Carbonization of urban biowaste in Dar es Salaam (Tanzania) Phase III

Searching for energy efficiency

Benjamin Pfyffer
Civil Service
Dar es Salaam, 2016

Contact:
Benjamin Pfyffer
benjamin.pfyffer@bluewin.ch

University of Dar es Salaam:
Dr Hasan Mtoro Rajabu
hmrajabu@gmail.com

Eawag, Switzerland
MSc Imanol Zabaleta
imanol.zabaleta@eawag.ch

Table of Contents

1. Introduction

1.1.Rationale

The provision of affordable, reliable and sustainable cooking fuel for urban residents in many low- and middle-income settings is still a major challenge (Maes and Verbist, 2012). Charcoal, a solid fuel resulting from carbonization of wood biomass in the absence of air at a temperature above 300°C, is the main cooking fuel for millions of households in urban and peri-urban Sub-Saharan Africa (SSA; IEA, 2009). Most of this charcoal derives from unsustainable sources of wood biomass and is produced using traditional earth-mound kilns with char yields around 10 – 15% (Bhattacharya et al., 2002; Antal and Grønli, 2003; Sebokah, 2009). Such charcoal production is causing severe pressure on local forest stocks.

Char production however does not necessarily need to be limited to wood only. Also organic solid wastes generated in agriculture and even urban environments can be carbonized (Lohri 2015). The obtained char can be further processed into uniform char-briquettes which can then be used as cooking fuel (Vest, 2003; Mwampamba et al., 2013). Urban biowaste, currently unutilized and often discarded hereby impacting severely on the environment, represents a potential alternative feedstock for char production. In spite of the unexploited potential, of urban biowaste-based briquettes, there is still limited research available on practical decentralized carbonization solutions for different types of municipal organic solid waste which could be applied in low-income settings (Lohri et al., 2015).

The research presented in this paper is one outcome of a collaboration project between the University of Dar es Salaam and the Swiss Federal Institute of Aquatic Science and Technology (Eawag). The aim was to explore the suitability of urban biowaste as feedstock and test a locally designed and built reactor using slow pyrolysis to produce char from waste. The first phase of the project attested a small-scale experimental pyrolysis unit which consisted of a closed standard oil drum (208 L) inserted horizontally into a brick kiln (Figure 1) and heated with an external fuel source. The required heat was supplied by combusting liquefied petroleum gas (LPG). Three biowaste types (packaging grass (PG), wood waste (WW) and cardboard waste (CB)) were carbonized in this reactor. Results of the produced char showed promising char yields (PG: 38.7%; WW: 36.2%; CB: 35.7% on dry basis), proximate composition (volatile carbon, fixed carbon and ash content) and heating values (PG: 20.1 MJ/kg; WW: 29.4 MJ/kg; CB: 26.7 MJ/kg) which compared well with literature data (Lohri et al., 2015). However, the energy content of the char generated was not able to surpass the energy applied in form of LPG to obtain the char.

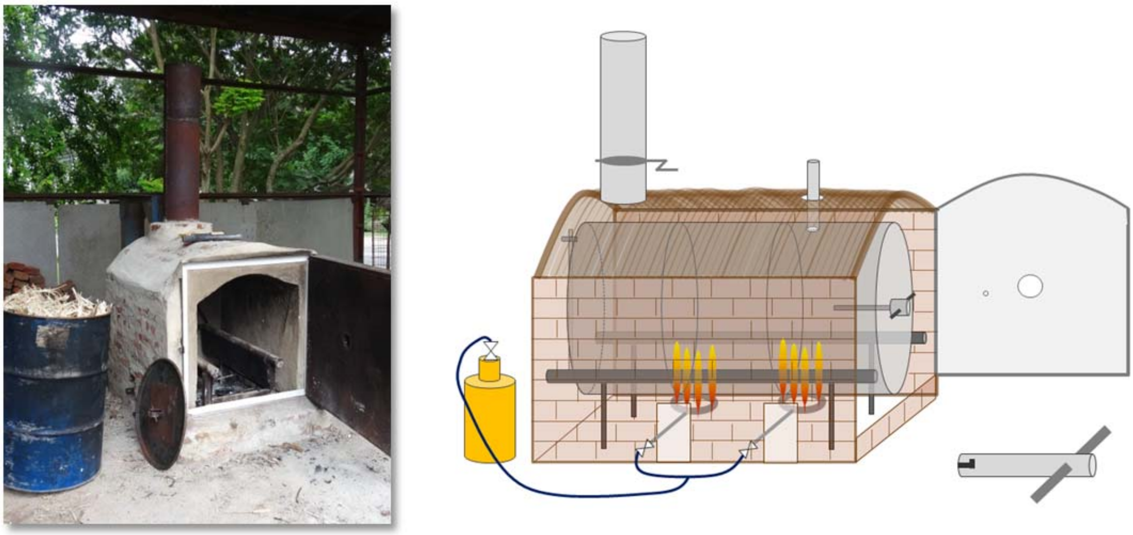

Figure 1: Photo and schematic of first experimental slow pyrolysis unit (Lohri et al., 2015).

The second phase of the project aimed at building and testing a new small scale experimental reactor to improve the energy efficiency and obtain a positive energy balance.

1.2.Previous reactor system

In the second phase a vertical reactor system was built by Manuel Rohr which consisted of three main components. A furnace, a reactor and a chimney as shown in Figure 2

The furnace, located at the bottom, was constructed using a part of an oil barrel (nominal volume 208L, 880mm length, 610mm diameter). The barrel was cut at 44cm height and the bottom was sealed. To allow secondary air to enter, five evenly distributed holes were implemented in the upper part of the furnace, with an area of about 80cm2 each. Another hole (15x15cm) is located in the lower part to enable the mounting of the burner. It was fueled with Liquefied Petroleum Gas (LPG), contained in 15 kg Mihan gas cylinders (about 7000L at 1bar). By means of bricks and cement an interior insulation wall was built to about 9cm thickness. To reinforce the furnace and enable it to carry the load, steel rods were attached externally. The design does not have means to regulate the amount of secondary air entering.

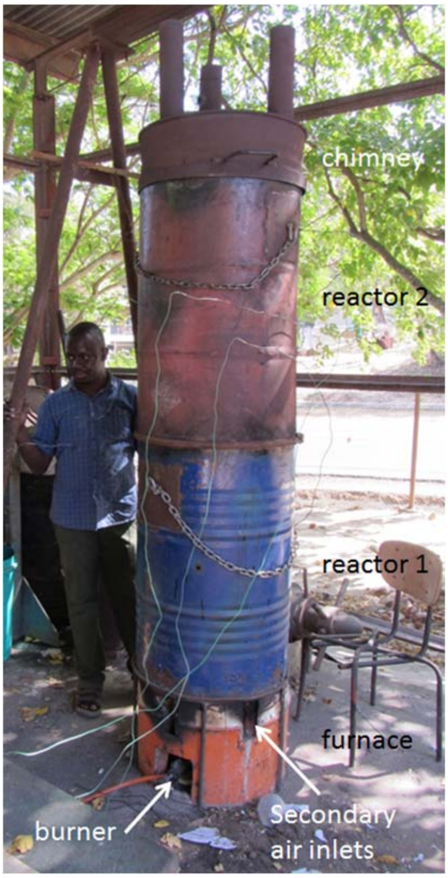

Figure 2: old reactor system

The system also consists of two reactors (number 1 and 2) which were built following a similar design. Each reactor consists of the following components: seven tubes, seven lids, and an insulated barrel. The seven tubes are contained in the interior of the reactor as shown in Figure 3. The tubes are hermetically closed at one end and have a lid at the other end, through which feedstock is inserted.

Figure 3: components of Reactor 1

The tubes of Reactor 1 were welded together to form one single unit. These tubes have a wall thickness of 2.5mm, a diameter of 18cm and a length of 79cm. The tubes without lids weigh about 70 kg and will later on be referred to as the reactor with the heavy tubes. The whole reactor weighs approximately 110kg (including barrel, tubes and lids). The design of the lids is as shown in Figure 4.

Figure 4: the two different types of lids

Reactor 2 has unattached tubes and the lids were inserted in the tubes as shown in figure 4. The tubes have the same dimensions as the ones in Reactor 1, except that they have a thinner wall thickness of 1.5mm. These tubes weigh 50kg all together and the reactor will later on be called the reactor with the light tubes. The total weight of Reactor 2 is about 90kg.

Two identical barrels insulated interiorly with a double wall (about 1cm gap width) and blocked at one end with a grid, incorporate the tubes. The grid thereby prevents the tubes and the lids from falling out.

The system can be operated either with one reactor or with two reactors on top of each other.

Using a part of a barrel too (20cm in length and closed at the top) a chimney was constructed. This chimney has 3 pipes (8cm diameter, 30 cm length), allowing the exhaust gases to exit. The pipes are arranged as shown in Figure 2. The chimney does not have a draft control.

To set the reactor(s) on top of the furnace, a crane system is used. An I-beam is at the top and it has 4 legs of 2" metal pipes. The height of the I-beam above the ground is 3.40m. A manual chain hoist can slide along the I-beam, allowing to lift and move objects horizontally too.

Drawback and limitations of previous system

Design and operation

The design and the operation of the previous system are poor and the process was not well understood. But it has to be remarked that the idea of using seven tubes with lids at the bottom and an oil barrel as a shell for everything is a good concept.

Energy ratio

The energy ratio is defined as the ratio of the energy content in the char formed to the external energy used for pyrolysis as shown in Equation 1.

$ER = mass_{char} * HHV_{char} / mass_{LPG} * HHV_{LPG}$ **Equation 1**

With the described reactor, using cardboard as feedstock and just a single reactor, an energy ratio of 1.49 was reached whereas using two reactors on top of each of each other, an energy ratio of 0.65 was achieved (Rohr, 2015).

1.3.Research objectives

Continuing the project "Carbonization of urban biowaste in Dar es Salaam (Tanzania) Phase II" by Manual Rohr, this projects aims at improving the existing vertical reactor. The project intends to increase the efficiency as well as to better understand the pyrolysis process in the chosen reactor system design.

Furthermore the following specific objectives were tackled. The first and fundamental goal was to improve the existing reactor, by identifying the weaknesses of Manuel's system, and understand the process of pyrolysis so far as the system is able to carbonize a chosen feedstock completely with an energy ratio significantly bigger than one. Based on these findings, the tasks of this phase was to study the influence in overall performance of certain parameters, namely moisture content and particle size of the feedstock. Besides, the effect of double stacking was examined, different feedstocks were tested and the performance of the two reactors was compared.

2. Methodology

2.1. Redesign and construction

The goal of this phase was to identify as many of the weaknesses in Manuel's system and improve the design. This was accomplished by a thorough understanding of the system and its components, which was obtained by screening experiments. These screening experiments were very valuable in order to understand the limitations of the system and consequently how each part of the system could be improved. Finally the overall operation of the system was optimized. In order to further simplify the operation, handling aspects had to be considered in the future.

With the objective of a functional system, the design is held as simple as possible. Furthermore the furnace and the chimney are easy to manufacture, with locally available materials. The basic tools needed are simple and easily obtainable and happen to be an arc welding machine and an angle grinder. In order to guarantee a functioning component (e.g. a furnace) no high precision work is needed.

Furnace

The main drawback of Manuel's furnace is that the control of the secondary air is not possible as there is no mechanism of regulating the amount of secondary air. Another problem is that the openings are in the upper part of the furnace, which doesn't make sense, because the hottest zone of the furnace is at the top, therefore, a lot of heat is lost through these openings. Furthermore the connection of the furnace and the reactor is not possible by means of a belt, because the rim of the furnace is not compatible with the rim of the reactor.

Besides, there are other important aspects to be taken into account. To use the available energy as much as possible, better insulation, and the combustion of the LPG should be complete. Another possible improvement was seen in enlarging the heated area of the barrel, by the use of a burner with a bigger diameter.

In order to overcome these limitations, two furnaces were constructed in the course of the project. The materials used to construct each furnace are shown in Table 1.

Table 1: Materials used to construct each furnace

Material	Furnace 1	Furnace 2
Parts of a barrel	1	2
1.5mm steel plate	< 0.5m^2	> 1m^2
0.8cm round bar	-	1.5m
1.5cm round bar	1m	-
flat bar 2cm	1m	-
cement and sand	-	15kg
bricks	-	10
hinges	2	-
screw and nut	2	1

Reactors

The same reactors as the ones used by Manuel were adopted; however some minor adaptations were carried out on the reactor with the light tubes, because pyrolysis was never complete with just this reactor. Analyzing the differences of the two reactors, namely the lids and the connection of the tubes, the reactor with the light tubes was changed until it showed the same performance as the reactor with the heavy tubes. For the modifications half a meter of an 8mm round bar and $1m^2$ of a 1.5mm steel plate were used.

Chimney

In Manuel's chimney the control of the draft is not possible. There is no possibility to regulate the air escaping the chimney. Furthermore it's not a good idea to use three chimneys, since this division into three parts hinders analysis of the exhaust gases.

Removing the three pipes and the lid of the old chimney, the lower part was reused for the new chimney. Additionally about $2m^2$ of 1.5mm steel plate was used and 4m of an 8mm round bar. To bend the steel plate for the chimney to a pipe, a professional rolling machine of an external company (SIDO) was used.

Operation

The efficiency of a system is directly correlated to the losses that occur. The main losses that have to be considered in a thermodynamical system are heat losses. Most of the heat losses are caused by the gases entering and leaving the reactor system.

There are two types of air entering the system. Primary air is the air mixed with the LPG before it is burned. Secondary air is entering through holes in the furnace. The exhaust gases escape mainly through the chimney. Controlling the flow rates of these gases is the main key for an efficient operation of the system. These aspects were completely disregarded in prior phases.

In the course of the trial experiments, the amounts of air allowed to pass the system were studied and a detailed approach for the operation was worked out.

Primary air

The amount of primary air can be adjusted by a sliding mechanism at the LPG inlet of the burner. This air mixed with the LPG before combustion determines mainly the color and shape of the flame of the burner.

A high amount of primary air leads to a blue flame. This flame does not flicker and has a slender shape. It is also relatively short. The area on the top is thereby quite small and the flame nearly only heats the central tube of the reactor. When the primary air inlet is almost closed the flame gets more orange, caused by the lack of oxygen. To have a good combustion of the LPG, secondary air is needed too. Looking for air, the flame spreads over a larger area and also flickers to a certain extent. Therefore a bigger area on the top is heated, which is to be favored.

Secondary air

Secondary air is the air entering through holes in the furnace. Its amount is much higher compared to the amount of primary air.

The draft created by the chimney determines how much air enters the system. This pulling of the air, controlled by the opening degree of the apertures at the top of the chimney, is much stronger than the pushing, controlled by the openings of the furnace. The apertures at the top of the chimney have a bigger influence on the amount of air that is sucked through the reactor in comparison to the openings of the furnace.

Lambda sensor is very useful to determine how much secondary air is needed at a certain point in time. It is mounted in the chimney and indicates the oxygen content in the exhaust gases. The oxygen content is indicative of how much of the air that has entered, has been combusted with the LPG and the pyrolysis gases. The goal is to allow the minimum volume of secondary air required in order to combust all the fuel. Surplus air cools the system down or rather slows down the heating up and deteriorates the efficiency.

Other improvements

A problem realized in the course of the project, was wind. By blowing through the apertures in the furnace, the flame of the burner is pushed to one side, disturbing the equally dispersed heating up of the reactor. Also the proper control of the secondary air inlet is complicated by an unsteady wind. To reduce the problem wind shields were used which consisted of three curved metal sheets (1.5mm) of 60cm height and 120cm length, arranged around the furnace.

2.2.Experimental set up

The aim of the experiments is to examine the behavior of the reactor under different conditions and show its possibilities and limitations. Experiments were conducted in order to assess five different aspects:

1) Double stacking: the performance of the system with two barrels was assessed.
2) Particle size: the influence of the particle size in the overall performance and energy balance was assessed. Three different particles sizes of softwood were studied, sawdust as first level, briquettes (6cm diameter) of 3cm length for the second level and 6cm in length for the third level.
3) Moisture content: the effect of moisture content in the overall performance and energy balance was assessed. Four different moisture contents levels were studied, 6%, 10%, 20% and 40%.
4) Feedstock comparison: experiments with several feedstock were conducted, namely, sawdust of hardwood and softwood, briquettes and coffee husks.
5) The performances of Reactor 1 and Reactor 2 were compared.

Table 2 provides a summary of the experiments conducted.

Table 2: summary table of conducted experiments. Code explanation: e2._ are the double stacking experiments, ps1l1 means: particle size, first level, first experiment; mc means moisture content; h and l (fourth column) means heavy and light tubes; d and l (column "feedstock") means diameter and length; dm (last column) means dry mass).

Exp. no.	Date	No. of barrels	Barrel used lower/ upper	Feedstock	Feedstock mass (kg wb) lower/upper
e2.1	25.10.	2	h/l	sawdust (hard wood)	18.9/ 17.4
e2.2	26.10.	2	h/l	sawdust (hard wood)	21.7/ 22.9
e2.3	30.11.	2	h/l	sawdust (hard wood)	25/ 24.4
ps1l1	3.11.	1	h	sawdust (soft wood)	20 dm
ps1l2	4.11.	1	h	sawdust (soft wood)	20 dm
ps1l3	17.11.	1	h	sawdust (soft wood)	20 dm
ps2l1	2.11.	1	h	briquettes (l=30+-5)	61.8
ps2l2	15.11.	1	h	briquettes (l=30+-5)	64
ps2l3	18.11.	1	h	briquettes (l=3+-5)	64.6
ps3l1	1.11.	1	h	briquettes (d=l=60+-5)	53.5
ps3l2	14.11.	1	h	briquettes (d=l=60+-5)	59.9
ps3l3	16.11.	1	h	briquettes (d=l=60+-5)	60
mc0l1	30.11.	1	l	sawdust (soft wood)	20 dm
mc1l1	9.11.	1	l	sawdust (soft wood)	20 dm
mc1l2	14.11.	1	l	sawdust (soft wood)	20 dm
mc1l3	18:11	1	l	sawdust (soft wood)	20 dm
mc2l1	7.11.	1	l	sawdust (soft wood)	20 dm
mc2l2	8.11.	1	l	sawdust (soft wood)	20 dm
mc2l3	17.11.	1	l	sawdust (soft wood)	20 dm
mc3l1	4.11.	1	l	sawdust (soft wood)	20 dm
mc3l2	15.11.	1	l	sawdust (soft wood)	20 dm
mc3l3	16.11.	1	l	sawdust (soft wood)	20 dm
coffee husks 1	01.12.	1	h	coffee husks M10%	43.3
coffee husks 2	02.12.	1	h	coffee husks M10%	43.8

As can be seen in Table 2, most of the levels were done in triplicates.

Double stacking

These experiments aimed at getting an energy ratio as high as possible.
Hardwood shavings, with a moisture content of 10% were used. The reactor was loaded as much as possible, in each reactor about 20kg. Due to the fact that the natural moisture content of this feedstock lies around 10%, the shavings could be loaded without pre-drying.

Particle size

To study the effect of particle size, three levels were chosen. These experiments were done using one barrel. All materials had a moisture content of 10%. For the first level (ps1) softwood sawdust was used and for every run 20kg dry mass was loaded. Some of this sawdust had to be dried in advance, due to the too high moisture content. The second level (ps2) was testing chopped briquettes of 3cm length and a diameter of 6 cm. Without using a binder these briquettes were made of softwood sawdust too. Also the third level (ps3) used the same briquettes but chopped to a length of 6 cm. These briquettes had a natural moisture content of 10%. Due to the high density, an amount of about 60kg of briquettes could be loaded in one barrel, in the second level as well as in the third.

Moisture content

In this experiment four levels were tested, with moisture contents of 6% (mc0), 10% (mc1), 20% (mc2) and 40% (mc3). The level with 6% was tested once, because of lack of time. As basic amount of feedstock, 20kg dry mass of softwood sawdust was taken. Then depending on the targeted moisture content the sawdust was either dried or water was added. Equation 2 was used to calculate how much water had to be added.

$$water_{add} = mass_{fs}*(100-M_{fs})/(100-M_{target}) - mass_{fs} \qquad \text{Equation 2}$$

where $water_{add}$ is the water that has to be added to get M_{target} the targeted moisture content. $mass_{fs}$ is the mass of the feedstock treated and M_{fs} its measured moisture content.

Subsequently the prepared sawdust was packed in black plastic bags and exposed to the sun (at least two days), in order to let the moisture distribution become uniform.

Feedstock comparison

To test another feedstock, coffee husks were chosen, because of their good properties, meaning low ash and moisture contents. The coffee husks had a natural moisture content of 10% and could therefore be processed without previous drying.

Comparison of different barrel designs

Because the first level of the particle size and the moisture content experiments were carried out with the same feedstock (softwood sawdust, 10% moisture content) and under the same conditions, the performance of the two almost identical reactors can be compared.

Table 3: amounts, costs and source of used feedstock

	Hardwood	Softwood	Briquettes	Coffee husks
Used amount	125kg	325kg	400kg	90kg
Costs	for free	26000TZS	292000TZS	100000TZS
Supplier	workshop UDSM	local workshop at Mwenge	briquetting company in Moshi	from coffee company in Mbeya.
Drying	no	yes	no	no

2.3. Monitoring parameters

During an experiment three parameters were observed, described subsequently.

The exhaust gases were observed using a lambda sensor (lambda check) The sensor was screwed into the chimney, while its electronics and the power supply where hung on the crane. To protect the cable of the sensor from the high heat of the furnace, a piece of wood is laid under the sensor, supported by a brick.

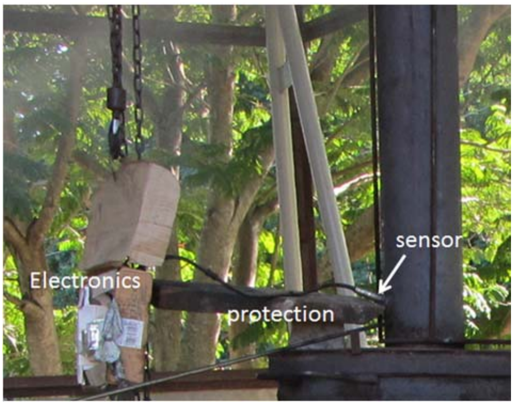

Figure 5: lambda sensor with protection and electronics

Temperatures were recorded by means of two to four thermocouples (Omega, K-type, model: TJ1-CAXL-IM80U-900) and a data logger from Pico Technology.

Figure 6: thermocouple installed and connected to the data logger

To control the LPG flow rate, a rotameter (Wagner, C4H10, 2-19l/min) was used.

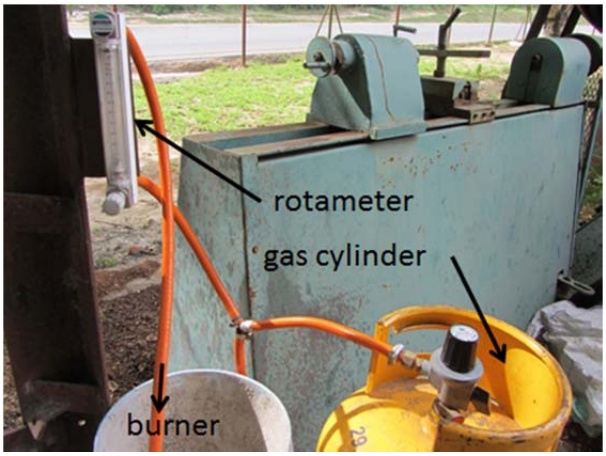

Figure 7: the gas passes through the rotameter from the bottom to the top, proceeding to the burner

2.4.Description of an experiment

In all the experiments the newly built furnace (second version) and chimney were used. For each experiment dealing with particle size, the heavy tubes (Reactor 1) were utilized. Whereby for the moisture content experiments the light tubes (improved Reactor 2) were applied. To exclude the influence of the wind, the wind shield was used in all experiments.

All experiments have the same procedure. Hereinafter the preparation, ignition, the run and the follow-up after experiment.

Preparation

When the feedstock was too moist, it had to be dried in advance. This was done using a black plastic sheet (10x1.5m). The drying was done in front of the reactor site, on a place with direct sun between 11 o'clock and 15.30, if it wasn't cloudy. The feedstock was spread as evenly as possible and mixed from time to time (Figure 8: drying of sawdust). About 50kg of feedstock could be dried at one time.

Figure 8: drying of sawdust

Before the prepared sawdust can be loaded, the gaps between the tubes were blocked with papers, to prevent the feedstock from falling in between and stuck. The feedstock has to be compressed so that it all fits. For this purpose a wood-log is used for compacting during filling. The above filling procedure was not used for briquettes which were filled without jamming the gaps and were also too compressed.

Figure 9: almost filled tubes with papers to prevent the coffee husks from clogging the gaps

As soon as the tubes are loaded, they are closed with the lids. Then, using the crane, the barrel is lifted up upside down and is put over the tubes. After that the composed reactor is turned over by 180 degrees. Next the reactor is put on the furnace by means of the crane. The furnace and the reactor are then connected with a steel belt.

Before the run can be started, the chimney is set on top of the reactor and also fixed with a steel belt. Furthermore the gas cylinders are installed, the lambda sensor is set up and the temperature sensors are inserted into holes drilled for this purpose. One sensor goes into the central tube (if possible, sometimes it is not and then this sensor is put aside), a second one inside the reactor and a third one into the chimney. Then they are connected to the PicoLog which for his part is connected to a computer.

After the computer is prepared and ready to record, the burner is ignited. Therefore a stick is equipped with a paper, which is lighted. Subsequently the burning stick is inserted into the furnace and the gas is turned on. Finally the wind shield is arranged.

Run

This part of the operation is an essential part of the know-how gained in this project. The operation according to the subsequent description is crucial. A run can be divided into three phases: heating up, pyrolysis and cooling down.

In the first phase the reactor is heated up by burning LPG. When part of the feedstock in any tube dries, it is heated up and starts pyrolysis. When more feedstock is pyrolyzed more pyrolysis gases comes out needing more air to burn . At this point the chimney apertures are fully opened and the oxygen content is 0%, then the LPG can be turned off. This is the start of the second phase. The material continues to carbonize using heat from burning pyro gases. When pyrolysis is finished, the reactor is left to cool down.

In the following detailed description the procedure for a single reactor is described. If two reactors on top of each other are operated, the same procedure applies. The only difference is that the taller set up, creates more draft, so the apertures have to be opened less. But in any case the system should be operated according to the values delivered by the lambda sensor.

Heating up

During this phase the feedstock is dried and heated up until pyrolysis starts. The LPG flow is controlled to a flow rate of 6 - 6.5l/min by using a rotameter. This flow rate was found to be optimal. The burner can't handle much more LPG and the flame is big enough to touch the bottom of the reactor. To use as little LPG as possible during the whole heating up, the secondary air is controlled, using the lambda sensor as a monitor, to an oxygen content of between 3 and 3.5%. The amount of secondary air has to be as low as possible, ensuring a proper combustion of the LPG. The rough opening positions for the chimney and the furnace at the beginning of the heating up can be seen on picture ref. 2.

Figure 10: opening position of the chimney in the beginning (almost fully closed)

Figure 11: opening position of the furnace in the beginning

Figure 12: opening position of the primary air inlet and optimal flame

Figure 12 shows the position of the primary air inlet. This position was held during the whole experiment.

Due to the fact that drying and also pyrolysis are continuous process, the apertures opening have to be increased slowly during heating up, in order to keep the oxygen content in the exhaust gas constant when pyrolysis gases start to escape slowly. By rule of thumb the apertures of chimney and furnace should be opened by about the same amount at all time. As soon as both openings are fully open, the production of pyrolysis gases is enough to keep the process going and the LPG can be switched off. This is the start of the second phase.

Pyrolysis

When pyrolysis is strong, temperatures above 800° C were reached inside the barrel. Depending on the amount of feedstock, the strong pyrolysis can go for 30 – 90 minutes. During pyrolysis the oxygen content should be held constant between 0 and 1%, trying to keep as much energy in the system as possible. Then as pyrolysis is finishing up, the openings have to be closed synchronously. When they are closed completely and the oxygen content is still rising, indicates completion of pyrolysis and the end of the second phase. This is when the cooling down starts.

The lambda sensor is the most important device to monitor in which stage pyrolysis is. Together with the opening degree of the apertures, the current amount of pyrolysis gases can be estimated.

Cooling down

The reactor has to cool down after pyrolysis, to prevent the feedstock catching fire when the reactor is opened and air comes into contact with the feedstock. This takes several hours and it’s recommended to let it cool down overnight and to offload the char the next morning.

Emptying procedure

After complete cooling the reactor is emptied. In order to do that, the chimney, the sensors and the wind shelter are removed and the reactor is taken down off the furnace. The reactor is turned upside down and the barrel is slowly pulled up by means of the crane and the lids are taken off. The carbonized feedstock can now be poured out and weighed. If pyrolysis was not complete, the carbonized and non-carbonized material has to be separated and weighed separately as shown in Figure 13. Complete pyrolysis means that in all the tubes the feedstock is carbonized entirely. This is detected after opening the reactor and all the feedstock is completely black (Figure 14). A sample of the char is taken and analyzed with proximate analysis.

Figure 13: separation of incomplete carbonized feedstock

Figure 14: complete pyrolysis of briquettes (experiment ps3l2) ready to empty

2.5.Further analysis

Proximate analysis of the samples from the char and the raw feedstock were conducted following the method D1762 – 84 (Reapproved 2007), the standard test method for chemical analysis of wood charcoal. The proximate analysis was done in triplicates and then the average and the standard deviation were taken.

According to the previous method, moisture content (MC%) was determined by measuring the percent weight loss after the samples were dried at 105° for 2h. The volatile content (VC%) was determined by measuring the percent weight loss of the dried samples after heating at approximately 950°C in absence of air. The ash content (ASH%) was measured by the percent weight loss after burning the dried samples in a muffle furnace at 750°C for 6h. Fixed carbon (FC%) was calculated by the sum of ash and volatile matter percentage and its difference to 100%. Char yield (y_{char}) was calculated on dry basis:

$y_{char} = m_{char,\ db}/m_{feedstock,\ db}$ **Equation 3**

where $m_{char,db}$ is the mass of the generated char (dry basis) and $m_{feedstock,db}$ is the mass of the original feedstock (dry basis). The fixed-carbon yield (y_{FC}), which is an indicator of carbon efficiency, was calculated according to:

$y_{FC} = y_{char} \cdot [FC\%_{char} / (100 - ASH\%_{feedstock})]$ **Equation 4**

where $\%FC_{char}$ is the fixed carbon content of char in percent and dry basis and $\%ASH_{feedstock}$ is the percentage ash content in the feedstock on dry basis (Antal et al., 2000). In addition, the higher heating values (HHV) of the chars were determined using an empirical calculation based on proximate analysis (Parikh et al., 2005).

$HHV = 0\ 3536 \cdot FC\%_{db} + 0\ 1559 \cdot VC\%_{db} - 0\ 0078 \cdot ASH\%_{db}$ **Equation 5**

The energy ratio was calculated as shown in Equation 1.

$ER = mass_{char} * HHV_{char} / mass_{LPG} * HHV_{LPG}$ **Equation 1**

3. Results and discussion

3.1. Redesign and construction

In the course of this phase a reactor system was refined and tested. The system, when operated properly, works reliably and is able to carbonize different feedstock and provides constantly good performance.

The components built in the course of this project, namely the furnace and the chimney, are easy to operate and allow a precise control of the draft. Due to the reliably working and user-friendly modules, it is an easy task to run an experiment. Figure 15 shows a photo of the entire reactor system.

Figure 15: whole new reactor system

Furnace

In the course of the project two furnaces were constructed. The first one uses a paella burner with two rings and an outer diameter of 40 cm (Figure 16). This burner was chosen to enlarge the area of the reactor heated by the burner. A part of a barrel of 27cm height is used for the outer wall. It is standing on three legs out of 1.5cm steel rods and 25cm length. The furnace is equipped with a secondary air inlet at the bottom, consisting of two identical disks with six cake-slice-shaped holes. The amount of air entering can be adjusted by rotating the movable disk relatively to the fixed disk. To install and ignite the burner a door is implemented using two hinges.

Figure 16: furnace with paella burner

This design would have worked well, if the performance of the burner was not so poor. As soon as the secondary air inlet is adjusted to an appropriately low lambda value, only half of the holes of the burner were supporting the flame Because the reactor is not heated up uniformly.
Due to the fact that this burner was designed to be operated outside and with supply of as much secondary air as needed, this problem couldn't be solved. After a second iteration, using the old burner from Manuel and a stainless steel deflector plate (to spread the flame of the burner) (22cm diameter, 15cm distance to the burner) this furnace was not performing well and was abandoned. In direct comparison with Manuel's furnace its performance was worse.

The second furnace (Figure 17) built was inspired by the furnace constructed by Manuel Rohr. Because of its good performance, the main features were adapted.

To use a rim of the barrel at the top and a lid at the bottom, a barrel was cut into three pieces, then the middle part was put away and the other two parts were welded together. The height of this configuration is 44cm. Four secondary air inlets (10x20cm) were made on the lower part of the furnace, equipped with a sliding mechanism to adjust the amount of air allowed to enter. To place these openings in the lower area makes more sense, due to the fact that the upper part of the furnace is hotter than the lower one, thus the heat losses through these openings are minimized. For insulation purposes the furnace is insulated interiorly with a wall of 9cm thickness out of cement and bricks. There is also a spyhole implemented, but It turned out to be not useful, because everything can be seen through the secondary air inlets.

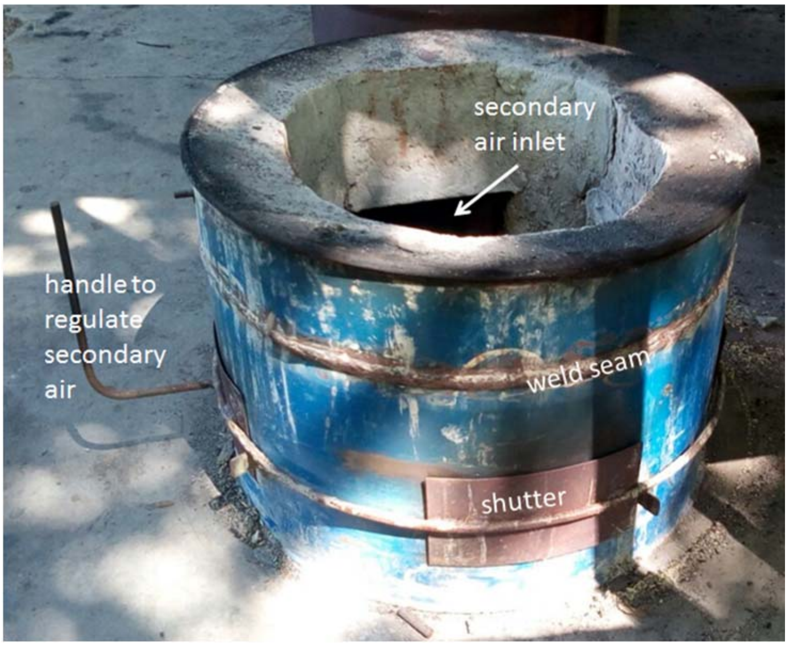

Figure 17: final version of the furnace

Reactor

In the course of the trial experiments it was observed that the performance of the reactor with separated tubes and the internal lids (Reactor 2) was much lower than the one of the other reactor (Reactor 1), resulting in incomplete pyrolysis.

In order to compensate this, the separated tubes were welded together to improve the heat transfer between the tubes. This was done using 4cm long pieces of 8mm steel rod. After testing this new configuration, it became clear that the main factor for the poor performance was not the heat transfer between the tubes but the different design of the lids (Figure 4). Therefore new exterior lids were manufactured and the new set up was tested again. The modified reactor showed good performance after changing the lids design.

The lids play a very important role in the course of pyrolysis. The gases escaping during pyrolysis through the gaps around the lids burn. Whereas the flames of the interior lids come out mainly downward, and thus heat more the bottom part of the tubes, the flames of the exterior lids escape upwards along the tubes (Figure 18). This direct heating of the tubes is very important to drive pyrolysis and ensure a complete carbonization.

Figure 18: flames escaping the tubes with different lids

New chimney

With the new chimney (Figure 19) the handling should be simplified. The old chimney has no possibility to control the draft. Removing the three pipes and the lid of the old furnace, the lower part was reused for the new chimney. A single but longer pipe was mounted (90cm long, 15cm diameter) and a control mechanism was implemented. When fully opened the three apertures (7.5x9cm) are equivalent to the cross-sectional area of the chimney. The top of the furnace is closed permanently with a steel disk. To facilitate the handling for the operator, a rod extension was made. In this way, the handle to open and close the apertures is easily reachable when standing next to the reactor.

Furthermore a hole for a temperature sensor and a thread for the lambda sensor are mounted.

Figure 19: new chimney

Other improvements

The wind shield protects the LPG-flame and thereby ensures a uniformly heating up of the reactor.

Economic assessment

The costs below are rough estimations. Because it is a development work, it is difficult to determine the exact costs of the components. For example some materials used were already present.

It is not possible to determine the costs of the labor for a single component, because all labor costs were lumped together. Therefore the figure given here to labor is not accurate.

Component	Costs
Furnace with paella burner (materials)	~200,000TZS
Second furnace (materials)	~70,000TZS
Reactor changes (materials)	~30,000TZS
Chimney (materials)	~70,000TZS
Wind shield (materials)	~120,000TZS
Other materials	~370,000TZS
Labor	~750,000TZS
Total	**1,610,000TZS**

This amounts to approximately 740 USD.

3.2. Experimental phase

The results of the experiments done are presented subsequently, whereby the description is divided into a part about yields and proximate analysis and a second about energy ratios obtained.

Yields and proximate analysis

In the table below, the char yields, the results of proximate analysis and C_{fix} yields are shown. Proximate analysis was done in triplicates and the average and the standard deviation was taken.

Table 4: char yields, proximate analysis, and Cfix yields

Exp. no.	Feedstock	Feedstock mass (kg wb) lower/upper	Char mass (kg)	Non-carbonized (kg wb)	Char yield (%)	TS (%)	VS (%)	Ash (%)	Cfix (%)	Cfix yield (%)
hard wood	-	-	-	-	-	88	81	1	18	-
soft wood	-	-	-	-	-	88±1	86	2	13	-
briquettes	-	-	-	-	-	90	79	2	18	-
coffee husks	-	-	-	-	-	92	82±1	1	17±1	-
e2.1	sawdust (hard wood)	18.9/ 17.4	11.5	0	35	97	14	4±1	82±1	30
e2.2	sawdust (hard wood)	21.7/ 22.9	13	0	32	98	13	3±1	83	27
e2.3	sawdust (hard wood)	25/ 24.4	17.5	0	39	97	12±1	5±1	84±1	34
ps1l1	sawdust (soft wood)	20 dm	6	0	30	99	13	7±1	81±1	26
ps1l2	sawdust (soft wood)	20 dm	6.3	0	32	99	11	6±1	83±1	28
ps1l3	sawdust (soft wood)	20 dm	5.8	0	29	98	14±1	6±1	80±1	25
ps2l1	briquettes (l=30+-5)	61.8	16.7	0	30	99	12	9±1	79±1	26
ps2l2	briquettes (l=30+-5)	64	17.5	0	30	100	9	9±1	82±1	27
ps2l3	briquettes (l=3+-5)	64.6	17.68	0	30	99	21	7	72	23
ps3l1	briquettes (d=l=60+-5)	53.5	15.5	0	32	99	7	9±2	84±2	30
ps3l2	briquettes (d=l=60+-5)	59.9	16.8	0	31	99	12	8	80±1	27
ps3l3	briquettes (d=l=60+-5)	60	17.2	0	32	99	10±1	12±4	78±5	28
mc0l1	sawdust (soft wood)	20 dm	6	0	32	98	13	8±2	79±2	27
mc1l1	sawdust (soft wood)	20 dm	6.5	0	33	99	15	6±1	80	28
mc1l2	sawdust (soft wood)	20 dm	6.2	0	31	99	19±1	6	75	25
mc1l3	sawdust (soft wood)	20 dm	6	0	30	99	16±1	4	80±1	25
mc2l1	sawdust (soft wood)	20 dm	2	11	10	97	9±1	7±3	84±3	9
mc2l2	sawdust (soft wood)	20 dm	4.4	4.9	22	98	9	9±1	82±1	20
mc2l3	sawdust (soft wood)	20 dm	4	4.5	20	98	17	3±1	80±1	16
mc3l1	sawdust (soft wood)	20 dm	3.2	8.8	16	97	9	9±1	82±1	14
mc3l2	sawdust (soft wood)	20 dm	2.7	9.8	14	98	11±1	8±1	81±1	12
mc3l3	sawdust (soft wood)	20 dm	0.8	16.8	4	98	16±1	12±1	72±1	3
coffee husks 1	coffee husks M10%	43.3	12.3	0	32	97	12	4	84±1	31
coffee husks 2	coffee husks M10%	43.8	12.8	0	32	96	14±1	4	82±1	31

The results from proximate analysis are for all tested raw materials very similar. Comparing soft and hardwood, softwood has slightly higher volatile solids (VS) content (86% compared to 81% for hardwood) and a lower fixed carbon content (Cfix) (13% compared to 18% for hardwood). The ash content is for both materials very low and between 1 and 2%.

Briquettes are made out of softwood, but the results from proximate analysis are more similar to the results for hardwood.

Coffee husks have similar properties as the wood materials.

The char yield was throughout about 30% (just for the successful experiments, meaning complete pyrolysis). In Figure 20 the shrinking in volume in radial direction can be seen, using the example of a briquette. The briquette seems to gain volume in longitudinal direction but this elongation has been put down to expansion (or relaxation) of the briquettes due to loss of binding forces leading to cracking of briquettes.

Figure 20: raw vs. carbonized briquette, decrease in diameter and increase in length

Pyrolysis increases the Cfix drastically as the VS decrease. The ash content increases slightly due to the mass reduction in the course of pyrolysis. Cfix yields of around 30% resulted for the successful experiments.

All analyzed samples show about the same properties and there are no big differences between the samples.

For all material the Cfix reaches from 75% to 85%. VS lay between 7 and 21% and ash content between 6 and 12%.

Energy ratios

In Table 5 heating up times and energy ratios are shown. For all energy ratios a HHV of 50MJ/kg was assumed for LPG.

All analyzed samples have comparatively high HHV of between 29 and 32MJ/kg. Experiment mc3l3 has a heating value of only 28MJ/kg, probably due to mistakes during proximate analysis.

Table 5: heating up times and energy ratio related results.

Exp. no.	Heating up time (min)	LPG (kg)	HHV (MJ/kg)	ER
hard wood	-	-	19	-
soft wood	-	-	18	-
briquettes	-	-	19	-
coffee husks	-	-	19	-
e 2.1	50	1.1	31	6.5
e 2.2	55	1.1	32	7.5
e2.3	130	2.8	31	3.9
ps1l1	45	1	30±1	3.6
ps1l2	46	1	31	3.9
ps1l3	40	1	30	3.5
ps2l1	77	1.9	30	5.2
ps2l2	78	1.6	30	6.6
ps2l3	70	1.7	29	5.9
ps3l1	75	1.8	31±1	5.3
ps3l2	65	1.7	30	5.9
ps3l3	78	1.6	29±2	6.2
mc0l1	23	0.6	30±1	6
mc1l1	38	1	30	3.9
mc1l2	32	0.7	30	5.2
mc1l3	28	0.8	31	4.6
mc2l1	50	1	31±1	1.2
mc2l2	70	1.7	30	1.6
mc2l3	69	1.6	31	1.5
mc3l1	180	4.3	30	0.4
mc3l2	180	3.6	30	0.5
mc3l3	180	3.4	28	0.1
coffee husks 1	93	1.6	32	4.9
coffee husks 2	135	2.6	31	3.1

Double stacking

The experiments conducted with two barrels on top of each other revealed that this set up almost doubles the efficiency compared to the set up with a single barrel. This is because first the lower barrel is heated and dried by burning LPG. As soon as pyrolysis is strong enough, the LPG is switched off. After that the burning pyrolysis gases of the lower barrel heat up and dry the upper barrel, until it starts to pyrolyze.

Two experiments were successful and resulted in energy ratios of 6.5 and 7.5. The heating up time was proportionately short, 50 and 55 min, consuming 1.1kg of LPG, resulting in complete pyrolysis of both reactors. The process for both of them was quite different, that is the dynamics of pyrolysis in the upper barrel were different. In the first experiment, the lower barrel started pyrolysis first and the upper one slowly by slowly after the first one. In the second experiment pyrolysis started almost at the same time in the upper barrel as in the lower one.

The third experiment took much longer heating time and consumed more LPG, because after the experiment was started, a power cut occurred. Therefore it was not possible to determine the optimal time for switching of the LPG and heating up took longer. The energy ratio in this experiment was 3.9.

In Figure 21 the temperature profiles of experiment e2.1 are shown. These profiles are representative of a double stacking experiment. High temperatures in the reactor above 600°C indicate strong pyrolysis.

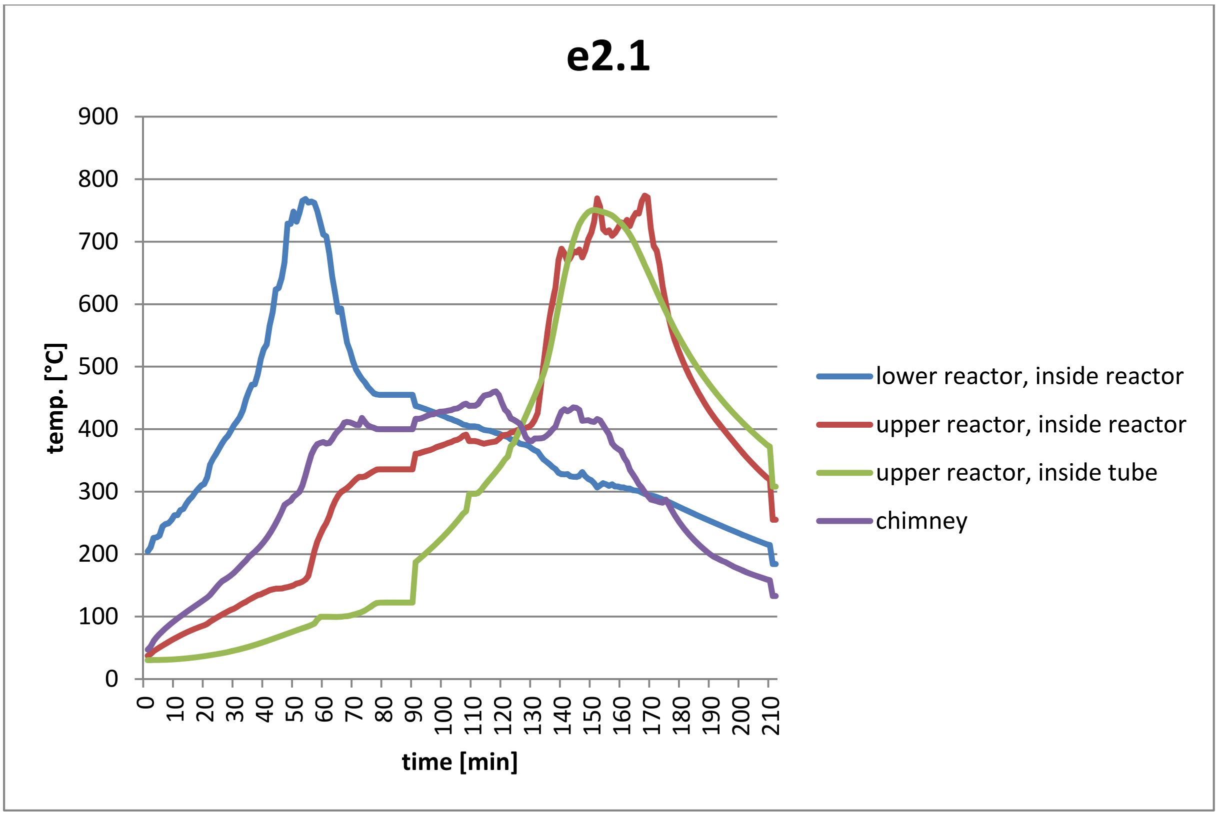

Figure 21: temperature profiles of experiment e2.1

There are two major peaks. The first one indicates pyrolysis in the lower reactor, starting after about 50min. In this experiment the LPG was switched off after 50min. Then the strong pyrolysis of the lower barrel heated up the upper barrel and around minute 135 pyrolysis in the upper barrel starts and gets very strong.

The temperature in the chimney rises first, stays then more or less constant and decreases again in the end when pyrolysis fades out.

Particle size

All the particle size experiments were carbonized completely. Pyrolysis started uniformly, meaning in all tubes at about the same time, and was throughout strong and also faded out quickly. For a certain time there even was a flame reaching the apertures of the chimney. The time of pyrolysis (not shown in a table) depends on the amount of feedstock and was about 30 min for sawdust and up to 90min for briquettes. Heating up times ranged from 40min (1kg LPG) for sawdust to 78min (1.9kg) for briquettes. The highest energy ratio obtained from the third level was 6.2.

Figure 22: carbonized briquettes (experiment ps3l2)

In Figure 23 the temperature profiles of experiment ps2l3 are shown. Characteristic for this experiment is that pyrolysis takes very long, around 90min in this case. This is due to the high amount of material (64.6kg), producing a lot of gases.

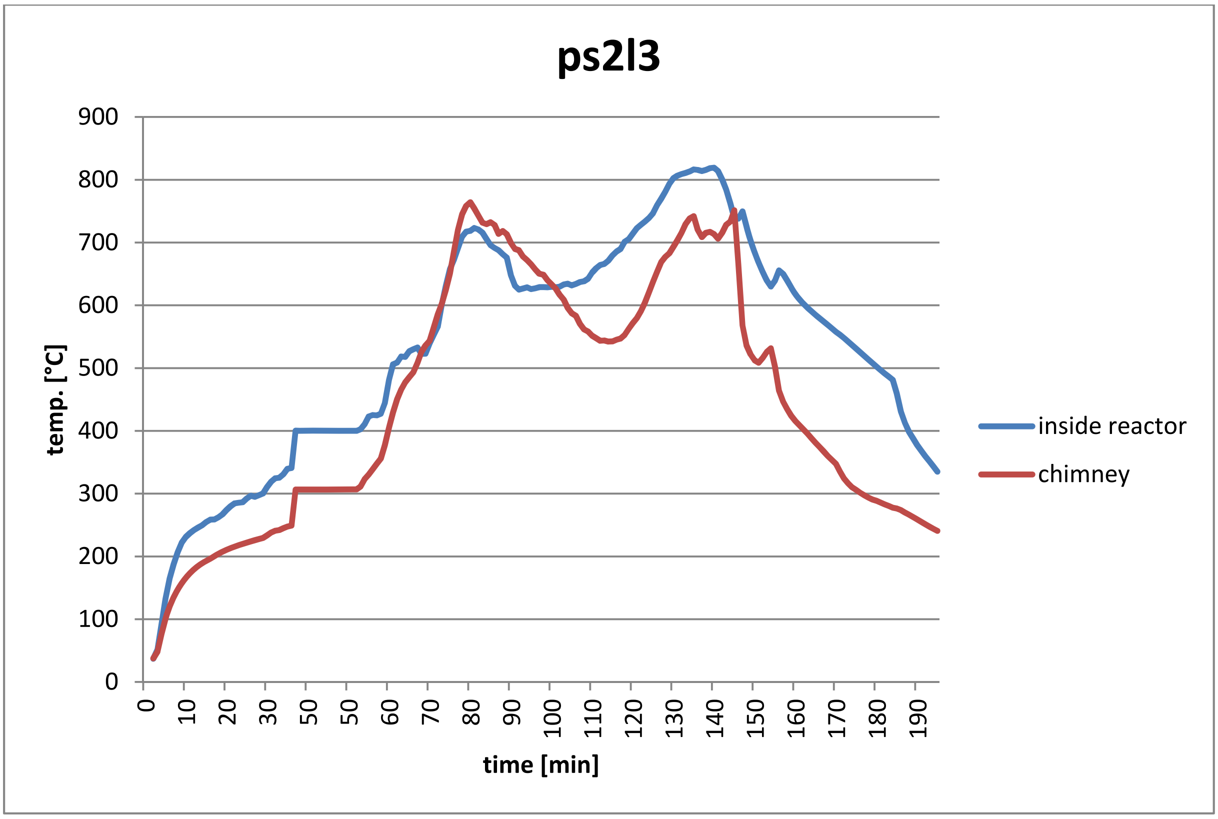

Figure 23: temperature profiles of experiment ps2l3

The two peaks during pyrolysis suggest that not all tubes reacted at the same time. First some tubes showed strong pyrolysis. After these tubes faded, other tubes started and caused the second peak in the graph.

Moisture content

The experiment with 6% moisture content showed very good performance, just taking 23min to heat up and consuming 0.6kg LPG. This experiment has the highest energy ratio of 6.
The first level having a moisture content of 10% carbonized without problems, taking at the minimum 28min (0.7kg LPG) for heating up and an averaged energy ratio of 4.6 was achieved.
For 20% moisture content, pyrolysis was not completed in all tests. Heated up for 50 to 70min (1 to 1.7kg LPG), pyrolysis was always strong when LPG was switched off. But afterwards, pyrolysis decreased too quickly, leaving about one third of the material non-carbonized (mc2l2 and mc2l3). Average energy ratios of 1.4 were achieved.

For 40% the performance was even worse. Pyrolysis was never strong, and heated for 180min (3.4 to 4.3kg LPG), just a fraction of the sawdust was carbonized, leading to an average energy ratio of 0.3.

Figure 24: incomplete pyrolysis (experiment mc2l2)

Figure 25 and Figure 26 present the temperature profiles of two different experiments. The first one shows experiment mc1l2, as an example of an experiment with low moisture content (10%) and therefore a good performance. The second graph, shows experiment mc2l3, an experiment with higher moisture content (20%) and therefore bad performance and uncompleted pyrolysis in the end.

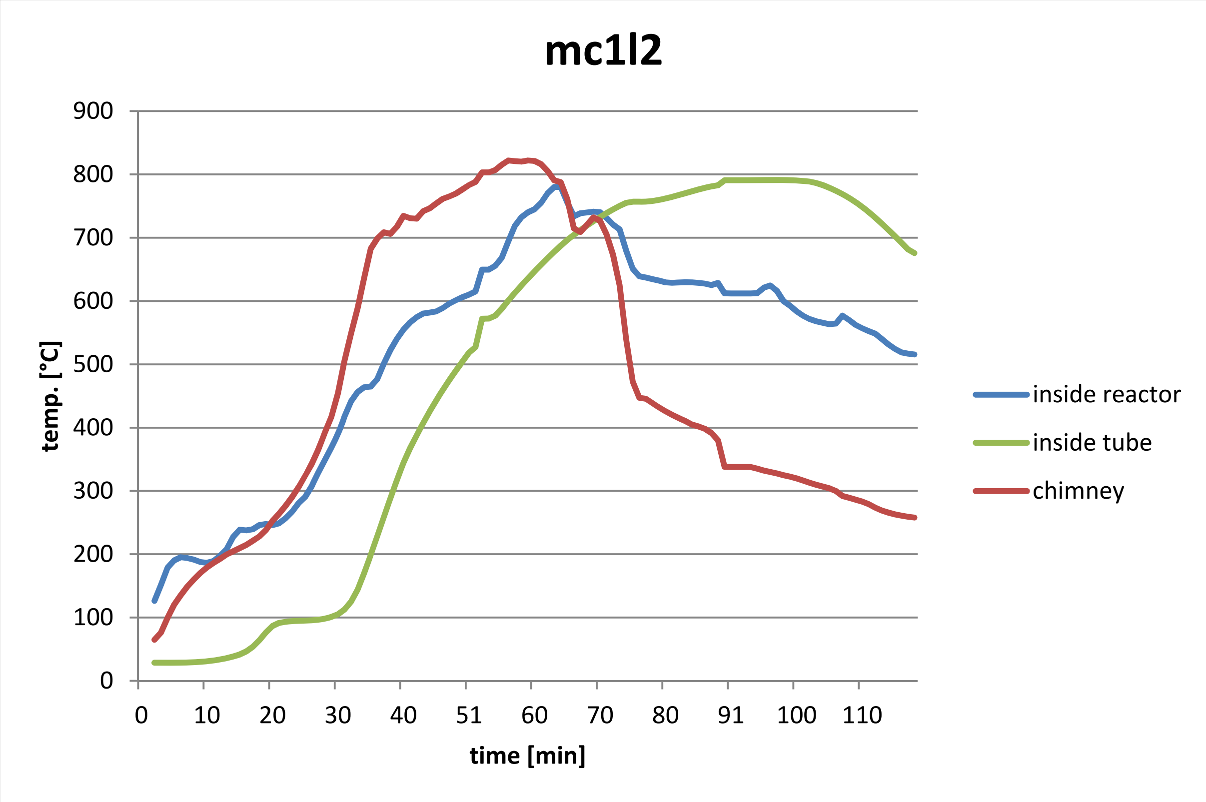

Figure 25: temperature profiles of experiment mc1l2 (10%)

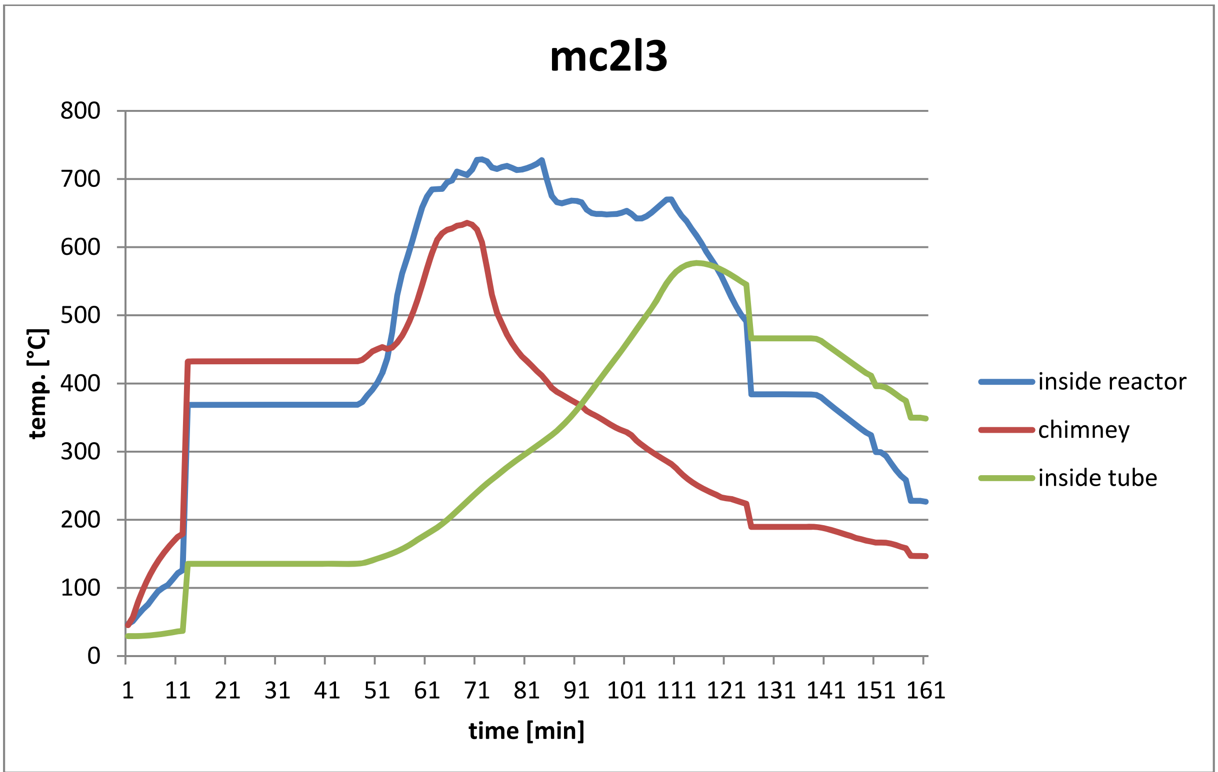

Figure 26: temperature profiles of experiment mc2l1 (20%). The straight temperature increase in minute 12 and the constant temperature between minute 12 – 51 are due to a measurement error. The lines are expected to grow gradually.

In the low moisture content experiment (mc2l3), pyrolysis starts faster, which is seen by the line depicting the temperature increase inside the tube. In exp. mc1l2, this line increases considerably after 30min whereas in experiment mc2l3 heating up takes longer and pyrolysis is less strong, resulting in lower temperatures. This can be seen comparing the chimney temperatures of the two experiments. The chimney in m1l2 reaches over 800°C, whereas m2l3 it not much exceeding 650°C.

Feedstock comparison

All analyzed raw materials have about the same HHVs (19 MJ/kg).

All analyzed char samples have comparatively high HHV of between 29 and 32MJ/kg. Experiment mc3l3 has a heating value of only 28MJ/kg, probably due to faults during proximate analysis.

Two additional experiments with coffee husks were done. The first one was successful showing an energy ratio of 4.9. Due to the relatively high amount of feedstock, heating up took relatively long (93min, 1.6kg of LPG).

The second experiment, shows a lower energy ratio (3.1), because there was a power cut after starting the experiment and therefore the optimal point to switch off LPG could not be determined, resulting in a higher heating up time (135min, 2.6kg of LPG).

Comparison of different barrel designs

Contrasting the heating up times for both reactors, it can be found that the reactor with the light tubes heats up faster and is therefore more efficient than the reactor with the heavy tubes. The light tubes consumed at the minimum 0.7kg of LPG while the heavy tubes took 1kg.

4. Conclusion

4.1. Design and improvement phase

This project showed that a reactor system like the one described, can work and has a big potential in order to produce biochar efficiently and with high quality.

The design of the reactor system and the understanding of the whole process is the most important factor for successful pyrolysis of biowaste. If this phase is not done properly, all further efforts are meaningless.

Both the furnace and chimney were redesigned, function well and their operation is easy and reliable. The basic principle of the reactors and their performance is good, even though their handling needs to be improved. Unfortunately there was no time left to build improved reactors, but in chapter 5 there are some suggestions for new reactors.

4.2. Experimental phase

Double stacking

Using two reactors on top of each other is in any case favorable in terms of efficiency. The heating up time is not significantly higher than having one reactor. The energy of burning pyrolysis gases generated by a single reactor is wasted escaping into the surroundings. In contrast, the heat of the lower reactor is used to dry and heat up the upper reactor. Therefore the energy needed to carbonize two reactors is almost the same needed for the pyrolysis of one reactor.

The best experiment, having an energy ratio of 7.1 is not the best possible result. Using for example two reactors filled with briquettes would result in an appreciably higher energy ratio above 10.

Particle size

Due to the low moisture content throughout these experiments, complete pyrolysis was always obtained. The main difference between the three levels was the amount of feedstock loaded. The mass of briquettes fitting in a rector, considering their high density, was about three times higher than that of sawdust. Although more feedstock results in longer heating-up times, the energy ratios increase with increasing quantity of feedstock. It was concluded that it is not the particle size which influences the energy ratio, but the density of the material and consequently the amount of material inserted in the drum. In these experiments, the feedstock with bigger particle size (briquettes) happened to have a much higher density and therefore much more feedstock could be inserted, yielding higher energy ratios. Furthermore, the experiments done suggest, that particle size has minor impact on char quality, that is, its proximate analysis and achieved HHV-s as well as on the procedure of an experiment. All chars obtained in the experiments at different levels obtained similar HHV values.

Moisture content

These experiments show that, as might be expected, high moisture contents deliver bad results. The drier the material is, the easier it is to carbonize. The experiment mc0l1 (6%) showed very good performance. While 10% works out very well, the performance of 20% is insufficient and 40% is not working at all. The heat required to evaporate water is simply too high.

The conducted experiments cannot conclude on the maximum moisture content for pyrolysis to be completed. What can be concluded is that it lies between 10 – 20%.

The fact that high moisture contents do not work, in the view of the author, is not that much of an issue. This research proved that it is possible to dry feedstock in the sun, achieving a moisture content of 5% (starting with 20%) within two days.

Comparison of the reactor

The two reactors used are designed identically except for the thicknesses of the walls of the tubes. Therefore the better performance of the lighter tubes can be traced to the lower wall thickness of these tubes compared to the heavy tubes. Heating up is faster with the light tubes because less steel has to be heated up and the heat conduction through thinner walls is faster. Low wall thicknesses therefore should be favored in further designs of tubes.

Different feedstock

The tested feedstocks are very suitable for pyrolysis, due to their low ash contents. All tested raw material show about the same properties in proximate analysis. Also the chars obtained do not differ and are throughout of outstanding quality.

4.3.General potential of the system

The reactor system works well with all tried feedstock provided the moisture content is not exceeding 10% (probably higher contents still work). Furthermore there are some factors required to obtain a high efficiency. Most important the draft has to be controlled properly; otherwise too much energy is wasted during heating up. Then, as much material as possible should be loaded. More feedstock takes slightly longer heating up times, but is far more efficient in the end generating higher char yields and energy ratios. In addition, the feedstock used should have a very low ash content, otherwise the HHV is low, resulting in a low efficiency, and the whole procedure is pointless. In the experiments performed particle size has a minor impact.

5. Outlook/recommendations

With an eye on the future of the project, there are some ideas and key points worth considering.

5.1.Continuous system

This project proves, that a reactor system, as the one described, can work. In order to generate a profitable business, in a further project first of all one should think about the continuous operation of the system. One option is using several reactor systems at the same time to produce enough char. Another way could be, and this is a much more promising approach, to use the hot exhaust gases of one reactor to heat up another and so on, wasting much less energy and probably even just using LPG to start pyrolysis in the first reactor. The set up with two reactors on top of each other is a step in this direction but not yet continuous in the proper sense.

5.2.New reactor with better handling (theoretical ideas)

The procedure of loading and unloading a reactor is exhausting and time-consuming. To facilitate and speed up operation, one should come up with ideas for improving the existing reactor.
A new reactor design should unite the tubes and the barrel into one module. The lids should be separated and hold in position by a lockable mechanism.
In order to empty the reactor, the barrel should have two handles in the middle. By hanging the reactor on these two handles on the crane, it is easily rotatable and can be turned without much effort and emptied quickly.

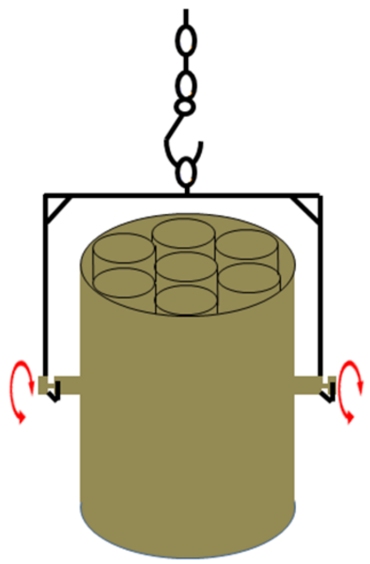

Figure 27: sketch for new reactor, improving the handling

5.3.Firing with produced char and not LPG

Another improvement could be, to use produced char in order to heat up the reactor and not LPG. This would result in higher autonomy and using the fuel anyway present is sensible. On the other hand LPG is cheap, so this aspect doesn't have priority.

Another furnace would have to be constructed, to be operated with char. Secondary air inlets should be on the bottom. On top of this a grid to hold the char should be mounted, such that the air entering the system passes the char from below, combusts with the char and heats up the reactor. The grid should be very close to the reactor tubes on top (around 10cm) to be as close as possible to the burning char. There should be an insulation wall out of cement and bricks. To refill char, a door should be implemented.

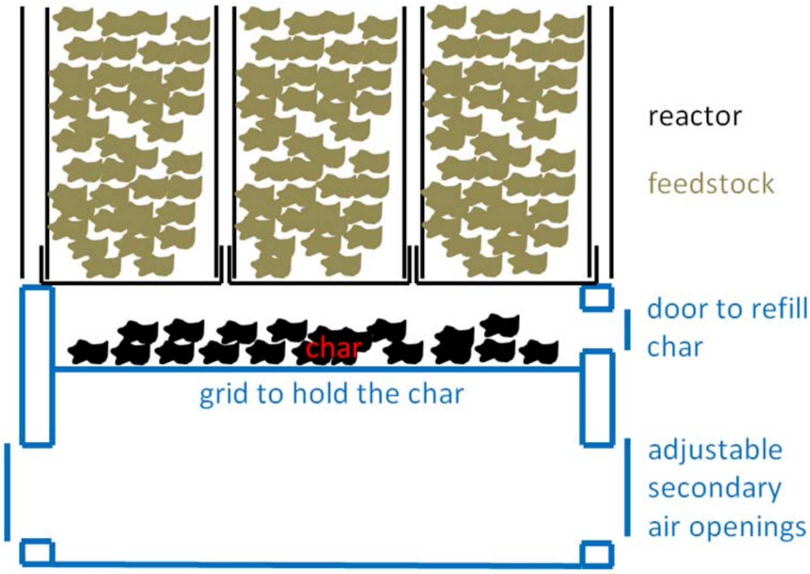

Figure 28: furnace fired with char

5.4.Operation without lambda sensor

The system could also be operated without lambda sensor. In the course of this project the lambda sensor was a crucial device to operate the system, by gaining experience with the lambda sensor, one could stop using it, even though efficiency would be reduced.

As general guide line, first the apertures in the furnace and chimney should be opened as described in section 2.4, chapter “Heating up”. As soon as first pyrolysis flames are detected, for example through holes in the barrel, the apertures should be opened a little more. Other indications of pyrolysis are black/ yellow smoke (water vapor from the heating up phase is white/ gray), and a significant increase in temperature around the barrel. Strong pyrolysis mostly results in a flame at the chimney, which is a sign for strong pyrolysis. As soon as the flame disappears, the apertures can be closed again slowly by slowly.
But an operation without lambda sensor will never be comparably efficient as happened in experiment e2.3, which was conducted without the lambda sensor due to a power blackout.

Bibliography

Antal M.J. and Grønli M. (2003). The art, science, and technology of charcoal production. Ind. Eng. Chem. Res. vol 42, 1619–40.

Bhattacharya S., Albina D. and Abdulsalam P. (2002). Emission factors of wood and charcoal-fired cookstoves. Biomass Bioenerg. vol 23, 453–69.

IEA. World energy outlook (2009). Paris Cedex, France: International Energy Agency (IEA) 2009

Lohri C.R., Faraji A., Ephata E., Rajabu H.M. and Zurbrügg C. (2015a). Urban biowaste for solid fuel production waste suitability assessment and experimental carbonization in Dar es Salaam, Tanzania. Waste Manage. Res. vol 33, n 2, 175-182.

Maes W.H. and Verbist B. (2012). Increasing the sustainability of household cooking in developing countries: Policy implications. Renew. Sust. Energ. Rev. vol 16, 4204– 4221

Mwampamba T.H., Owen M. and Pigaht M. (2013). Opportunities, challenges and way forward for the charcoal briquette industry in Sub-Saharan Africa. Energy for Sustainable Development vol 17, 158-170

Rohr M. (2015). Carbonization of urban biowaste in Dar es Salaam (Tanzania) Phase II. Improvements of energetic aspects for carbonization kilns. Civil service report at the department of Water, Sanitation and Solid Waste for Development (Sandec), Swiss Federal Institute of Aquatic Science and Technology (Eawag).

Sebokah Y. (2009). Charcoal production: opportunities and barriers for improving efficiency and sustainability. In: Bio-carbon opportunities in Eastern and Southern Africa Harnessing carbon finance to promote sustainable forestry, agroforestry and bio-energy. New York, USA: UNDP (United Nations Development Programme); p. 102–26.

Vest H. (2003). Small-scale briquetting and carbonisation of organic residues for fuel. Gate Information Service, gtz, Eschborn, Germany.