UNIVERSITY OF TWENTE.

Torrefaction gradients in biomass

Internship report

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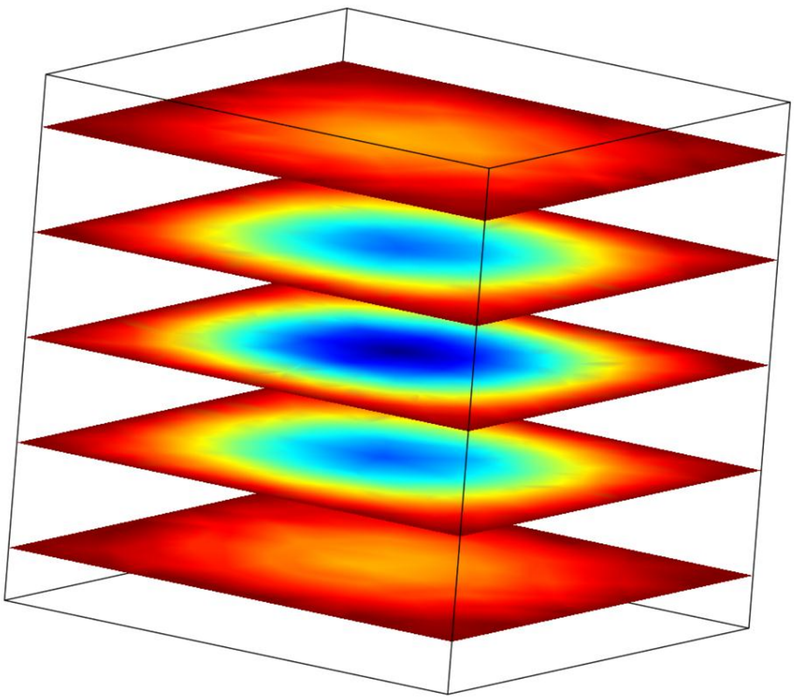

During torrefaction of biomass particles there are temperature gradients within the particles. If these temperature gradients influence the torrefaction and therefore create torrefaction gradients is examined by torrefying 40x40x40mm wooden blocks and analysing if the centre and edge material of the blocks show differences.

Preface

This is an internship report from my internship which is part of my 2 year Master program of Sustainable Energy Technology at the University of Twente. This internship is carried out at Tsinghua University at the department of Thermal Engineering in Beijing (PR China). The topic of the Internship is Torrefaction of Biomass.

From the beginning until the end of my 3.5 month stay in China I've been amazed by how different everything is. Daily things like traffic, housing, food, crowdedness and shopping are totally different than in The Netherlands. The kindness and helpful attitude of my fellow students was a really warm welcome. I have been shown around by a lot of people and I also went on some trips by myself. A small list of all the famous places I visited: Great Wall, Forbidden City, Mao's Mausoleum, National Museum, Ming Tombs, Temple of Heaven (all in Beijing). I also visited two other big city's, Shanghai and Xi'an were I walked on the famous boulevard The Bund and visited the Terracotta Army.

At the University I played soccer with the Thermal Engineering Department. The guys really looked up to me because I come from the country of Marco van Basten and Ruud Gullit and they really wanted to learn how I play soccer in The Netherlands. We had a lot of fun together practicing, playing matches and having dinner together.

This incredible experience was not possible without a few people. I want to thank Lixian Xu for putting me in touch with my Chinese supervisor Professor Zhenshan Li from Tsinghua University. Professor Li together with Zhao Wenying arranged al the paperwork necessary for my visa application and enrolment at Tsinghua University. At my arrival at the airport Zhao Wenying and Sun Hong Ming picket me up, arranged an apartment and the first weeks they showed me around at the beautiful campus of Tsinghua University and helped me to get all necessary things (like a bike, dining court card, telephone card, train tickets, etc.). Finally I want to thank everybody in my office, the guys from my soccer team and Sebastian Bob and Marc Enchelmaier, they all have been very friendly and helpful both during the assignment and in the weekends!

Summary

Torrefaction is a thermal pre-treatment of biomass in order to (co)-fire biomass in a power plant. Research is done to the differences in torrefaction within a biomass particle. This chapter will briefly describe how this is done.

Literature study

First a literature study is done about torrefaction. From this study the most commonly used conditions for torrefaction where determined. This turned out to be 1 Hour at 250°C in a Nitrogen (N_2) environment. For the experiments a batch reactor with a fixed bed is used.

Experiments

For the actual experiments two types of wood are used: 'pallet wood' and 'poplar wood'. From the pallet wood four pieces are torrefied in aforementioned conditions. Three pieces of poplar wood where torrefied at 250°C in a Nitrogen environment but for different residence times (60, 45 and 30 minutes). After the torrefaction the blocks are split. Material from the centre and edge of the block is prepared for analysis by grinding it to fine powders.

Analysis

The two samples of each block are analysed and the results are compared to see if there are any differences in the degree of torrefaction. The samples are analysed in three ways: Heat value, Thermographic Analysis (TGA) and Element Analysis.

Results

For the pallet wood blocks (all with a residence time of 1 hour) no significant difference can be found between the centre and edge material. Heat values are similar, TGA graphs match (except for what looks like a contamination which gives a different final weight percentage) and Element Analysis show that both samples consist of the same elements and the ratio of the different elements is the same.

When the poplar wood is torrefied for 1 hour, again the heat values are the same for the centre and edge samples. But when the poplar wood is only torrefied for 45 or 30 minutes differences appear in the heat values. The heating values of the centre material are higher than the edge material whereas the opposite was expected. This conclusion should be validated by performing more experiments.

Content

Introduction

In order to provide energy for next generations in a sustainable way, the worldwide use of fossil fuels has to be reduced and alternative energy sources have to be developed. Around 30% of the worldwide energy produced is generated in coal-fired power plants (International Energy Agency, 2010) by reducing the use of coal in a power plant a big reduction can be realized worldwide.

To reduce the amount of coal used in coal-fired power plants a part of the coal can be replaced by biomass. Biomass is considered a clean energy source because it is carbon neutral. The amount of CO_2 emissions from the combustions of biomass should be compensated with the adsorption of CO_2 during the growth of the biomass.

Biomass consists of long fibers which are hard to grind into a powder. This will give problems when the biomass powder should be mixed with the coal powder. Also the raw biomass is an inhomogeneous material so there will not be one optimal combustion condition. So before the biomass can be co-fired in a power plant together with coal it should be pre-treated.

A widely used pre-treatment is torrefaction. During torrefaction the biomass is heated to around 250 °C in an environment without oxygen at atmospheric pressure. Under these conditions the long hemicellulose fibers of the biomass will be weakened which makes the torrefied biomass easier to grind and mix with coal powder also the material becomes more homogeneous. Other advantages are a mass reduction whereas the energy content stays high and less influence by moisture so the product can be stored more easily.

In order to torrefy biomass properly for different particle sizes and materials, it should be investigated if differences occur between the surface and centre material of biomass particles after torrefaction. It is likely that differences occur because of temperature gradients in a block of material during heating so the applied temperatures and time at a certain temperature at different positions will be different throughout the block.

Before the investigation, with experiments and analysis, a literature study should be done to determine what conditions influence the torrefaction process and in what way these conditions influence the degree of torrefaction.

Literature research

Information about torrefaction is extracted from different articles. What and from which article is extracted is described in this chapter. The articles where found using www.scopus.com and were given by Professor Zhenshan Li.

Torrefaction

Torrefaction is a thermal pretreatment process where raw biomass (for example wood) is heated in an inert (nitrogen N_2) atmosphere up to temperatures between 200°C and 300 °C under atmospheric pressure. The temperature and the residence time are the two properties which determine the degree of torrefaction. Torrefaction is a mild form of pyrolysis and therefore information about pyrolysis can be used for torrefaction.

Reaction

The actual chemical reaction of torrefaction of biomass is very complex because of the formation of over a hundred intermediate products (B.V. Babu, 2004). Roughly the reaction can be described in the following way:

$$Wood \rightarrow Gas + Char$$

The reaction consists in a decomposition of the wood polymeric chains (cellulose, lignine, etc.) (Enrico Grieco, 2010). In this paper the pyrolysis is examined by different temperatures including 250°C , 275°C and 300°C which are torrefaction temperatures. Results indicate that after torrefying for 1 hour at 250°C the reduction of the weight (and so the formation of gasses) is largely completed.

Energy content

Due to torrefaction the heating value is increased but the mass is reduced. A part of the energy in the biomass is stored in gasses which arise during torrefaction. In present reactors the gasses are simply discharged and the energy it contains is lost.

The torrefaction reaction is an exothermic reaction (Enrico Grieco, 2010). The reaction heat will be the cause of a higher temperature in the centre than at the edge of the biomass. Although the reaction heat is weak it should not be neglected.

Temperature gradients

While the biomass is heated temperature gradients inside the biomass will arise, especially when the heating rate is high. Already some research is done if these temperature gradients influence the torrefaction throughout the biomass. But this is all done for small particles (cylindrical pellets). But already conclusions are drawn that there are temperature gradients present.

Temperature distribution 3D model

Before real time experiments are performed it is useful to make a substantiated approximation of the time necessary to heat up the biomass and the temperature gradients in the block. For this approximation a computer model is created. This model will simulate the block in a hot environment (the reactor) and temperature profiles from different points in the block are recorded. For this model some assumptions have to be made. The 3 dimensional model is built in COMSOL Multiphysics. A block of 40x40x40mm is modelled because this is the largest size which can be examined in the reactor in order to validate the model.

Assumptions

The following assumptions are made to create the model:

- The outside temperature of the block is the same as the reactor temperature (no influence of convection).
- The wood behaves like a homogeneous material so conductive heat transfer is the same in every direction.
- Poplar wood behaves like 'American Red Oak' because this is available in the COMSOL library.

Model

The initial temperature of the wood is set to 20°C. The surfaces planes are all given a constant temperature of 250°C through which the block will heat up. A Heat Transfer Coefficient (h) is set to 400 W/(m^2*K).

From the COMSOL library the material 'American Red Oak' is chosen with the following properties:

- Isotropic Thermal conductivity (k): 0.11+0.0003*(T-273) [W/(m*K)]
- Density (ρ): 630 [kg/m^3]
- Heat capacity (C_p): 1050+3.5*(T-273) [J/(kg*K)]

The created model shows the expected way of the block heating up. The outside is hot (red) and slowly the inside (blue) heats up. This screenshot (Figure 1) is taken half way the process.

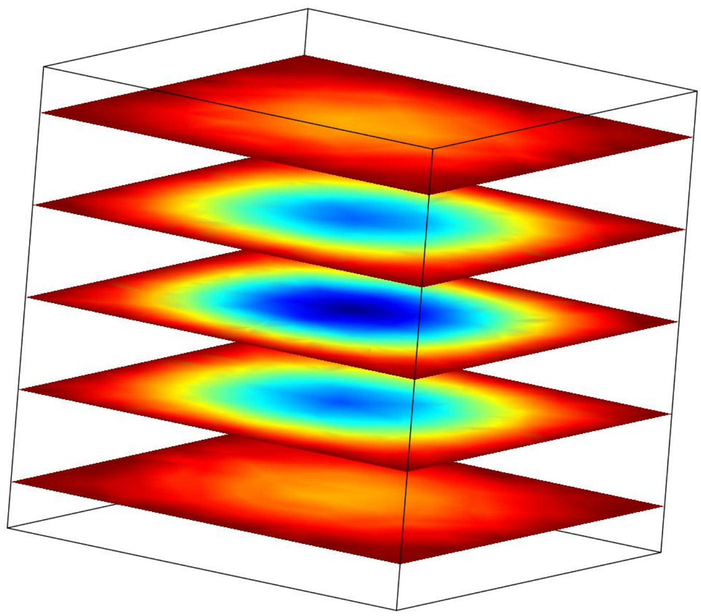

Figure 1: Heat distribution inside the block

Results

The temperatures at 4 points (Figure 2 in the centre of the block, at the edge and at 2 places in between) are evaluated in a COMCOL model and a graph is produced (Figure 3). The 'Edge' line shows the constant temperature of the surface of the block. The other 3 lines show a temperature rise with time and as expected at the point near the edge the temperature rise is faster than the temperature rise in the centre.

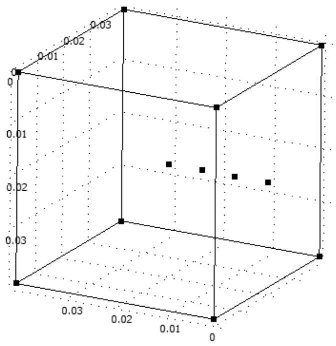

Figure 2: Evaluated points

The time before the temperature in the whole block is getting close to the reactor temperature is around 800 seconds as can been seen in Figure 3. That means it takes at least 13 minutes before the temperature of the centre material is at the desired temperature. These 13 minutes are more than 1/5 of the residence time of the biomass in the reactor. So the possibility that the centre material is not going to be torrefied as well as the surface material is quite realistic.

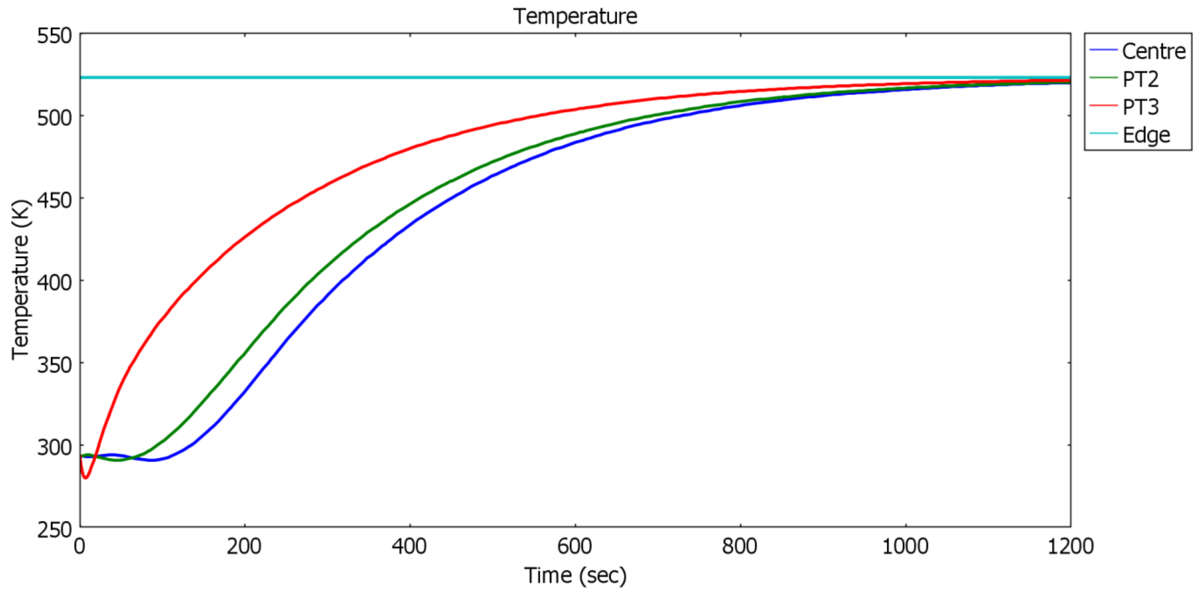

Figure 3: Temperature profiles

Modifications

In the previous paragraph the cooling time is not taken into account. The cooling of the centre material is also lagging the surface temperature in the same way during the heating. So maybe the time the centre material in not at the desired temperature in the beginning is compensated with a longer time at high temperature during cooling of the block. For this process also a model is made which results in Figure 4. It can be seen that the temperature of the centre material drops after approximately 200 sec. So the surface material is 60 minutes at 250°C and the centre material is 50 minutes at 250°C. This is a difference of 20%. So even with the cooling time taken into account it is reasonable to believe that there will be a difference in the grade of torrefaction.

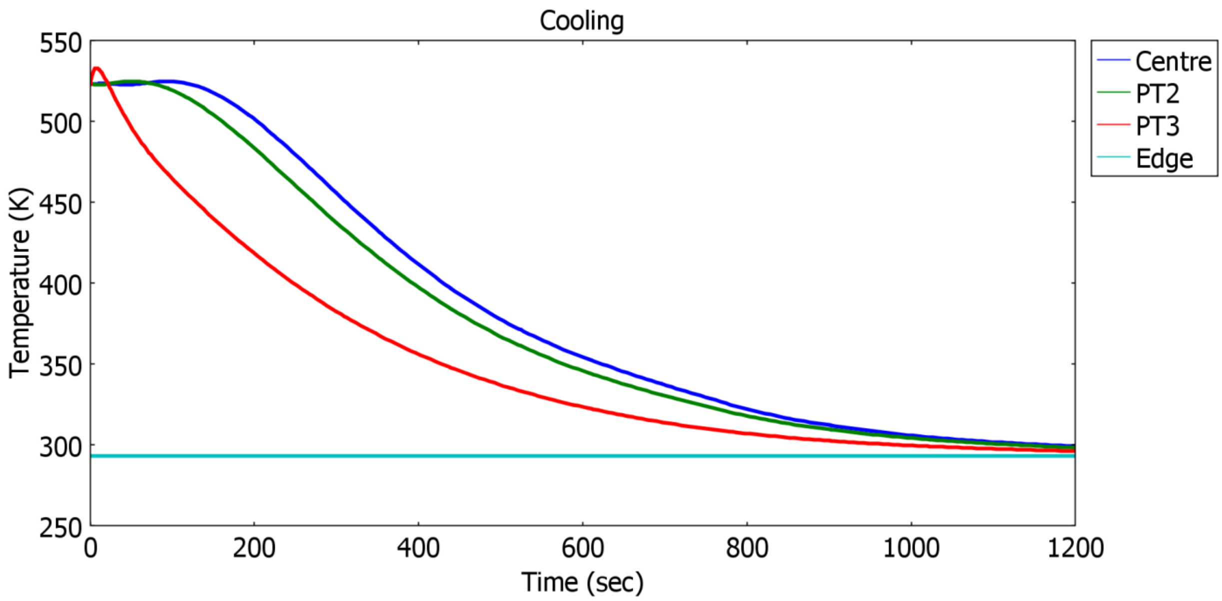

Figure 4: Cooling

Experiments

In this chapter the performed experiments are described. Also the purpose and the way to operate the reactor and its components is written down. In this way a better understanding is created about the experiments but also a possible future intern who might continue this research topic can read how to operate the devices.

Experiment components

1. Vertical tube reactor
2. Temperature control panel
3. N_2 flow controller
4. N_2 flow controller control panel
5. N_2 Bottle
6. Glass standard
7. 4 Thermocouples
8. Temperature recorder (including memory stick)
9. Wrench, pliers, 1mm drill, saw

Figure 5: Setup

Type of wood

This study focuses on Poplar wood as biomass because it is widely used in China and so it is likely that there is a lot of scrap material which can be used to co-fire in a power plant with coal. Some properties of Poplar wood are taken from (Matbase, 2010). It should be notice that these properties can differ from the Poplar wood in China, but these data will give a good indication.

Unfortunately the Poplar wood was not available at the beginning of the experiments. First some small wood pieces where torrefied to get familiar with the set up and data recording devices. After that pieces of 'Pallet wood' from a backyard scrap pallet where used and analyzed to get a first indication. Finally pieces of poplar wood are torrefied and analyzed.

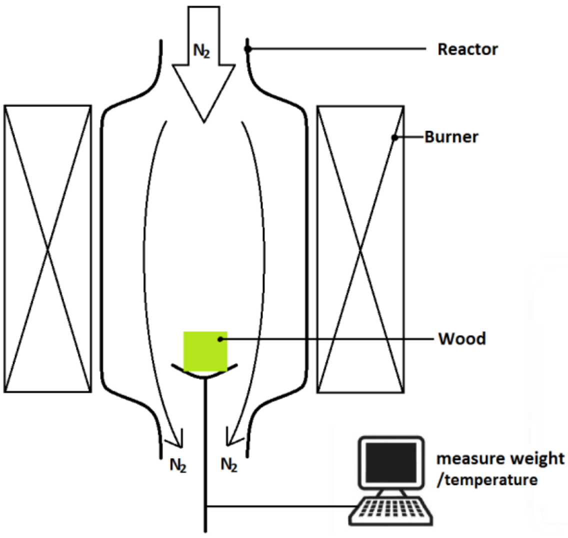

Figure 6: Setup scheme

Size and form

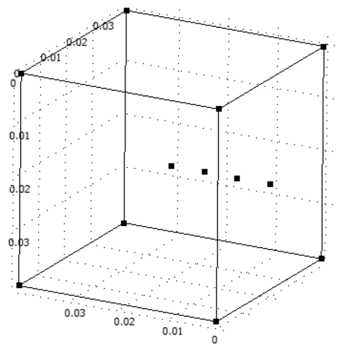

Figure 7: Evaluated points

It is easier to measure temperature gradients and determine possible torrefaction gradients in a bigger block of wood than is a small piece. That's why the size of the wooden blocks is given the maximum size possible which fits in the reactor. This turned out to be 40x40x40 mm.
Squares are taken because this is the most likely form of chopped raw wood.
To insert the 3 thermocouples (the fourth is placed on the surface of the block) 3 holes are drilled from the bottom side with a diameter of 1mm and 20mm deep. The tips of the thermocouples will measure the temperatures at the points indicated in Figure 7.

Figure 8: Sawing the wood blocks

In practice the wooden blocks were cut by hand saw from an untreated piece of a tree. This gave some trouble sawing proper square blocks which are similar in form and weight, also wood is not a homogenous material which will also give differences between the blocks.

Torrefaction experiment

As a first indication 4 pieces of pallet wood are torrefied and analysed. The reactor temperature is 250°C and the residence time is 1 hour. Later on the poplar wood is used for 3 similar experiments with different residence times of 60, 45 en 30 minutes.

The co-firing of the biomass will be done at a constant temperature so the biomass is added after the reactor reached a stable temperature. The reactor will take approximately 45 minutes to heat up to a constant temperature of 250°C.

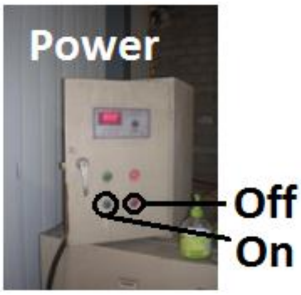

Figure 9: Power button

1. The reactor and its control panel are activated with the power button showed in Figure 9.
2. Make sure the fourth thermocouple is inserted from the side of the reactor into the glass tube.
3. Close and lock the reactor.

The reactor is divided in 3 compartments on top of each other. Every compartment can be controlled independently on the control panel shown in Figure 10.
All compartments can be programmed for 8 different time frames. In this case only 1 temperature is used and the total time the reactor is used (heating and reaction) is covered by the first 2 time frames. So it is sufficient to program the first 2 time frames.

4. Using the ‘Set’ button shown in Figure 10 select the first time frame and using the ‘up’ and ‘down’ arrow buttons set the temperature to 208°C. This will give a reactor temperature of 250°C.
5. Using the ‘Set’ button again select the second time frame and set the temperature to 208°C again. Do this for all three reactor compartments.
6. If all three compartments are programmed, switch on the heating by first turning the three round switches on the right side of the control panel to ‘Start’.
7. Press the ‘Set’ and ‘up’ arrow at the same time on each control panel like indicated at Figure 10.

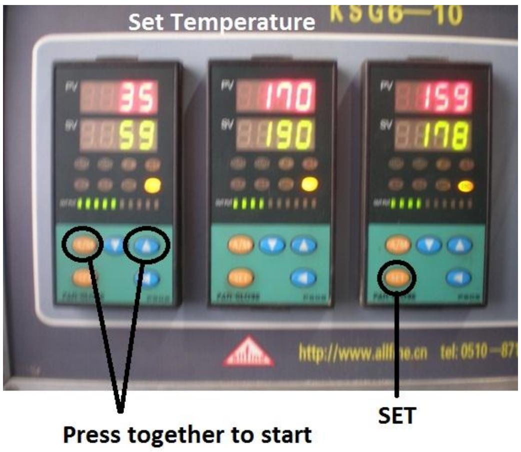

Figure 10: Temperature control panel

If everything went right the light bars behind ’output’ will start burning. If not, switch of the rounds switches from step 6 and repeat step 6 and 7 again.

8. Measure the weight of the biomass.
9. Insert the 3 thermocouples into to block of wood tough the holes of the glass standard using the pliers. (Be careful not to bend the thermocouples).

Approximately 40 minutes after the reactor started heating up is reaches a stable temperature

10. Open the Nitrogen bottle with the wrench and set the N_2 mass flow controller (Figure 11) to 10.0 L/min.

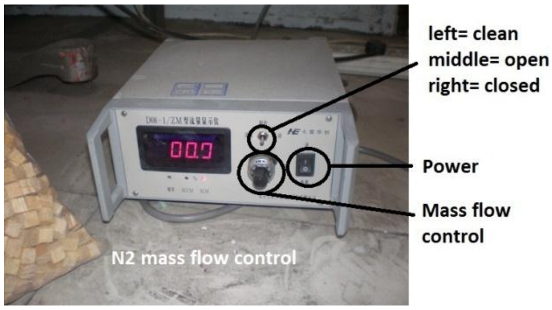

Figure 11: N_2 mass flow controller

It takes approximately 5 minutes for the reactor to reach a stable temperature again.

11. Start the temperature recording device (Figure 12).
12. Insert the biomass on the glass standard into the reactor from the bottom side.


Figure 12: Temperature recording device

Now the torrefaction starts, so be sure to ventilate the room because there will be some smoke coming from the reactor.

When the preferred residence time has passed, don’t take the biomass out of the reactor because the hot biomass will then react with the oxygen in the air.

13. Shut down the reactor by switching of the three round switches from step 6.
14. Unlock and open the reactor so it cools down faster.
15. After the reactor is cooled down remove the biomass
16. Stop the temperature recording
17. Close the N_2 bottle.
18. Measure the weight of the biomass.

Experiment Analysis

During the experiment the temperatures are recorded at 4 points and the mass of the biomass is measured before and after the torrefaction to show the mass reduction. This mass reduction together with het heat values will give the energy which is 'lost' during torrefaction. Because to gases which occur during the process are simply emitted to the surrounding air. It should be investigated if these gases can be used so the energy inside these gases will be recovered.

Weight loss

Table 1: Remaining weight

Experiment	Weight before (g)	Weight after (g)	Remaining weight (%)
Pallet wood 1	26,38	20,66	78,32
Pallet wood 2	27,10	20,81	76,79
Pallet wood 3	26,24	21,00	80,03
Pallet wood 4	26,04	20,11	77,23
Poplar wood 1	40,75	34,04	83,53
Poplar wood 2	34,09	29,67	87,03
Poplar wood 3	30,59	26,41	86,34

It can be seen clearly from Table 1 that the poplar wood has a higher density than the pallet wood. Also the remaining weight percentage of the poplar wood is higher than the pallet wood.

Weight loss during torrefaction

To get a better understanding on how the mass of the biomass reduces during torrefaction the mass is measured and recorded during the experiment. Measuring is done with a scale underneath the reactor. Unfortunately the thermocouples cannot be inserted into the biomass because the attached wires will influence the measured mass of the wood and standard. (The metal wires can push or pull on the biomass.) Also despite several attempts on different computers the scale cannot be connected to a computer. Therefore it was necessary to record the data from the scale by hand. This is the reason why only one time the mass versus the time is measured.

It can be seen that the mass reduces with time and stabilizes after one hour. This is also the time after which the heating of the reactor is turned off. It indicates that the residence time of one hour is sufficient and corresponds with the literature (Enrico Grieco, 2010)

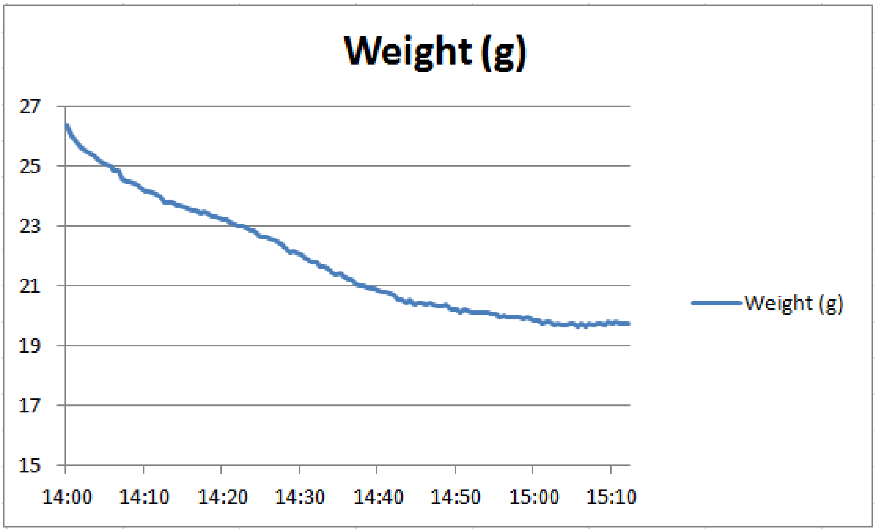

Figure 13: Weight versus time

Temperature profiles

The temperature profiles of the 4 points in the biomass during the experiment are recorded by 4 thermocouples. The graph of the profiles is given in Figure 14 and for the first 4 experiments with the 'pallet wood' the graphs look similar. Some remarks can be made with this graph.

- A small drop of the reactor temperature at the point where the biomass is inserted.
- At 100°C the temperature rise of the biomass slows down. This is due to moisture evaporating out of the biomass.
- Is takes around 25 minutes for the biomass to get a temperature near the desired temperature.
- After 30 minutes after the start the temperature of the biomass exceeds the temperature of the surface/reactor.
- When the reactor heating is turned off it takes 5 minutes before the centre temperature of the biomass drops.

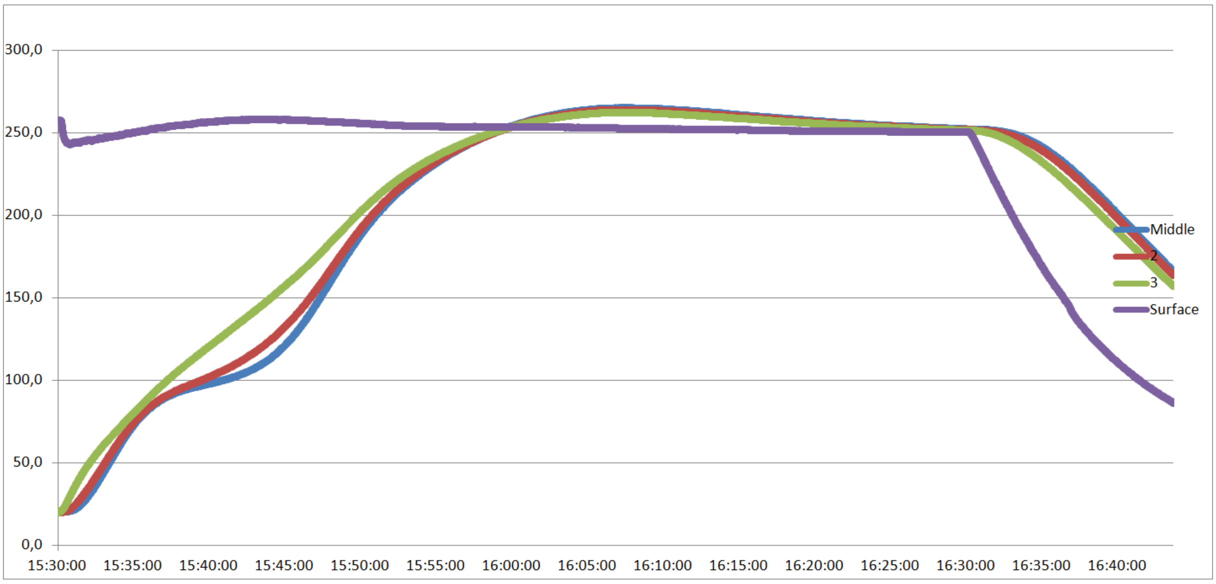

Figure 14: Temperature profile

Conclusions

- It takes much longer for the biomass centre material to heat up than approximated by the COMSOL model. A big part of this difference is made by the evaporating moisture from the biomass which is not modelled at all in COMSOL.
- The higher temperature of the centre of the biomass after 30 minutes implies a second heat source. This extra heat is coming from the torrefaction reaction which is an exothermic reaction.

Analysis Centre and Edge material

Each piece of wood is split into two parts, the centre material and de edge material. From both parts samples are made by grinding using a 'High Speed Pharmaceutical Grinder' which reduces the particle size between 0,600mm and 0,0486mm and a 'Fritsch Pulverisette 14 (grid 0,2mm)'.

After preparation the samples are examined in three ways: Heat Value, Thermographic Analysis (TGA) and Elemental Analysis. (The first sample was used two times to examine the heat value and unfortunately there was not enough sample left for the element analysis.)

Heating Values

The heating values are determined by a Bomb Calorimeter 'Parr 1281'. The residue from the Bomb Calorimeter is checked for remaining carbon using titration. Methyl Red ($C_{15}H_{15}N_3O_2$) is added to the residue giving it a yellow colour than Sodium Hydroxide (NaOH) is added until the colour of the residue changes to red.

The heating value is calculated with the following formulas:

$$Q_{gr,ad} = Q_{b,ad} - (94{,}1 * S_{b,ad} + a * Q_{b,ad})$$

$$S_{b,ad} = \left(c * \frac{V}{m} - a * \frac{Q_{b,ad}}{60}\right) * 1{,}6$$

Table 2: Symbols

Symbol	Description	Magnitude	Unit	Note
$Q_{gr,ad}$	Calculated Heating Value		(MJ/kg)	
$Q_{b,ad}$	Measured Heating Value		(MJ/kg)	
$S_{b,ad}$			(MJ/kg)	
c	Molar Concentration NaOH	0,1	(-)	
V	Volume NaOH		(mL)	
m	Mass of the sample		(g)	
a		0,001	(-)	$Q_{gr,ad} \leq 16{,}7$
a		0,0012	(-)	$16{,}7 \leq Q_{gr,ad} \leq 25{,}1$
a		0,0016	(-)	$Q_{gr,ad} > 25{,}1$

Results

For this 4 experiments pallet wood was torrified for 1 hour at 250°C. Al samples are measured twice except for the 'pallet wood 2, 3 and 4'. The results for the heating values are given in Table 3:

Table 3: Heat values

Experiment	$Q_{gr,ad}$ Centre	$Q_{gr,ad}$ Edge	Unit
Pallet wood Raw material 1	17,612	17,612	MJ/kg
Pallet wood Raw material 2	17,327	17,327	MJ/kg
Pallet wood 1.1	21,081	21,397	MJ/kg
Pallet wood 1.2	-	21,008	MJ/kg
Pallet wood 2	20,232	20,633	MJ/kg
Pallet wood 3	20,710	20,105	MJ/kg
Pallet wood 4	20,098	20,167	MJ/kg
Poplar wood Raw 1	18,483	18,483	MJ/kg
Poplar wood Raw 2	18,480	18,480	MJ/kg
Poplar wood 60 min 1	20,314	20,378	MJ/kg
Poplar wood 60 min 2	20,526	20,147	MJ/kg
Poplar wood 45 min 1	20,441	19,794	MJ/kg
Poplar wood 45 min 2	20,282	20,068	MJ/kg
Poplar wood 30 min 1	20,966	20,392	MJ/kg
Poplar wood 30 min 2	20,933	20,362	MJ/kg

The 4 samples of raw material have a significantly lower heating value compared to the torrefied samples. As expected the heating value is increased by torrefaction. The downside is that some mass is 'lost' in escaping gasses so the total energy content (not per kg) will be lower after torrefaction. Also a difference can be seen between the two types of raw material. The 'pallet wood' has a heating value of approximately 17,47MJ/kg whereas the 'poplar wood' has a heating value around 18,48 MJ/kg.
The torrefied 'pallet wood' has an average heating value of 20,53 MJ/kg for the centre material and 20,66 MJ/kg for the edge material. This is a very small difference so no hard conclusion can be drawn if there is any significant difference between the edge and centre material.

The torrefied poplar wood does not show any significant differences for the centre and edge material when the residence time is 60 minutes but when the residence time is reduced to 45 or even 30 minutes there appears to be a difference between the heating values of the centre and edge material. The heating values of the centre material are higher than the edge material whereas the opposite was expected. This conclusion should be validated by performing more experiments.

It is remarkable to see that the heating values after torrefaction of the two types of wood are much closer to one another than before torrefaction. This indicates that the properties of different types of wood are more similar after torrefaction. This is also mentioned in the literature and stated one of the big benefits of the torrefaction process.

Energy content

To calculate how much energy is 'lost' due to the escaping gasses during torrefaction the heat value of the raw material is compared with the heating value of the torrefied material. The mass of the wood is reduced by torrefaction. By multiplying the average remaining weight percentages with the average heating values the amount of energy in the torrefied wood can be calculated. The results are collected in Table 4.

Table 4: Energy content

Sample	Heating value (MJ/kg)	Remaining weight %	Energy content (MJ per kg raw material)
raw pallet wood	17,47	100	17,47
torrefied pallet wood	20,60	78	16,09
raw poplar wood	18,48	100	18,48
torrefied poplar wood	20,34	86	17,42

Per kg of raw material of is 1,38MJ and 1,06 MJ ´lost´ for ´pallet wood´ and ´poplar wood´ respectively. This is equal to an energy loss of 7,90% and 5,74%.

Thermographic Analyis (TGA)

In a TGA experiments are performed with a 'Q500' Thermogravimetric Analyser During the TGA the temperature is controlled and the weight loss in % is measured. The TGA are only done for the experiments with 'pallet wood'. Unfortunately there was no time left to analyse the Poplar wood.

Programmed temperature

The temperature during the experiment is programmed in three stages. The heating rate between the different stages is 10°C/min.

- First stage: 100°C for half an hour in Nitrogen (N_2) environment
- Second stage: 350°C for one hour in Nitrogen (N_2) environment
- Third stage: 900°C for two hours in Oxygen (O_2) environment

The programmed time is including the time it takes to heat up, see Figure 15.

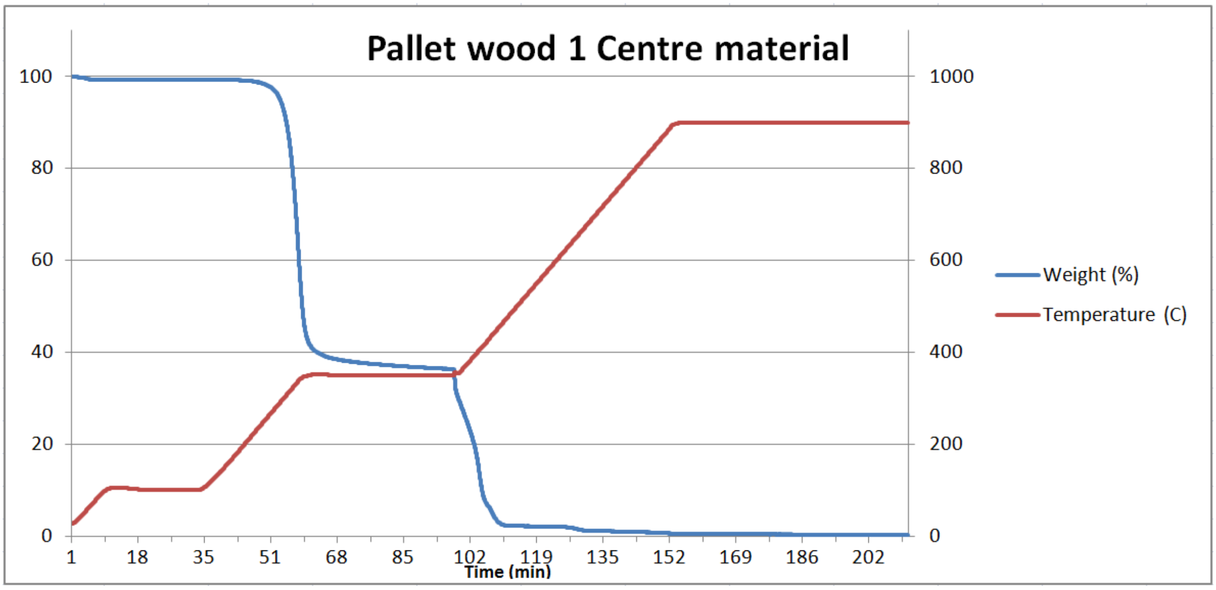

Figure 15: TGA experiment Centre material

Some comments can be made with this graph:

- A little weight loss in the first few minutes.
- When the temperature is raised from 350°C to 900°C with an oxygen atmosphere the mass is reduced quickly by combustion. When the temperature reaches 900°C the mass of the ash is almost constant.

A comparison is made between the Centre material and the Edge material. The result of the Edge material TGA is shown in Figure 16.

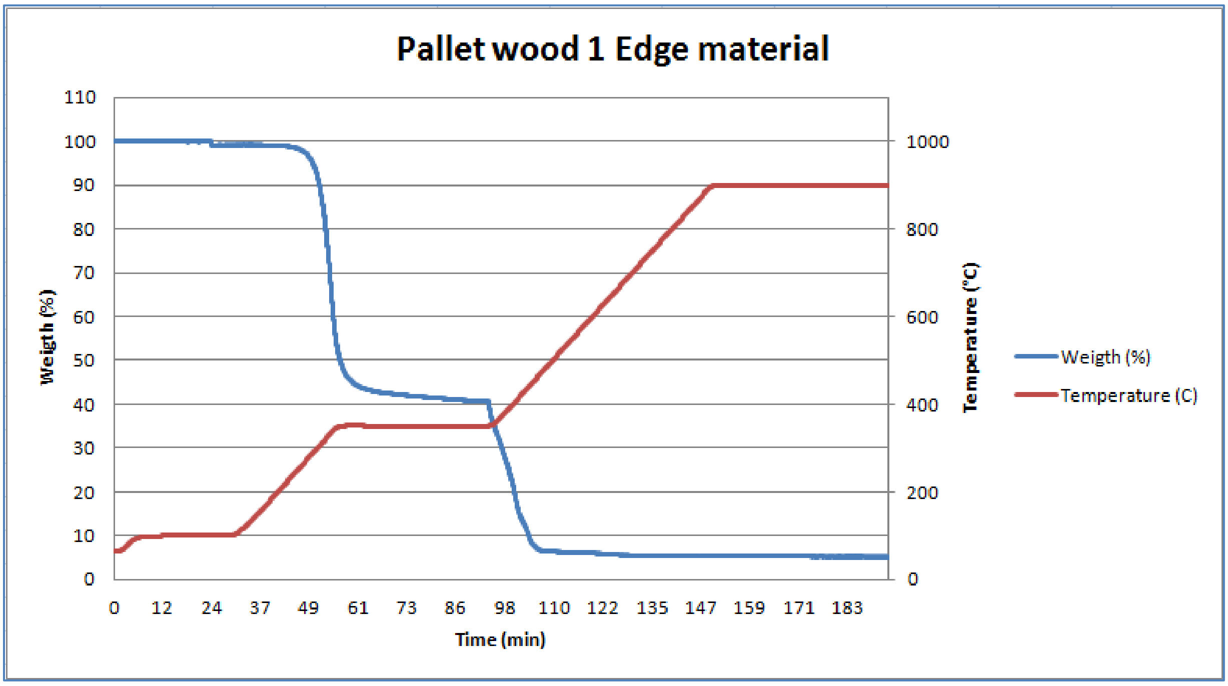

Figure 16: TGA Experiment Edge material

Here also some comments can be made:

- Little 'jump' in the weight % after approximately 24 minutes. This is probable the result of someone bumping into the table supporting the TGA machine.
- The line of the weight % is almost the same as the one of the Centre material (Figure 15) except that the weight % is 5% higher after 50 minutes. This 5% will be de cause of an contamination (sand) in de sample which does not react because it is still present at the end.

Weight % remaining

When the Thermographic Analysis is finished, the ash content of the biomass can be determined. The data cannot be taken from Figure 15 but it can from the Excel sheets. All the weight % left from the 'pallet wood' samples are collected in Table 5.

Table 5: Weight % left

Experiment	Weight % left Edge Sample	Weight % left Centre Sample	Unit
Pallet wood Raw	11,37	11,37	%
Pallet wood 1	5,21	0,25	%
Pallet wood 2	2,13	1,85	%
Pallet wood 3	2,13	2,13	%
Pallet wood 4	2,16	9,25	%

Despite the fact that there is only one sample examined with raw material in can be seen that the raw material has bigger ash content than the torrefied material. So the torrefaction will reduce the amount of ash in the power plant when torrefied material is burned instead of raw material. The big difference in 'Pallet wood 4' is probably caused by a contamination of the sample. The difference between the samples from the centre and the Edge is too small to prove that there is any difference between the two samples.

Conclusions

- The samples contain a little moisture which evaporates in the first few minutes of the TGA. While the literature research stated that the torrefied biomass would not attract any moisture.
- There is no structural difference in weight % left between the centre and edge material samples.

Element Analysis

To determine if there is any difference occurs in the ratios between the elements the wood contains an element analysis is carried out. The element analysis is separated into two steps. First the Carbon (C), Hydrogen (H) and Nitrogen (N) are examined and second an analysis is done to see if the samples contain any Sulphur (S).
In theory wood only contains Carbon, Hydrogen and Oxygen so very little Nitrogen and Sulphur can be expected. If this is indeed the case the amount of Oxygen can be calculated from the total weight (100%) minus the weight % of Carbon and Hydrogen (and Nitrogen and Sulphur).

Carbon (C), Hydrogen (H) and Nitrogen (N)

Each sample is examined three times. The three results from every element are collected in Table 6 and an average over these three values is calculated.

Table 6: Element analysis

Experiment	C	C	C	Avg C	H	H	H	Avg H	N	N	N	Avg N
Pallet wood 2 Centre	51,70	51,55	51,60	51,62	5,74	5,68	5,67	5,70	0,33	0,31	0,29	0,31
Pallet wood 2 Edge	51,70	51,56	51,61	51,62	5,60	5,55	5,56	5,57	0,37	0,35	0,35	0,36
Pallet wood 3 Centre	51,04	51,51	50,85	51,13	5,56	5,50	5,59	5,55	0,27	0,27	0,27	0,27
Pallet wood 3 Edge	51,26	51,20	51,38	51,28	5,60	5,61	5,62	5,61	0,28	0,27	0,28	0,28
Pallet wood 4 Centre	51,48	51,33	50,40	51,07	5,56	5,52	5,40	5,49	0,26	0,25	0,25	0,25
Pallet wood 4 Edge	50,94	50,64	51,28	50,95	5,37	5,38	5,32	5,36	0,25	0,24	0,23	0,24

Sulphur (S)

Table 7: Weight % Sulphur

Experiment	Sample Weight (g)	Sulphur (weight %)
Edge 2.1	0,0491	0,01
Edge 2.2	0,0465	0,01
Edge 2.3	0,0487	0,09
Centre 3.1	0,0495	0,01
Centre 3.2	0,0479	0,12
Edge 3.1	0,0517	0,01
Edge 3.2	0,0471	0,01
Centre 3.1	0,0483	0,10
Centre 3.2	0,0541	0,01
Edge 4.1	0,0517	0,09
Edge 4.2	0,0460	0,08
Centre 4.1	0,0500	0,01
Centre 4.2	0,0499	0,09

The results form Table 7 show as expected a very low amount of Sulphur.

Oxygen (O)

With the previous results the percentages of Oxygen are calculated and mentioned in Table 8.

Table 8: Oxygen

Experiment	Average C	Average H	Average N	Average S	Oxygen
Pallet wood 2 Centre Material	51,62	5,7	0,31	0,055	42,32
Pallet wood 2 Edge Material	51,62	5,57	0,36	0,065	42,39
Pallet wood 3 Centre Material	51,13	5,55	0,27	0,01	43,04
Pallet wood 3 Edge Material	51,28	5,61	0,28	0,055	42,78
Pallet wood 4 Centre Material	51,07	5,49	0,25	0,085	43,11
Pallet wood 4 Edge Material	50,95	5,36	0,24	0,01	43,44

Torrefaction is about increasing the Carbon over Oxygen (C/O) ratio. So if there is a difference in the C/O ration between the centre and edge material there will be a difference in torrefaction between de centre and edge material.

An element analysis was not performed on the raw biomass. But since the blocks of wood where randomly cut out of a big piece of wood it can be assumed the C/O ratio is constant throughout the block.

The C/O ratio is calculated and the result can be found in Table 9.

Table 9: C/O ratio

Experiment	Average C (%)	Oxygen (%)	C/O ratio
Pallet wood 2 Centre Material	51,62	42,32	1,22
Pallet wood 2 Edge Material	51,62	42,39	1,22
Pallet wood 3 Centre Material	51,13	43,04	1,19
Pallet wood 3 Edge Material	51,28	42,78	1,20
Pallet wood 4 Centre Material	51,07	43,11	1,18
Pallet wood 4 Edge Material	50,95	43,44	1,17

It can be concluded that no differences occur between the centre and edge material.

Conclusions/ Recommendations

As a result of the experiments and the analysis some conclusions can be drawn and some recommendations are done for arranging a future assignment and for the content matter of similar assignments.

Conclusions

For pallet wood when the residence time is one hour no significant difference can be found between the centre and edge material for:

- Heat values
- TGA profiles (Weight loss and remaining weight percentage)
- Element composition (including C/O ratio)

For poplar wood:

- No differences in heat value between centre and edge material for a residence time of 60 minutes
- A difference between the heat values of the centre and edge material for a residence time of 45 or 30 minutes. The heating values of the centre material are higher than the edge material whereas the opposite was expected.

Recommendations

- Be sure to have a good assignment description. In my case the preparation time was not sufficient and the assignment I thought I was going to do was not possible. (The original idea was to do tests with Co-firing biomass in a drop tube furnace.)
- Before a proper assignment description can be made knowledge is necessary about the available equipment. Not only for the experiments but also for the analysis after the experiments.
- In order to make biomass an energy source what is as sustainable as possible research should be done on the recovering of the energy trapped in the discharged gasses droning torrefaction.
- More similar test should be done (and analysed) so it can be said with a bigger certainty that there is no difference between the centre and edge material as long as the residence time is longer than X minutes.
- For a residence time of 30 to 45 minutes the results show a higher heating value for the centre material then for the edge material. This implies that for a residence time the biomass particles are preferred to be bigger instead of smaller which is an opposite conclusion than any (Chemical) Engineer would assume in terms of speeding up a reaction. This should be carefully validated with more (precise) experiments.