\[ (5.14) \]

Using calculated yields \(Y\) and molar flow of fuel \(\dot{n}_{fuel}\), the molar flow \(\dot{n}_i\) and mass flow \(\dot{m}_i\) of reaction products can be calculated.

\[ \dot{n}_i = (Y_i + Y_{u,i}) \cdot \dot{n}_{fuel} \]  
\[ [kmol/s] \]  
\[ (5.15) \]

\[ \dot{m}_i = \dot{n}_i \cdot M_i \]  
\[ [kg/s] \]  
\[ (5.16) \]

where:
\[ i = C, CO, CO_2, N_2, etc \]
With the set of equations now available the mass flow of the fuel (reaction) components can be calculated. Since the (negative) yield of oxygen is known, the required molar flow and mass flow of oxygen can be determined. Taking into consideration the mass fraction of oxygen in air, the required stoichiometric mass flow of air is calculated. This also determines the air to fuel ratio (AFR). Combining this value with $\lambda$, the actual mass flow of air into the bed is calculated.

$$n_{O_2} = \left( Y_{O_2} + \left( \frac{Y_O + Y_{u,O}}{2} \right) \right) \cdot n_{fuel} \quad [\text{kmol/s}] \quad (5.17)$$

$$m_{O_2} = n_{O_2} \cdot M_{O_2} \quad [\text{kg/s}] \quad (5.18)$$

$$m_{air} = \frac{n_{O_2}}{w_{O_2}} \cdot \lambda \quad [\text{kg/s}] \quad (5.19)$$

$$AFR = \frac{m_{air}}{m_{fuel}} \quad (5.20)$$

where:

$w_{O_2} = 0.21 \quad (mass \ fraction \ in \ air)$

$\lambda = 1.20 \quad 20\% \ excess \ air)$

At this point the mass flow of air and the mass flow of reaction products is known. This together forms the mass flow of flue gas $m_{fg}$. Knowing the content of the flue gas, the specific heat $c_{p,fg}$ of the flow can be calculated.

$$m_{fg} = m_{air} + \sum_i m_i \quad [\text{kg/s}] \quad (5.21)$$

$$w_{fg,i} = \frac{m_i}{m_{fg}} \quad (5.22)$$

$$c_{p,fg} = \sum_i \left( w_{fg,i} \cdot \frac{c_{p,i}}{M_i} \right) \quad [\text{kJ/(kg*K)}] \quad (5.23)$$

where:

$i = C, CO, CO_2, N_2, etc$

<table>
<thead>
<tr>
<th>Variable</th>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCV\textsubscript{wb}</td>
<td>Net calorific value (wet based)</td>
<td>16.36</td>
<td>MJ/kg</td>
</tr>
<tr>
<td>$m_{fuel}$</td>
<td>Mass flow fuel in</td>
<td>0.0672</td>
<td>kg/s</td>
</tr>
<tr>
<td>$m_{air}$</td>
<td>Mass flow air in</td>
<td>0.4845</td>
<td>kg/s</td>
</tr>
<tr>
<td>AFR</td>
<td>Air to fuel ratio</td>
<td>7.2</td>
<td>-</td>
</tr>
<tr>
<td>$c_{p,fg}$</td>
<td>Specific heat flue gas</td>
<td>1.24</td>
<td>kJ/kg*K</td>
</tr>
</tbody>
</table>

Table 5.3: Combustion results
5.2 Energy balance

The main goal of the FBC is to convert the chemical energy of biomass into (useful) thermal energy in the way of thermal oil with a certain temperature potential. Looking at the energy balance of the system, inputs and outputs can be defined. The energy flows should be balanced $\dot{E}_{in} + \dot{E}_{out} = 0$. The main contribution to the energy flow into the system, is the fuel (obviously) $\dot{E}_{fuel}$, which consists for a small part of internal energy $\dot{Q}_{fuel}$, but is mainly chemical energy $\dot{E}_{chem,fuel}$. The medium used for energy transfer out of the system, thermal oil, also carries remaining energy in the return flow $\dot{Q}_{oil,in}$. A last minor energy contribution comes from the internal heat of the air flow $\dot{Q}_{air}$. These flows are combined in equation (5.24).

$$\dot{E}_{in} = \dot{E}_{fuel} + \dot{Q}_{air} + \dot{Q}_{in} \quad [\text{J/s}] \quad (5.24)$$

Considering the out flow of energy, there are several aspects. The out flow of energy due to flue gas $\dot{E}_{fg}$ consists of internal energy $\dot{Q}_{fg}$ and unused chemical energy $\dot{E}_{chem,fg}$. The main contribution of energy out of the system is by the thermal oil $\dot{Q}_{oil,out}$. The remaining losses are the heat losses through the combustor external area $\dot{Q}_{wall}$ and some energy in the ashes $\dot{E}_{ash}$. This combined gives equation (5.25).

$$\dot{E}_{out} = \dot{E}_{fg} + \dot{Q}_{out} + \dot{Q}_{wall} + \dot{E}_{ash} \quad [\text{J/s}] \quad (5.25)$$

5.2.1 Fluidized bed

In the FB, the chemical energy of the biomass is converted to thermal energy. The energy flow $\dot{E}_{fuel}$ is fed into the FB, just like the minor flow $\dot{Q}_{air}$. In order to keep the FB at steady state with a constant temperature, the same amount should exit the FB. The thermal energy leaves the FB in several ways: flue gas $\dot{E}_{fg,FB}$, heat exchanger $\dot{Q}_{HE1}$ and wall losses $\dot{Q}_{wall,1}$. The flue gas leaves the FB at approx. bed temperature, this contains a lot of energy of internal heat. The use of a heat exchanger in the FB enables the extraction of thermal energy from the FB, by thermal oil. The heat losses through the walls are mainly dependent on bed temperature. The flue gas also contains the unburnt fuel, so it also containd chemical energy. This combined is $\dot{E}_{fuel}$ and creates equation (5.26).

$$\dot{E}_{fuel} + \dot{Q}_{air} + \dot{E}_{ash} + \dot{E}_{fg,FB} + \dot{Q}_{HE1} + \dot{Q}_{wall,FB} = 0 \quad (5.26)$$

The contribution of each energy flow is specified in equation (5.27). The chemical part is explained in section 5.1. The part of internal energy is very small compared to the chemical component, but will be included in order to keep the energy balance complete.

$$\dot{E}_{fuel} = \dot{E}_{chem,fuel} + \dot{Q}_{fuel} \quad (5.27)$$

$$\dot{E}_{chem,fuel} = m_{fuel} \cdot NCV^{wb} \quad (5.28)$$

$$\dot{Q}_{fuel} = m_{fuel} \cdot C_{p,fuel} \cdot T_{fuel} \quad (5.29)$$

The contributions of internal energy of other the other components are small too, because of the low temperatures.
\[ Q_{\text{air}} = \dot{m}_{\text{air}} \cdot C_{p,\text{air}} \cdot T_{\text{air}} \quad (5.30) \]

\[ \dot{E}_{\text{ash}} = -\dot{m}_{\text{ash}} \cdot C_{p,\text{ash}} \cdot T_{\text{ash}} \quad (5.31) \]

Considering the out flows of the system, the biggest flow is the flue gas that leaves the FB at bed temperature. The energy is enclosed in internal energy and a remainder of the chemical energy because of part of the fuel did not combust \((1 - X)\). These values are based on the \(\dot{m}_{fg}\) and \(\dot{m}_{fuel}\), both calculated in section 5.1. The remaining flows in the FB are the thermal oil flows of heat exchanger 1 (HE1) \(\dot{Q}_{\text{HE1}}\) and the heat losses through the walls \(\dot{Q}_{\text{wall,FB}}\). These values will be discussed in sections 5.3 and 5.2.3.

\[ \dot{E}_{fg,FB} = \dot{Q}_{fg,FB} + \dot{E}_{\text{chem,fg,FB}} \quad (5.32) \]

\[ \dot{Q}_{fg} = -\dot{m}_{fg} \cdot C_{p,fg,FB} \cdot T_{fg,FB} \quad (5.33) \]

\[ \dot{E}_{\text{chem,fg}} = -(1 - X) \cdot \dot{m}_{\text{fuel}} \cdot NCV^{\text{wb}} \quad (5.34) \]

### 5.2.2 Freeboard zone

In the FBZ, the remaining energy in the flue gas need to be recovered by the use of a second heat exchanger. No reactions take place here, so the equation mainly exists of flue gas flow and the thermal oil flow of the heat exchanger. Of course, wall losses are also considered.

\[ \dot{E}_{fg,FBZ}^{\text{in}} + \dot{Q}_{\text{HE2}} + \dot{E}_{fg,FBZ}^{\text{out}} + \dot{Q}_{\text{wall,FBZ}} = 0 \quad (5.35) \]

In the system the flue gas that exits the FB enters the FBZ, hence equation (5.36).

\[ \dot{E}_{fg,FBZ}^{\text{in}} = \dot{E}_{fg,FB} \quad (5.36) \]

Evaluating the energy flows out of the FBZ, the remaining chemical energy is regarded in the flue gas. This energy will not be recovered in the FBZ, so \(\dot{E}_{\text{chem,fg}}\) remains unchanged and leaves the combustor in the flue gas exit stream. The internal energy of the flue gas will decrease due to the heat exchange with heat exchanger 2 (HE2) and leaves the FBZ at temperature \(T_{fg,FBZ,\text{out}}\). The remaining flows in the FBZ are the thermal oil flow of (HE2) \(\dot{Q}_{\text{HE2}}\) and the heat losses through the walls \(\dot{Q}_{\text{wall,FBZ}}\). These values will be discussed in sections 5.3 and 5.2.3.

\[ \dot{E}_{fg,FBZ}^{\text{out}} = \dot{Q}_{fg,FBZ} + \dot{E}_{\text{chem,fg}} \quad (5.37) \]

\[ \dot{Q}_{fg,FBZ}^{\text{out}} = -\dot{m}_{fg} \cdot C_{p,fg,FBZ}^{\text{out}} \cdot T_{fg,FBZ}^{\text{out}} \quad (5.38) \]

\[ \dot{E}_{\text{chem,fg}} = -(1 - X) \cdot \dot{m}_{\text{fuel}} \cdot NCV^{\text{wb}} \quad (5.39) \]
5.2.3 Wall losses

For each zone there are convection losses, which are calculated in the same way for each zone. According to Basu [3], the convection heat losses are about 0.8% of the total heat flow through the FB. In the following calculations these appear to be higher. In the calculations it is assumed the that FB wall consists of a 15 cm thick concrete wall with an internal coating of stainless steel of 8 mm.

Because the heat losses are calculated per zone of the combuster, the heat losses were calculated for the FB, the splashing zone and the free board zone. The following equations where used to calculate the convection heat loss.

\[
\dot{Q}_{\text{wall}} = A_{\text{wall}} \cdot \frac{\Delta T}{R_{\text{tot}}}
\]

\[
\Delta T = T_{\text{zone}} - T_{\text{ext}}
\]

\[
A_{\text{wall}} = h_{\text{zone}} \cdot 2 (w_{\text{zone}} + d_{\text{zone}})
\]

\[
R_{\text{tot}} = \frac{1}{h_{\text{zone} \rightarrow \text{steel}}} + \frac{t_{\text{steel}}}{k_{\text{steel}}} + \frac{t_{\text{concrete}}}{k_{\text{concrete}}} + \frac{1}{h_{\text{concrete} \rightarrow \text{air}}}
\]

The input for and the results from equations (??) to (5.43) are given in table 5.4 (FB) and table 5.5 (FBZ).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(w_{\text{zone}})</td>
<td>Width of zone</td>
<td>(\sqrt{1.1}) m</td>
<td>m</td>
</tr>
<tr>
<td>(d_{\text{zone}})</td>
<td>Depth of zone</td>
<td>(\sqrt{1.1}) m</td>
<td>m</td>
</tr>
<tr>
<td>(h_{\text{zone}})</td>
<td>Height of zone</td>
<td>0.33 m</td>
<td>m</td>
</tr>
<tr>
<td>(T_{\text{zone}})</td>
<td>Average zone temperature</td>
<td>1123 K</td>
<td>K</td>
</tr>
<tr>
<td>(T_{\text{ext}})</td>
<td>External temperature</td>
<td>293 K</td>
<td>K</td>
</tr>
<tr>
<td>(t_{\text{concrete}})</td>
<td>Thickness concrete wall</td>
<td>0.15 m</td>
<td>m</td>
</tr>
<tr>
<td>(t_{\text{steel}})</td>
<td>Thickness steel wall</td>
<td>0.008 m</td>
<td>m</td>
</tr>
<tr>
<td>(k_{\text{concrete}})</td>
<td>Thermal conductivity concrete</td>
<td>0.29 W/m K</td>
<td>W/m K</td>
</tr>
<tr>
<td>(k_{\text{steel}})</td>
<td>Thermal conductivity steel</td>
<td>13.0 W/m K</td>
<td>W/m K</td>
</tr>
<tr>
<td>(h_{\text{zone} \rightarrow \text{steel}})</td>
<td>Thermal resistance</td>
<td>5e3 W/m² K</td>
<td>W/m² K</td>
</tr>
<tr>
<td>(h_{\text{concrete} \rightarrow \text{air}})</td>
<td>Thermal resistance (free convection)</td>
<td>25 W/m² K</td>
<td>W/m² K</td>
</tr>
<tr>
<td>(\Delta T)</td>
<td>Temperature difference</td>
<td>830 K</td>
<td>K</td>
</tr>
<tr>
<td>(A_{\text{wall}})</td>
<td>Wall area</td>
<td>1.3816 m²</td>
<td>m²</td>
</tr>
<tr>
<td>(R_{\text{tot}})</td>
<td>Total thermal resistance</td>
<td>0.1080 m² K/W</td>
<td>m² K/W</td>
</tr>
<tr>
<td>(\dot{Q}_{\text{wall,FB}})</td>
<td>Heat losses wall FB</td>
<td>1.06e4 W</td>
<td>W</td>
</tr>
</tbody>
</table>

Table 5.4: Convection losses input and results of the FB

<table>
<thead>
<tr>
<th>Variable</th>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(h_{\text{zone}})</td>
<td>Height of zone</td>
<td>1.54 m</td>
<td>m</td>
</tr>
<tr>
<td>(T_{\text{zone}})</td>
<td>Average zone temperature</td>
<td>873 K</td>
<td>K</td>
</tr>
<tr>
<td>(h_{\text{zone} \rightarrow \text{steel}})</td>
<td>Thermal resistance (forced convection)</td>
<td>200 W/m² K</td>
<td>W/m² K</td>
</tr>
<tr>
<td>(\Delta T)</td>
<td>Temperature difference</td>
<td>580 K</td>
<td>K</td>
</tr>
<tr>
<td>(A_{\text{wall}})</td>
<td>Wall area</td>
<td>6.4519 m²</td>
<td>m²</td>
</tr>
<tr>
<td>(R_{\text{tot}})</td>
<td>Total thermal resistance</td>
<td>0.1128 m² K/W</td>
<td>m² K/W</td>
</tr>
<tr>
<td>(\dot{Q}_{\text{wall,FBZ}})</td>
<td>Heat losses wall FBZ</td>
<td>3.32e4 W</td>
<td>W</td>
</tr>
</tbody>
</table>

Table 5.5: Convection losses input and results of the FBZ
5.3 Heat exchangers

The heat exchangers (HE’s) are the components that actually transfer the energy to the thermal oil, which is the medium to drive the toluene cycle. As shown in figure 3.1, the HE’s are connected in series and in counterflow. This means that the thermal oil enters the combustor at the point where the temperature is the lowest, the top of the FBZ and the thermal oil leaves the system at the point where the combustor temperature is the highest, the FB. In this way the thermal energy is optimal used. Initially, the required heat capacity of both HE’s is determined, in subsections 5.2.1 and 5.2.2. These are rewritten in equations (5.44) and (5.45).

\[
\dot{Q}_{HE1} = - \left( \dot{E}_{fuel} + \dot{Q}_{air} + \dot{E}_{ash} + \dot{E}_{fg,FB} + \dot{Q}_{wall,FB} \right)
\]  
(5.44)

\[
\dot{Q}_{HE2} = - \left( \dot{E}_{in,fg,FBZ} + \dot{E}_{out,fg,FBZ} + \dot{Q}_{wall,FBZ} \right)
\]  
(5.45)

5.3.1 Thermal oil flow

The thermal oil has a certain operating range of temperature in which the thermal properties are most suitable for heat transfer and transport [21]. Because the HE’s are series connected, the oil will flow into HE2 with temperature \( T_{in,oil,HE2} \), after HE2 the oil has an intermediate temperature \( T_{out,oil,HE2} \). The oil then flows through HE1, where it will reach the final temperature \( T_{out,oil,HE1} \). The toluene cycle can use the heat contained in \( T_{out,oil,HE1} - T_{in,oil,HE2} \). Because the energy transported by the thermal oil \( \dot{Q}_{oil} \) is linear proportional to the temperature \( T_{oil} \), the temperature increase in HE1 compared to HE2 should be the same ratio as the transferred heat in both HE’s. With the temperature boundaries of the thermal oil, lowest operating point \( T_{oil,l} \) and highest operating point \( T_{oil,h} \), and the results of equations (5.44) and (5.45), the intermediate temperature \( T_{out,oil,HE2} \) can be found according to equation (5.46).

\[
T_{out,oil,HE2} = \dot{Q}_{HE2} \cdot \frac{T_{out,oil,HE1} - T_{in,oil,HE2}}{\dot{Q}_{HE1} + \dot{Q}_{HE2}} + T_{in,oil,HE2}
\]  
(5.46)

\[
T_{in,oil,HE2} = T_{oil,l}
\]  
(5.47)

\[
T_{out,oil,HE1} = T_{oil,h}
\]  
(5.48)

The energy contained by the flow of thermal oil is stated in equation (5.49). Since the specific heat capacity \( C_p \) is an extensive property of the thermal oil [21], the only remaining value that needs to be determined for this system is the mass flow of oil \( \dot{m}_{oil} \). By using values from equations (5.47) and (5.48), the required massflow can be determined. With these values, each heat exchanger can be designed in more detail.

\[
\dot{Q}_{oil} = \dot{m}_{oil} \cdot C_{p,oil}(T) \cdot T_{oil}
\]  
(5.49)

\[
\dot{Q}_{HE} = \dot{Q}_{oil}^{in} - \dot{Q}_{oil}^{out}
\]  
(5.50)

\[
= \dot{m}_{oil} \cdot \left( C_{p,oil}(T_{oil,HE1}) \cdot T_{out,oil,HE1} - C_{p,oil}(T_{oil,HE2}) \cdot T_{out,oil,HE2} \right)
\]  
(5.51)

\[
\dot{m}_{oil} = \frac{\dot{Q}_{HE1} + \dot{Q}_{HE2}}{C_{p,oil}(T_{out,oil,HE1}) \cdot T_{out,oil,HE1} - C_{p,oil}(T_{out,oil,HE2}) \cdot T_{out,oil,HE2}}
\]  
(5.52)
5.3.2 Heat exchanger design

At this point certain variables of HE1 are known. With the values calculated in the previous paragraph, the heat capacity of the thermal oil is known. With the specified mass flow and temperatures, the amount of heat can be transported using the thermal oil. This however does not automatically mean that this amount of energy $\dot{Q}_{HE1}$ can actually be transferred from the FB to the thermal oil with that rate. This has to do with the design of the heat exchanger.

The heat transfer from bed to thermal oil actually consists of three stages. The first stage is the heat transfer from the bed particles to the surface of the tube of the heat exchanger, which is a convective process. The second stage is the heat transfer through the tube, from outer surface to inner surface, which is a conductive process. The last stage is the heat transfer from tube inner surface to the thermal oil, which is again a convective process. These stages can be modeled as series resistances. This resistance determines the actual heat transfer from FB to oil.

\[
\dot{Q} = U \mathcal{P} L \cdot \Delta T \quad (5.53)
\]

\[
\dot{Q}_{HE1} = \int_0^L U \mathcal{P} \cdot \Delta T \bigg|_x \, dx \quad (5.54)
\]

\[
\frac{1}{U \mathcal{P}} = \frac{1}{2\pi \cdot r_o \cdot h_{bw}} + \frac{\ln \frac{r_o}{r_i}}{2\pi \cdot k_w} + \frac{1}{2\pi \cdot r_i \cdot h_{wo}} \quad (5.55)
\]

\[
\Delta T \bigg|_x = T_{FB} - T_{oil} \bigg|_x \quad (5.56)
\]

where

- $L$ = HE tube length
- $r_o$ = tube outer radius
- $h_{bw}$ = heat transfer coefficient bed to tube
- $r_i$ = tube inner radius
- $k_w$ = thermal conductivity tube
- $h_{wo}$ = heat transfer coefficient tube to oil

In order to simplify equation (5.54), the Effectiveness and Number of Transfer Units method is used [22]. Using tabulated data, the Efficiency $\epsilon$ of a certain heat exchanger can be determined, at a certain Number of Transfer Units $N_{tu}$. Using the value of $N_{tu}$, the dimensions of the heat exchanger can be determined. The detailed dimensions of the HE’s were beyond the scope of this research.
Chapter 6

Results summary and Discussion

This chapter shows the results obtained by the model. The energy balance results of both heat exchangers are compared in the first subsection. The second subsections shows the temperature profile of the FBC. A discussion of the model is presented in the last section.

6.1 Results

6.1.1 Energy balances

Most of the energy extracted from the FBC comes from the FBZ heat exchanger. The heat extracted by the FBZ exchanger is $3.6 \left( \frac{305}{140} \right)$ times larger than the heat extracted from the bed, as can be seen in tables 6.1 and 6.2. This is comparable to the residence time ratio $\left( \frac{t_{FBZ}}{t_{FB}} \right)$ of the gasses and also to the temperature increase of the oil in the different zones, which can be found in table 6.3 and figure 6.1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Name</th>
<th>Value</th>
<th>% of $E_{in}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{air}$</td>
<td>Heat flow air</td>
<td>$\ll 1\text{ kW}$</td>
<td>$\sim 0%$</td>
</tr>
<tr>
<td>$Q_{fuel}$</td>
<td>Heat flow fuel</td>
<td>$\ll 1\text{ kW}$</td>
<td>$\sim 0%$</td>
</tr>
<tr>
<td>$E_{in_fuel}$</td>
<td>Chemical energy fuel</td>
<td>1100 kW</td>
<td>100%</td>
</tr>
<tr>
<td>$Q_{FG}$</td>
<td>Heat flow flue gas</td>
<td>840 kW</td>
<td>76%</td>
</tr>
<tr>
<td>$E_{out_fuel}$</td>
<td>Chemical energy fuel</td>
<td>110 kW</td>
<td>10%</td>
</tr>
<tr>
<td>$Q_{HE1}$</td>
<td>Heat flow to HE1</td>
<td>140 kW</td>
<td>13%</td>
</tr>
<tr>
<td>$Q_{L1}$</td>
<td>Thermal energy lost</td>
<td>10 kW</td>
<td>$\sim 0%$</td>
</tr>
</tbody>
</table>

Table 6.1: Energy flows in FB

<table>
<thead>
<tr>
<th>Variable</th>
<th>Name</th>
<th>Value</th>
<th>% of $E_{in}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{in_FG}$</td>
<td>Heat flow flue gas in</td>
<td>840 kW</td>
<td>76%</td>
</tr>
<tr>
<td>$E_{in_fuel}$</td>
<td>Chemical energy fuel</td>
<td>110 kW</td>
<td>10%</td>
</tr>
<tr>
<td>$Q_{FG}$</td>
<td>Heat flow flue gas out</td>
<td>310 kW</td>
<td>28%</td>
</tr>
<tr>
<td>$Q_{HE2}$</td>
<td>Heat flow to HE2</td>
<td>505 kW</td>
<td>46%</td>
</tr>
<tr>
<td>$E_{out_fuel}$</td>
<td>Chemical energy fuel</td>
<td>110 kW</td>
<td>10%</td>
</tr>
<tr>
<td>$Q_{L2}$</td>
<td>Thermal energy lost</td>
<td>25 kW</td>
<td>2%</td>
</tr>
</tbody>
</table>

Table 6.2: Energy flows in FBZ
6.1.2 FBC efficiency

Table 6.1 and 6.2 also show the percentages of the fuel energy inserted in the combustor. These values were used to calculated the FBC efficiency with equation (6.1). The efficiency is 59%. It should be noted that the efficiency of the Toluene heat exchanger is not taken into account in this efficiency.

\[
\eta_{FBC} = \frac{Q_{HE1} + Q_{HE2}}{E_{fuel}}
\]  

(6.1)

It can also be seen in the tables that the largest loss (28%) is the out flowing flue gas (\(Q_{FG}^{out}\)). The other losses are the unburned fuel (10%) and heat losses (3%).

6.1.3 Temperature profiles

Figure 6.1 shows the temperature profile of the FBC and the temperature of the thermal oil that is used in the heat exchangers. It can be seen that the temperature in the FB is constant and that the temperature of the flue gas linearly decrease in the FBZ. The oil temperature linearly increases from the top to the bottom of the FBC. It can be seen that the selected flow direction of the oil is in the opposite direction of the air flow, since the oil temperature increase from top to bottom.

![Temperature profiles](image)

Figure 6.1: Temperature profile of the FBC
6.2 Discussion

6.2.1 Energy balances

Although the largest part of the energy is extracted in the FBZ heat exchanger (HE2), the temperature is much higher in the FB. The main reason for this contradiction is that most (840 kW) energy flows out of the FB in the flue gas ($\dot{Q}_{out,fg}$), as can be seen in table 6.1. The main reason that this value is large compared to the total energy flow is that the factor $C_{fg} \cdot T_{fg}$ is very high.

6.2.2 FBC efficiency

The efficiency of 59% is very high compared to other combusters [3] (p.14). The main reason for this is that the sizing of the heat exchangers was done after the calculation of the heat flows in the gas. It is assumed that all the energy that was not flowing out in the flue gas could be taken up by the heat exchangers. Especially in the FBZ heat exchanger (HE2) this is not realistic, since the temperature difference at the exit is very small (20°C). The heat exchanger was assumed to use the average temperature difference, which was (∼ 185°C).

6.2.3 Temperature profiles

It should be noted that the oil temperature in the FB heat exchanger would normally increase faster near the end of the FB, since the temperature difference is the largest at this point. The opposite holds for the FBZ heat exchanger, where the temperature difference is biggest at the beginning of the FBZ. The linear temperature profile that was assumed is therefore unrealistic, especially because the temp difference in the FBZ varies from 530°C to 20°C.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Name</th>
<th>In</th>
<th>Out</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{oil,HE2}$</td>
<td>Oil temperature</td>
<td>180</td>
<td>321</td>
<td>°C</td>
</tr>
<tr>
<td>$T_{oil,F1}$</td>
<td>Oil temperature</td>
<td>321</td>
<td>360</td>
<td>°C</td>
</tr>
<tr>
<td>$T_{air/fg}$</td>
<td>Air/Flue gas temperature</td>
<td>293</td>
<td>850</td>
<td>°C</td>
</tr>
<tr>
<td>$T_{FG}$</td>
<td>Flue gas temperature</td>
<td>850</td>
<td>200</td>
<td>°C</td>
</tr>
</tbody>
</table>

Table 6.3: Temperatures of Oil, FB and FBZ gasses
Bibliography

[7] Soud, H.; Suppliers of FGD and NO\textsubscript{X} Control Systems, IEA Coal Research, London, United Kingdom, November 1995
[17] Hoogwijk, M.M.; On the global and regional potential of renewable energy sources Utrecht University, Utrecht 2004
[19] Matti Parikka; lobal biomass fuel resources Department of Bioenergy Swedish University of Agricultural Sciences (SLU), 2003