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Pyrolysis of Biowaste in Low and Middle Income Settings

A Step-by-Step Manual

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Figure 1: Charcoal vendor in the Philippines

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GLOSSARY

Biomass:	All biodegradable matter. In this manual, it typically refers to the carbon rich fraction of waste which can be processed to char.
Carbonisation:	Is the conversion of an organic substance into char by the process of pyrolysis.
Char:	A porous black solid material, consisting of an amorphous form of carbon, obtained when biomass is heated in the absence of air. Charcoal typically refers to the same, but derived from wood.
Lambda:	A parameter that describes the ratio of supplied oxygen to the amount of oxygen which is required for complete combustion. This value allows partial[1] evaluation of the combustion process, efficiency and pollutant generation.
LPG:	Liquefied petroleum gas (LPG) is a flammable mixture of mainly propane and butane produced during refining of petroleum oil or natural gas processing.
Primary air:	In this manual this term refers to the air that enters the combustion zone and is mixed with the fuel before it is ignited.
Pyrolysis:	A process where solid biomass is heated to temperatures from around 300°C to 600°C, in absence of oxygen, thereby decomposing into gaseous, liquid and solid substances.
Reactor barrel:	Consists of a metal oil barrel (208 L volume, height of 890 mm and a diameter of 590 mm) that contains 7 metal extractable metal tubes, each with a lid, where the feedstock is insterted.
Reactor system:	In this manual this term refers to the combination of the furnace, two reactor barrels and the chimney.
Secondary air:	Is the air used during burning of the fuel to complete combustion.
Slow pyrolysis:	Is a pyrolysis process where the biomass is heated using low heating rates to reach temperatures between 300-500°C. Slow pyrolysis increases the production of a solid fraction (char) during the pyrolysis process.
Pyrolysis gases:	Are combustible gases such as carbon monoxide (CO), methane (CH_4), methanol (CH_3OH) hydrogen (H_2) as well as volatilized tars produced during biomass pyrolysis.

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[1] Ensuring enough oxygen is only one of the requirements of effective combustion. Good mixing of oxygen and fuel (turbulence), enough time and high temperature are also prerequisites for good combustion (the so called 3T-s). Therefore, "partial" evaluation.

Thermocouple:	A device to measure temperature based on thermoelectric voltage. It consists of two dissimilar metals joined together where the thermoelectric voltage developed between the two junctions is proportional to the temperature difference between the junctions.
Type K thermocouple:	Type K thermocouples consist of chromel and alumel, and can operate in a temperature range of -270 °C to +1370 °C.

1. RATIONALE

1.1.General Introduction

Supply of affordable, reliable and sustainable cooking fuel and provision of adequate and equitable urban solid waste management (SWM) are considered two serious environmental and development problems confronting urban governments in low- and middle-income settings (LAMIS) (IEA, 2011). The severity of these challenges will increase in the future given the trends of rapid urbanisation. Households in LAMIS use 90% of the consumed energy for cooking, relying primarily on biomass (Rajendran et al., 2013). Currently 40% of the global population, 2.7 billion people, share this reality, whereby more than 95% live either in Sub-Saharan Africa (SSA) or Asia [1]. At the same time, SWM in LAMIS is characterized by low collection rates and inadequate disposal methods, where organic waste material (biowaste) generally represents the predominant fraction (Scheinberg et al., 2010; Hoornweg et al., 2012; Wilson et al., 2012; Guerrero et al., 2013; Zurbrügg, 2013). Both of these urban challenges pose considerable risks to the environment and to human health (for charcoal: (Seidel, 2008; Chidumayo et al., 2013; Zulu et al., 2013); for SWM: (Cointreau, 2006; Manga et al., 2008; Scheinberg et al., 2010; Zurbrügg, 2013). Due to growing public pressure and environmental concerns, waste experts worldwide are being called upon to develop more sustainable methods of dealing with municipal waste that embrace the concept of a circular economy.

Despite major efforts to promote sustainable cooking fuels during the past decade, charcoal still remains the primary source of cooking energy for many urban citizens in LAMICs, and the predominately informal charcoal supply chains are typically linked to unsustainable forest mining, low efficiency charcoal production methods, and long transportation routes (IEA, 2011; Maes et al., 2012; Owen et al., 2013). Carbonization of wood is a widespread practice, whereas the recycling of biowaste through the process of slow pyrolysis is still fairly limited.

This book covers urban organic municipal waste from households, commercial activities and institutions. It describes the approach of biowaste conversion to char by slow pyrolysis. The produced char can be used as a substitute to wood-derived charcoal. Besides many research projects on this subject, enterprises and small entrepreneurs are also investing into this technology. Often however the technologies used are technically complex and challenging. They require specialized construction, high level of skills for operation as well as high investment costs. This publication provides knowledge on a low-tech and cheap technology alternative for slow pyrolysis. The knowledge contained in this manual is an outcome of a research collaboration between the University of Dar es Salaam (UDSM) and Eawag/Sandec and reflects 4 years of iterative experiments with different reactors and feedstocks. The manual hopes to assist any potential user interested in converting biowaste into a renewable fuel.

Luc Forsyth for Dollar Street (CC BY 4.0)

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Figure 2: the conventional charcoal production: forest wood collection, earth mounds, transportation, commercialization and consumption.

1.2.Scope and target audience

There are numerous ways to design and operate a slow pyrolysis unit. Typically it requires a single, homogenized and dry material as feedstock. The primary goal of this manual however, is to show that urban biowaste can be used. The output, the char, can be used as renewable fuel (as described in this manual) but also as soil amendment (biochar) given its beneficial impacts on the soils and their fertility.

We start from the premise that creating value from biowaste can trigger improvements in sustainable waste management practices and impact of the well-being of dwellers in LAMIS. Based on our results we are confident that slow pyrolysis can produce char as renewable fuel, or soil amendment .Although source-separated “clean” biowaste is a precondition for a well-functioning slow pyrolysis facility, this aspect of waste sourcing is not discussed in this manual.

This manual is for practical use. It lists all materials, equipment and actions that are required to build and operate a reactor. The design of the reactor is based on using locally available construction material and equipment and relies of human labour instead of automation. Costs and revenues presented in this manual, rely on the case study in Dar es Salaam, Tanzania, for the period of 2015 – 2017.

This manual targets readers with little basic knowledge of waste management in general and slow pyrolysis in particular, but who have the willingness to work with waste and to implement and operate such a facility.

1.3.Navigating through this guide

This manual is structured as follows :

1. **Rationale:** you are about to finish this chapter.
2. **Thermochemical conversion of biomass:** this section summarizes the theory of the thermochemical processes. The most common thermochemical processes are described and compared.
3. **The double barrel reactor system:** this section describes in brief a reactor made out of barrels, which is the main subject of this report.
4. **Constructing the double barrel reactor system:** this section provides a description on how to build a modular slow pyrolysis reactor system using oil barrels. Other materials and equipment needed are detailed.
5. **Operating the double barrel reactor system:** this section describes the steps required to operate the double barrel reactor system in an efficient way.
6. **Financial analysis:** this section provides some figures on the financial viability of investment in- and operation of this technology.
7. **Recommendations:** this final section provides an outlook and some recommendations for further improvements.

The report also includes several appendixes. These appendixes explain how to operate the reactor system with some additional monitoring equipment, such as thermocouples and a Lambda sensor. Throughout the report, the reader might find references to these technical equipment since the experiments based on which this report has been written were conducted with such equipment. All the required instructions on how to use this equipment are provided in the appendixes. Nevertheless, the main text of the report is explained for future users who do not necessarily poses thermocouples and a Lambda sensor.

2. THERMOCHEMICAL CONVERSION OF BIOMASS

Thermochemical conversion processes use heat to induce chemical reactions as a means of extracting and creating energy carriers as products. These processes are combustion, pyrolysis, liquefaction and gasification. They differ in terms of temperature, heating rate, and the oxygen level present during the process. The energy stored in the biomass can be directly released as heat via combustion, or can be transformed into solid (e.g. char), liquid (e.g. bio-oils), or gaseous (e.g. pyrolysis gas) fuels with various utilization purposes (Zhang et al. 2010b). Thermochemical conversion processes are fast, but require substantial energy input. Table 1 presents the main differences between the different thermochemical conversion processes.

Table 1: Typical operating conditions and product yields (dry basis) of slow and fast pyrolysis, gasification and combustion (Lohri et al., 2017)

	Operating conditions			Product yield (wood pyrolysis)		
	Residence time	**O_2 supply (λ)**	**Temp. (°C)**	**Solid (%)**	**Liquid**	**Gas (%)**
Slow Pyrolysis	Minutes to days	0	300–500	35	30% bio-oil (70% water)	35
Fast Pyrolysis	Seconds	0	400–650	12	75% bio-oil (25% water)	13
Gasification	Seconds - minutes	0.2 – 0.5	750-900	10	5	85
Combustion		>1	>700	10	0	90

The λsymbol denotes the ratio between the amount of oxygen supplied and the amount of oxygen which would be required for complete combustion. This parameter can be measured with a lambda sensor (see Appendix A and Appendix B).

$$\lambda = \frac{m_{O_2,suppplied}}{m_{O_2,required\ for\ complete\ combustion}}$$

λ values higher or equal to 1, together with the fulfilment of the 3T-s (turbulence, time and temperature, see section "Combustion") are prerequisites for complete combustion. Values less than 1 imply incomplete combustion, as there is not enough oxygen for the process. Pyrolytic decomposition is achieved when the biomass is heated at λ value of zero, in other words when no oxygen is supplied from the outside.

In practice, the processes of pyrolysis, gasification and combustion often occur simultaneously depending on the available oxygen. In a flaming match (Figure 5) all these process can be observed at the same time. The heat needed for pyrolysis is provided by the flame radiation; the resulting gases and vapours burn in the luminous zone, where oxygen is available, in a flaming combustion process, leaving behind ashes. When the flame is extinguished, the remaining part of the fuel (wood) will most likely contain already combusted parts (grey and white ashes), unburnt but carbonized parts (black char) and raw wood. With absence of a flame and the drop of the temperature, part of the releasing smoke condenses as tar droplets.

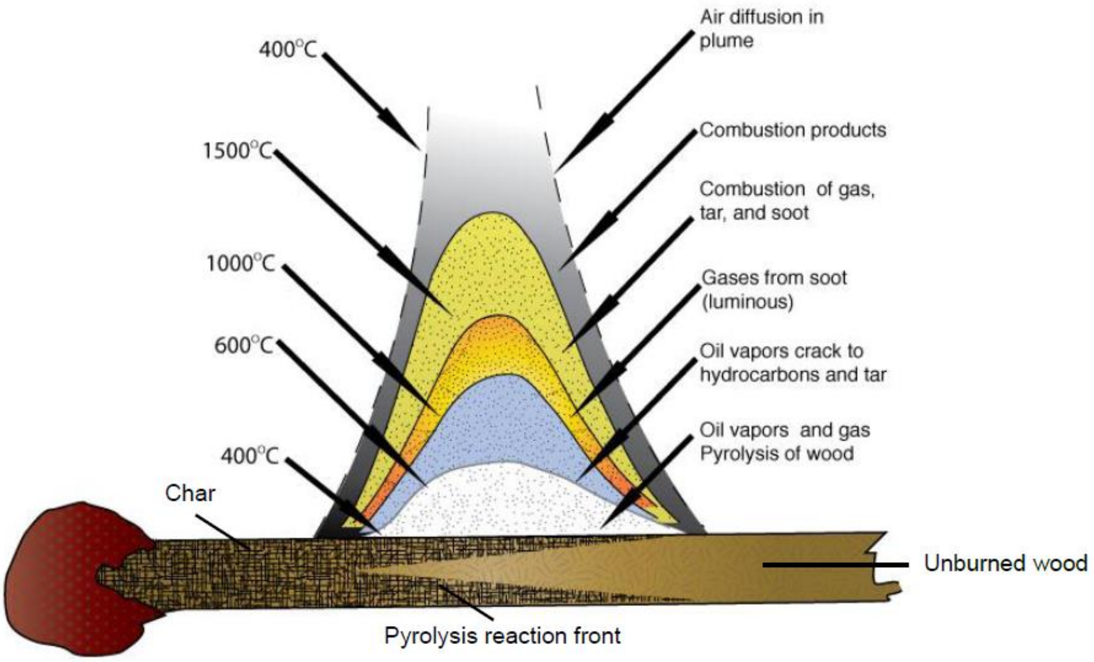


Figure 3: Pyrolysis, gasification and combustion in a burning match stick (Lohri et al., 2015)

Each thermochemical reaction begins with an increase in temperature in the solid biomass until the boiling point of water where drying of the biomass begins. At ambient temperature fuels will not increase in temperature beyond 100°C until they are water-free, since all the heat energy provided will be used to volatilize contained moisture. In a big particle of biomass, such as a match stick, drying and pyrolysis occur simultaneously but at different locations in the match stick and closely follow each other.

Figure 4 shows the complete thermochemical transformation of a wood particle as a function of time. First, heating and drying of the wood takes place, followed by the pyrolytic decomposition of the fuel and finally the gasification of the solid charcoal. The products passing into the gas phase are then oxidized strongly exothermically. In the case of a conventional fire, the released heat energy from the oxidation maintains the drying and pyrolytic decomposition of the surrounding biomass. This in turn releases gases which serve to maintain the oxidation. As long as there is sufficient heat energy and biomass, the process will continue until the biomass is consumed.

In the next sections the three main thermochemical reactions are presented: pyrolysis, gasification and combustion. Since heating up and drying are preliminary phases before any thermochemical conversion happens, some explanation on these processes is included. The section on pyrolysis then provides a more detailed description of the slow pyrolysis reactions, as it is the scope of this manual. Most of the information in this section was published in the review paper by Lohri et al. (2017).

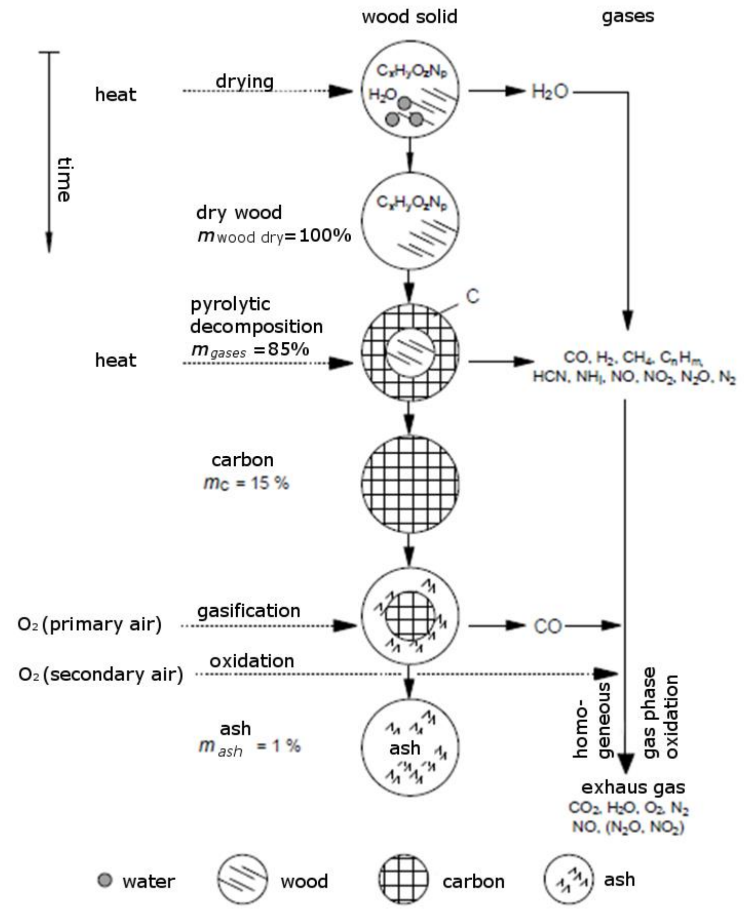


Figure 4: Chain of thermochemical reactions in a wood particle

2.1.Heating up and drying

By providing heat to an organic material, the water contained in the mass and the porous structures begins to evaporate. The higher the moisture content of the biomass, the more heat energy must be supplied to dry the biomass. A thermos-gravimetric curve as shown in Figure 5 shows how the temperature remains constant at 100°C until all the water is removed. Once the material has gotten rid of all the moisture, providing the right conditions, the thermochemical decomposition will start. Afterwards, the dry mass is not substantially reduced until temperatures of 300°C, when the volatile compounds from the pyrolysis front start to degrade and migrate out of the biomass.

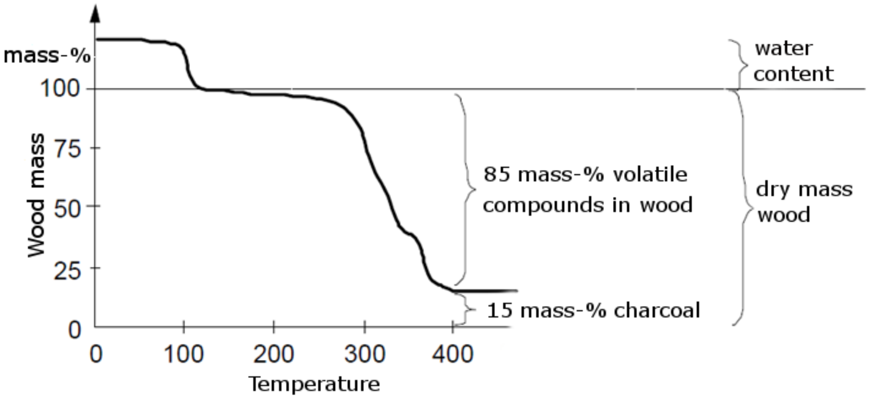


Figure 5: Thermal behaviour of moist wood biomass. Mass decrease as a function of the temperature during heating without oxygen supply

2.2.Pyrolysis reaction

This chapter takes a closer look at the process of slow pyrolysis as a suitable treatment method for organic solid waste. It is important to learn how the process can be engineered to enhance the waste conversion efficiency and to produce a valuable product.

Pyrolysis entails the decomposition of biomass by heat in the absence of oxygen ($\lambda = 0$), resulting in the production of solid, liquid and gaseous products. In principle, there are two main types of dry pyrolysis techniques, named according to their heating rates: slow pyrolysis, where the main output is a solid product called char, and fast pyrolysis with bio-oil as the main product. Slow pyrolysis involves heating biomass for hours to days and has traditionally been used in earth pit/mound kilns for the conversion of wood into charcoal. Fast pyrolysis is characterized by high heating rates and rapid condensation of the vapours in a continuous flow system with the main goal to produce bio-oil (Tripathi et al., 2016).

Slow pyrolysis, as a treatment method, dates back thousands of years when it was used for charcoal production (Jahirul et al., 2012). Even today, charcoal is still one of the primary cooking fuels in many low- and middle-income settings, with 80–90% of urban households in sub-Saharan Africa depending on it (Lohri et al., 2016). Apart from cooking, charcoal is used for heating, air and water purification, in industrial processes requiring heat, and as soil amendment (Guo et al., 2015).

Charcoal mounds are a simple form of slow pyrolysis reactors frequently used still nowadays in low and middle income settings. They are used exclusively for the production of charcoal. The mounds are filled with logs. In the middle very flammable material is placed, which serves as ignition and fuel source. An air supply channel ensures that sufficient oxygen is available to the fire during the start-up phase. After some time of burning, the emanating gases turn to a brownish-yellow colour, which indicates that the core of the mound is being pyrolyzed. The pyrolysis front moves from top to bottom (Figure 6). Whether in pits in the soil, as an earth mound or in bricked kilns, the process is the same for all systems.

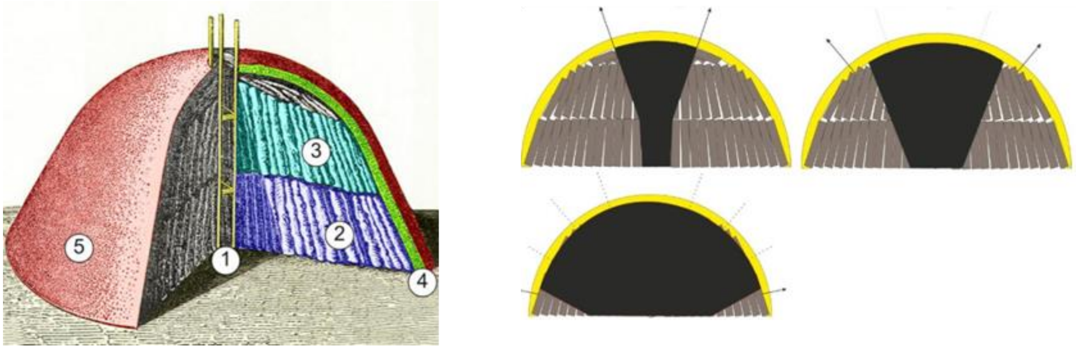


Figure 6: Left: mound with ignition slot (1), logs (2 and 3), covering made of brushwood and turf (4), covering made of sand, clay and soil (5). Right: course of charring by putting holes in the cover.

In earth mounds the process parameters, such as temperature inside the reactor, are poorly controlled and pyrolysis gases with a high global warming potential may be emitted directly into the atmosphere. This so called oxic pyrolysis, where a portion of feedstock is combusted as initial energy source, has very low yields (around 5%).

Different attempts have been made to come up with more efficient slow pyrolysis technologies for low and middle income settings. An efficient, environmental friendly and low-cost kiln-retort system (called Adam-retort) was developed for carbonization of biomass waste (J. C. Adam, 2009). It has been further optimized and implemented in various low and middle income countries (C. Adam, 2013, 2014). Continuous feeding reactors have also been developed, such as the one developed by the Center of Appropriate Technology and Social Ecology (CATSE) of Ökozentrum Langenbruck. This reactors facilitate a treatment of emissions and can also enhance the energy efficiency (Lohri et al., 2016). Nevertheless, this approach is higher in investment and operation costs and requires more complex operation and maintenance skills. The reactor described in this manual represents a low tech, and easy to operate model.

Input material

Common requirements of feedstock characteristic for slow pyrolysis are: dry, unmixed, homogeneous, uncontaminated substrate, preferably with high carbon and low ash content, available at no or low costs. Other feedstock that may not meet these requirements can also be pyrolyzed if a treatment step is added first to ensure these parameters can be met. For instance a drying of feedstock to a moisture content of 10–15% is often required for more moist substrates as only few materials are naturally dry enough, for example straw (Bridgwater, 1999; Isahak et al., 2012). High moisture contents fed to the reactor will result in large amounts of energy losses as every kilogram of water in biomass requires 2.26 MJ for vaporization (Basu, 2010). In addition, the biomass feedstock frequently requires some form of pre-treatment to evenly break down the lignocellulosic structure and enhance pyrolysis efficiency (Kan et al., 2016). The feedstock particle size has a major influence on the heating rate and yields (Isahak et al., 2012).

In theory, virtually any form of biomass can be considered for pyrolysis. In the urban solid waste context, lignocellulosic waste from carpentries and saw mills, park and garden waste (trimmings/ pruning), paper and cardboard waste are very suitable for pyrolysis. Wood remains the substance most extensively studied given its uniformity that allows comparability among tests. To select suitable waste types as feedstock for slow pyrolysis, simple assessment tools have been developed with criteria such as feedstock, market, technology selection and production cost selection (BTG, 2013), or availability/ accessibility criteria and physicochemical properties (Lohri et al., 2016).

Conversion process

The exact decomposition mechanism and reaction scheme for the conversion of most biomass types into gaseous, liquid, and solid fractions are not fully understood due to the complexity of the process. Many intermediate products are produced, given the variation in composition of biomass feedstock (Babu, 2008; Burhenne et al., 2013). A large number of reactions take place in parallel and series, including dehydration, depolymerisation, isomerization, aromatization, decarboxylation, and charring (Kan et al., 2016). From a thermal standpoint, the pyrolysis process can be divided into four stages, which partly overlap and occur simultaneously but at difference locations in the fuel agent (Basu, 2013).

1) Drying (ca. 100 °C): The biomass is heated at low temperature and releases moisture and loosely bound water through evaporation.

2) Initial stage (ca. 100–300 °C): Endothermic dehydration of the biomass takes place during the torrefaction stage with the release of water and low-molecular-weight gases like carbon monoxide (CO), carbon dioxide (CO_2), methanol (CH_3OH). These gases prevent oxygen from entering into contact with the biomass and reacting with it. The macromolecules from which the biomass is composed are irreversibly broken up by thermal action.
3) Intermediate stage (200 °C): an exothermic reaction (primary pyrolysis) takes place in the temperature range of 200–600 °C. This produces combustible gases such as carbon monoxide (CO), methane (CH_4), methanol (CH_3OH), hydrogen (H_2) acetic acid ($C_2H_4O_2$), formic acid (CH_2O_2) and formaldehyde (CH_3OH). Many of these gases represent the precursors to bio-oil. Due to the rapid discharge of gases, small organic particles released from the solid material which become visible as smoke. Large molecules of biomass particles decompose into (primary) char, condensable gases (vapours and precursors of the liquid yield), and non-condensable gases. The exothermic process ends at about 400°C and a carbon rich residue –charcoal– remains. Above this temperature, the process is again endothermic and carbon monoxide (CO) and hydrogen (H_2) are predominantly discharged from the already charred biomass. The biggest mass loss of the biomass as gases occurs mainly at temperatures between 280°C and 500 C. Above 500°C most biomasses do not show a significant mass loss anymore. Towards the end of the pyrolytic decomposition, depending on the temperature, up to 80 to 85 % of the biomass can be converted into gaseous products.
4) Final stage (ca. 300–900 °C): The final stage of pyrolysis above 300 °C involves secondary cracking of volatiles into char and non-condensable gases. If they reside in the biomass long enough, relatively large-molecular-weight condensable gases can crack, yielding additional (secondary) char and gases. Fast pyrolysis involves the quick removal and rapid quenching of the condensable gases at the end of the process to terminate the secondary conversion process and results in higher bio-oil yield. Temperatures above 450 C also favour the formation of tars and the yield of pyrolysis coal is reduced.

Products and uses

The relative amounts of the main products of pyrolysis, char (the black, solid residue), bio-oil (the brown vapour condensate), and pyrolysis gas (the non-condensable vapour), depend on several factors including the heating rate, peak temperature and residence time (Basu, 2013; Guo et al., 2015) as shown in Table 1.

Char: Char has received increasing attention due to its suitability for several purposes, which include the use as a solid fuel, soil amendment (bio-char), or precursor for making catalysts and contaminant adsorbents. Waste-derived char needs further processing (densification) into charcoal-briquettes and can then be used for household cooking as alternative to wood based charcoal (Mwampamba et al., 2013). Higher heating value of char is reported to be between 20 and 36 MJ/kg (Vamvuka, 2011; Lohri et al., 2015; Kan et al., 2016). Char can contain 15–45% (by mass) of volatile matter, which facilitates the ignition of the char, but at the same time emits more visible smoke. In comparison, a good-quality commercial charcoal can have net volatile matter content (moisture free) of about 30% (Vamvuka, 2011; Lohri et al., 2016).

Bio-oil: The liquid pyrolysis product is known as bio-oil, tar, pyrolysis oil, bio-crude oil, wood oil, wood distillates, pyroligneous acid, liquid wood and liquid smoke (Mohan et al., 2006). It is typically of dark red-brown to almost black colour, has a distinctive acid, smoky smell, and can irritate the eyes (Venderbosch et al., 2010). The long residence times applied in slow pyrolysis lead to bio-oils (or tars) that are further split up and converted into charcoal and gas (Figure 7). Therefore, long residence times favour a maximum yield of solid pyrolysis products in the form of charcoal. Often, the elevated temperatures of the process also result in the volatilization of the bio-oils, which, if they enter in contact with oxygen, are combusted and not recovered.

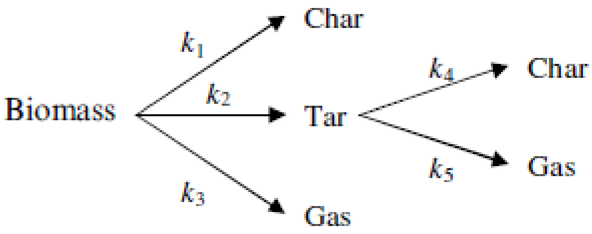


Figure 7: Biomass derived products during slow pyrolysis

Bio-oils are a complex mixture of water and organic chemicals with more than 300 identified compounds. Due to the high moisture content and acid content, crude pyrolysis bio-oil is instable, corrosive, viscous, low in energy density, and difficult to ignite (Guo et al., 2015). The high water content, typically 15–35 % which cannot be removed by conventional methods like distillation, is a serious drawback in terms of the heating values: the higher heating value (HHV) is between 15 and 20 MJ/kg (Venderbosch et al., 2010; Basu, 2013; Kan et al., 2016). Due to the undesired properties, if the bio-oil will be used, it is essential to chemically upgrade it, i.e. reduce volatility, increase thermal stability, reduce viscosity through oxygen removal and molecular weight reduction to make it useful as transportation fuel (Jacobson et al., 2013).

Gas: The pyrolysis gas contains carbon dioxide, carbon monoxide, methane, hydrogen, ethane, ethylene, minor amounts of higher gaseous organics and water vapour (Vamvuka, 2011). The typical LHVs of the pyrolytic gases range between 10 and 20 MJ/Nm^3. The pyrolysis gas has multiple potential applications, such as direct use for production of heat or electricity, either directly or co-fired with coal, production of individual gas components, including CH_4, H_2 or other volatiles, or in production of liquid bio-fuels through synthesis. In some applications, the hot pyrolytic gas can be used to preheat the inert sweeping gas or can be returned to the pyrolysis reactor as a carrier gas (Kan et al., 2016). It is further recommended to measure and critically evaluate the emissions, which are released during the carbonization process, including critical pollutants and products of incomplete combustion (PICs) such as carbon monoxide (CO), polycyclic aromatic hydrocarbons (PAHs) and particulate matter (Lohri et al., 2015).

Heating methods

There are different heating methods to initiate the pyrolysis process and to maintain the required high temperatures. These methods vary depending on several aspects:

a) whether oxygen is present (oxic pyrolysis) or oxygen is absent (anoxic pyrolysis).

b) whether the energy required to drive the process is supplied (i) directly as the heat of reaction, (ii) directly by flue gases from combustion of by-products and/or feedstock, (iii) indirectly by flue gases through the reactor wall, or (iv) indirectly by heat carrier other than flue gases (e.g., sand, metal spheres, etc.) (Duku et al. 2012).

The first three heating methods are considered relevant for low-tech, small-to medium-scale production of char. The information provided in the following lines was obtained from Lohri et al. (2016).

1. Oxic pyrolysis by partial combustion (autothermal systems)

During oxic pyrolysis, a portion of the feedstock in the reactor is combusted with controlled addition of air to produce hot gases which provide heat to convert the remaining biomass. By combusting a portion of the biomass, the yield of char is reduced. Therefore, it is best to operate these systems when raw materials are inexpensive. To preserve the produced charcoal, air must be limited, which results in the formation of products of incomplete combustion (PIC), including methane and other species with high global warming potential. Many of these PICs condense and form particulates as soon as they are released in the atmosphere, creating visible smoke. Nevertheless, this is the method by which most fuel charcoal is made in low and middle income settings. Without proper control and expertise in the art, these rudimentary methods can be very inefficient, with yields as low as 5%. Oxic pyrolysis methods include controlled open fires, traditional earth mound kilns and masonry or metal kilns, and there is often poor control of the reactor’s internal temperature with regard to spatial uniformity and duration of treatment. These systems typically have low capital costs partly because no heat transfer surfaces are needed and condensable products are usually not recovered.

2. Anoxic pyrolysis by indirect heating

For indirect heating, the reactor is arranged as a retort, a reactor vessel that is heated externally and arranged to capture gaseous and vapour products, and into which no air can go in. The feedstock is placed in the retort and an external source provides the heat necessary for pyrolysis through the vessel walls. Initial heating first dries the feedstock, after which the continued heat application results in a temperature raise, reaching the point where pyrolysis starts. Pyrolysis gases are emitted and are routed to a combustion zone outside the retort vessel, where they can be combusted completely, and the heat generated is used to maintain pyrolysis process in the retort. In an efficient system, only a portion of the heat produced from combustion is needed to drive the pyrolysis, leaving excess heat to dry feedstock, initiate pyrolysis in subsequent reactors or is harnessed for other purposes (e.g., heating water). This method is suitable for the recovery of volatile matter and produces relatively high yields of char and by-products. Additionally, indirectly heated pyrolysis with a retort offers improved process control and reduced harmful emissions compared to most oxic pyrolysis methods. Since all heat required for pyrolysis is transferred through the reactor walls and heat transfer inside the biomass bed is relatively slow, large reactors cannot depend solely on indirect heating, but need to be supplemented with internal heat transfer surfaces or direct heating.

3. Carbonization by contact with hot gases (direct heating with inert gases)

As the size of the retort increases, retort designs suffer from increasing problems, which include poor heat transfer and, thus, slow carbonization. Both raw biomass and charcoal are good thermal insulators; therefore it can often take hours or days for the externally applied heat to fully carbonize the biomass feedstock. This problem can be addressed by introducing hot combustion gases, which are almost oxygen-free, into the retort. The hot gases make direct contact with the bed of feedstock and significantly increase the rate of heat transfer to the material. Once pyrolysis of the feedstock is occurring, the pyrolysis gases are combusted and recirculated into the retort vessel. One challenge when recirculating the combustion gases into the retort is the dilution of pyrolysis gases with non-combustible CO_2 and H_2O combustion products. The amount of combustion gases which are fed back through the reactor must be controlled and limited to maintain reactor product gas flammability [156]. Since some fuel is needed to initiate combustion, wood of inferior quality, leaves or other low-value residues can be combusted to initially provide heat. During carbonization with recirculated combustion gases, char and by-product yields are typically high, and due to the relatively high complexity and equipment requirements, these systems are suitable for use at medium-to large-scale.

Waste treatment by slow pyrolysis

Several key attributes make Slow Pyrolysis a promising treatment option for biowaste from the perspective of waste management and environmental protection:

- Waste biomass is converted into char and gases, achieving waste reduction rates of 70% on weight basis (char yields of 30%). If treatment is applied at source, the needs for transport and space requirements in landfills can be reduced considerably.
- All carbonized feedstock types showed very good fuel properties: high heating values (30 MJ/kg), proximate analysis (MC: 2%; VS: 12%; FC: 80%) and ash content (6%).
- When combustion conditions are kept ideal, emitted gases will not pose major environmental or health threats.
- The generated renewable fuel could partially substitute the unsustainably produced wood-derived charcoal without requiring significant changes in current cooking appliances and behaviour.
- The business opportunities of this technology could partially address the challenges of solid waste management as it can stimulate the collection rate of biowaste in cities of LAMIS-s and diminish the amount destined for disposal in dumpsites. This would lead to a reduction of emissions linked to the uncontrolled decomposition of inappropriately disposed waste and transportation requirements.
- There is no need for sophisticated high-end technology to operate such a facility. Therefore, it is suitable for low-income settings that rely mostly on simple technology and unskilled labour. However, upscaling or transferring this information to a larger facility might require some adaptation or adjustment of equipment.

Nevertheless, the process also poses several challenges. Apart from the environmental and public health risks, further challenges include socio-economic barriers, negative perceptions and attitudes towards (bio) char, and a lack of finance, empirical data and supportive policy framework. Enhancing the quality of pyrolysis products for better marketability, use and safety, and minimizing process energy input and losses are the points that require major further attention on the path towards commercialization.

2.3.Gasification

Gasification is a thermal treatment that converts carbonaceous material into a gas (producer gas, synthesis gas or syngas), which can be used as fuel or for the production of value-added chemicals. The main difference between the two closely related thermochemical processes of gasification and combustion is that gasification packs energy into chemical bonds in the gas by adding hydrogen (H_2) and stripping away carbon (C) from the feedstock, whereas combustion oxidizes the H_2 and C of the feedstock into water and carbon dioxide, thus breaking those bonds to release the energy.

Input material

Similar to other thermochemical conversion processes that do not take place in a liquid medium, gasification also requires dry biomass with moisture contents between 10 and 20% as feedstock. Biomass with higher moisture content must be dried before gasification. Other pre-treatment steps comprise homogenizing the biomass feedstock in size and composition.

Conversion process

The gasification process consists of a complex thermal and chemical process that converts organic matter into a gaseous product under oxygen-deficient conditions and temperatures between 750 and 1000 °C. Only limited air, oxygen or steam is supplied to the reaction as an oxidizing agent (λ = 0.2–0.5). Broadly speaking, typical biomass gasification involves the following, overlapping stages.

1. Drying: Occurs at temperatures between 100 and 200 °C and reduces the moisture content to below 5% (endothermic).
2. Pyrolysis (devolatilization): Occurs in the temperature range of 150–400 °C. This endothermic stage involves the thermal breakdown of larger hydrocarbon biomass molecules into smaller (condensable and non-condensable) gas molecules and results in the formation of char. One important product of this stage is tar, formed through condensation of vapour produced in the temperature range between 250 and 300 °C.
3. Oxidation: This is a reaction between solid carbonized biomass and oxygen, generating CO_2 and oxidization of hydrogen present in the biomass to generate water. With this exothermic oxidation of carbon and hydrogen a large amount of heat is released. When oxygen is present in only sub-stoichiometric quantities, partial oxidation of carbon may occur, generating CO.
4. Reduction: Occurs in a temperature range of 800 and 1000 °C. In the absence (or sub-stoichiometric presence) of oxygen, several endothermic reduction reactions take place in this stage.

Depending on the prevailing temperature and pressure conditions and the supply of the gasification agent, the complete (Equation 1) or partial oxidation of the carbon (Equation 2), the heterogeneous water gas reaction (Equation 3), the Boudouard reaction (Equation 4) and the hydrogenating gasification (Equation 5) are of relevance. The exothermic reactions (Equation 1 and Equation 2) take place mainly in controlled autothermal gasification plants and serve to provide the necessary heat energy for the heating and drying of the biomass. The main part of the combustible gases, carbon monoxide CO and hydrogen H_2, is generated by the reduction of the biomass (Equation 3 and Equation 4).

$$C + O_2 \rightarrow CO_2 \qquad \Delta H = -393,5\frac{kJ}{mol}$$ **Equation 1**

$$C + \frac{1}{2}O_2 \rightarrow CO \qquad \Delta H = -110,5\frac{kJ}{mol}$$ **Equation 2**

$$C + H_2O \rightarrow CO + H_2 \qquad \Delta H = +118,5\frac{kJ}{mol}$$ **Equation 3**

$$C + CO_2 \rightarrow 2\,CO \qquad \Delta H = +159,9\frac{kJ}{mol}$$ **Equation 4**

$$C + 2\,H_2 \rightarrow\ CH_4 \qquad \Delta H = -87,5\frac{kJ}{mol}$$ **Equation 5**

Products and use

The resulting hot fuel gases (syngas) from gasification contain large amounts of incomplete oxidized products. These have a heating value which can be utilized in a separate process, even at different times or locations (Arena, 2012). The syngas mixture consists of carbon monoxide (CO), hydrogen (H_2), methane (CH_4) and carbon dioxide (CO_2) as well as light hydrocarbons, such as ethane and propane, and also heavier hydrocarbons, such as tars. Hydrogen sulphide (H_2S) and hydrogen chloride (HCl), or inert gases, such as nitrogen (N_2), can also be present in the syngas (Molino et al., 2016). Amount of syngas produced from gasification range from 1 to 3 Nm^3/kg on a dry basis, with an average LHV spanning between 4 and 15 MJ/Nm3. These results are affected by the gasification technology and the operating conditions. Syngas can be used in a conventional burner, connected to a boiler and a steam turbine. Syngas is also a key intermediate substance in the chemical industry and used in many highly selective syntheses of chemicals and fuels, such as Fischer–Tropsch liquids, methanol and ammonia or as a source of pure hydrogen and carbon monoxide (Ahmad et al., 2016). Syngas from gasification requires conditioning, which involves cooling and disposal of particulate matter and tar (Abdoulmoumine et al., 2015; Heidenreich et al., 2015).

After a complete gasification of all organic substances, the ash, a remainder of inorganic material, remains. Depending on the biomass, the ash consists of different mineral salts, carbonates and metal oxides. Ash accounts for about 0.5 to 2% of the mass of the dry substance of the biomass.

2.4.Combustion

Combustion is an exothermic chemical reaction that occurs at high temperatures between a fuel and an oxidant, mainly atmospheric oxygen. The reaction end products resulting from complete oxidation are essentially carbon dioxide (CO_2) and water vapour (H_2O). In order for the oxidation to take place completely enough oxygen must be present. This means that the air excess number λmust be greater than 1.

The process of combustion is complex in nature and multiple parameters affect the combustion efficiency. There are however three very important parameters which are referred as 3T-s of combustion: time, turbulence and temperature. Ensuring these 3T-s is very important in order to get the maximum of the combustion process and to reduce the environmental impact of incomplete combustion.

Time: It is very important to provide sufficient time to a fuel so that it burns completely. 100% combustion means that the fuel is fully oxidized. If fuel remains in the combustion zone for a shorter time than necessary, it will be partially burned which implies wasting valuable fuel in to the air, with the potential negative environmental impacts. Alternatively, if it remains longer than the required, the performance of the combustion process will drop as new fuel will not be able to come in and get burned. Ideally, the fuel should stay for a time sufficient for the complete combustion and then replaced by the fresh fuel. Thus, the time plays a very important role in determining the combustion efficiency.

Turbulence: In the combustion process we distinguish two elements: the oxidant (mainly oxygen) and the fuel (the reductant). A thorough mix of these two materials is essential if good combustion is to be achieved. This is achieved by turbulence. Breaking down the fuel in small particles increases the surface area and ensures that it is much more accessible to the oxygen. If turbulence is not ensured, a portion of the fuel will have excess oxygen available for the combustion while the remaining will not have enough, which results in incomplete combustion of carbon forming carbon monoxide instead of carbon dioxide. Without sufficient turbulence, parts of the fuel might not get oxidized at all and be lost to the air. This reduces the efficiency of the combustion, contributes to environmental pollution and wastes valuable fuel.

Temperature: During the combustion, if the temperature is not sufficiently high, fuel will take some time to ignite thus increasing the time of the combustion. This will affect the heat output. Hence, it is very important to maintain correct temperature which ensures that fuel is quickly burnt releasing the complete energy. The temperature of the flames is different depending on the fuel, but should always be between 700 °C and 1300 °C, so that the formation of pollutants is minimized. Below 700 °C the formation of carbon monoxide is strongly favoured and a strong increase of nitrogen oxides is generated above 1300 °C.

As it can be seen, the 3T-s discussed above impact the process of combustion and can significantly affect the efficiency if not monitored closely. If these conditions are not met, the oxidation is incomplete and harmful substances such as carbon monoxide (CO) and non-combusted hydrocarbons (C_xH_y) are produced, which have an adverse effect on climate and health.

3. THE DOUBLE BARREL REACTOR SYSTEM

Most biowaste contains high moisture contents. Consequently, a reactor system that is capable to pre-dry the feedstock before pyrolyzing it will be advantageous. The double barrel reactor system separates the heating up and drying phase (upper barrel) from the pyrolysis phase (lower barrel). The reactor system comprises a furnace, two barrels stacked on top of each other, and a chimney (Figure 8). These components are subdivided into further subcomponents as explained in the coming chapters. While the carbonization occurs in the lower barrel, the drying takes place in the upper barrel. The waste heat from the lower barrel is thus used to pre-dry the feedstock in the upper barrel and reduce its moisture content to a value lower than 20%, which is suitable for pyrolysis.

As explained in the previous chapter, numerous factors affect the pyrolysis process and the yields, composition and properties of the products. It is generally accepted that the process parameters that have the major influence on the products are pyrolysis temperature, heating rate and pressure, as well as particle size, shape and properties. To achieve good yields of high quality products, the reactor system needs to control the reaction conditions. In this manual, an indirectly heated system is presented (anoxic pyrolysis). These systems obtain higher yields of char, low emissions, and enable a higher level of control of the process in comparison to the partial-combustion reactors (oxic pyrolysis or autothermal systems). Additionally, the reactor system makes use of the generated pyrolysis gases by combusting them and using the released heat to sustain the pyrolysis process in the kiln.

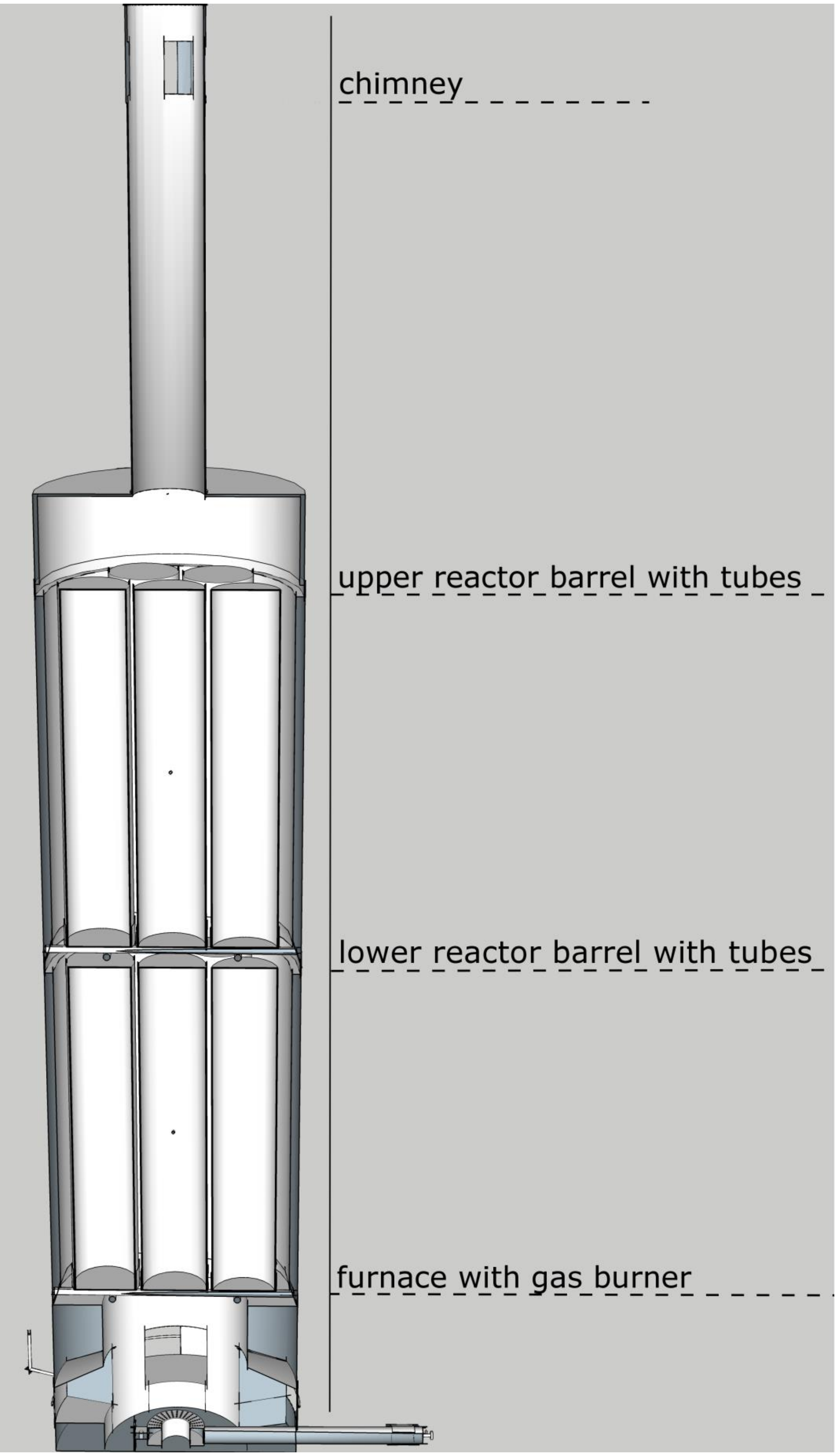


Figure 8: Blueprint with a general overview of the double barrel reactor system

4. CONSTRUCTING THE DOUBLE BARREL REACTOR SYSTEM

This section explains the required steps and materials needed to build a semi-continuous, community level slow pyrolysis reactor. The reactor system explained in this manual was inspired on the model developed a Swiss NGO "Abokobi Society Switzerland". This model, however, required high construction skills and specific construction materials. Therefore, the model presented in this manual was constructed with several objectives in mind. The reactor had to be simple, replicable without big investments and specific construction skills and should recreate ideal pyrolysis and combustion conditions in their corresponding compartments. Furthermore, only materials which are available in the vast majority of urban and rural settlements were used.

4.1.Furnace

The process of combustion is the most important process taking place inside the furnace. One purpose is to release the heat from an external fuel and use it to reach the required temperature to pyrolyze the feedstock in the lower barrel. A second purpose is to create the conditions to combust the pyrolysis gases that are produced, so that they can contribute to pyrolyze the remaining feedstock. Therefore, it is essential that the furnace optimizes the 3Ts (time, turbulence and temperature) for a complete combustion (see section "Combustion").

The furnace explained in the coming paragraphs was built to combust LPG.

Figure 9: Overview of the furnace

Criteria for construction

The furnace had to fulfil the following objectives:

- Capacity to hold the weight of the entire reactor system. The furnace is the component that stands at the base of the entire system.

- Allow control of secondary air flow. Together with the chimney, the furnace should contain a mechanism that controls the draft that enters to the furnace. This has an impact on the "time" and "turbulence" parameters.
- Good insulation to minimize heat loses. All the energy released through the combustion is required to heat up the metallic structure of the barrels and tubes that contain the feedstock, and ultimately the feedstock itself so that it is pyrolyzed. Consequently, losses must be minimized. This has an impact on the "temperature" parameter.
- Non-flammable material and able to withstand temperatures higher than 800°C.
- A round combustion chamber is preferred over a squared one due to better airflow and less heat loss.

Materials and labour needs for construction

Table 2 present the materials used for the construction of the furnace.

Table 2: Materials and labour required to construct the furnace. Prices given are Tanzanian prices in 2016.

Amount	Material	Costs in USD
1	208 L standard oil barrel	18
15	Bricks	3
10 kg	Cement	6
1	Steel rod Ø 8 mm, 2500 mm	5
1	Steel plate 0.5 m^2	32.5
1	Ring burner	50
1	Steel pipe Ø 40 mm, 300 mm (handle)	5
Labour costs (1 person, 16 hours = 2 days)		15
Total costs furnace		**134.5**

Constructing the furnace

1. Outer metal structure

The very first step is to construct the external metallic shell. Cut a standard 208 L steel drum into three pieces using a cutting disk as shown in Figure 10. After discarding the middle piece, weld the upper and the lower part of the barrel together (Figure 11). By keeping the thick rim of the upper part of the drum, the furnace retains the necessary stability to carry the weight of the reactor barrels, and both the furnace and the lower barrel can be attached with a belt.

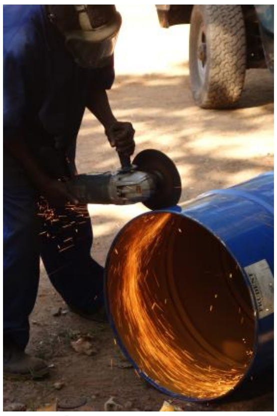


Figure 10: Cutting the barrel with a cutting disk.

Next, cut the four rectangles for air supply out of the case using a cutting disk. They should all be the same size (100 mm x 200 mm). Locate these air inlets at a height of 80 mm. Additionally, also drill a hole through which to insert the burner.

Figure 11: Welding the upper and lower part

Figure 12: Barrel separated into three parts

The furnace consists of a well-insulated combustion chamber with variable openings for secondary air and a gas burner. Figure 13 indicates the dimensions of the outer metallic structure as well as those of the rectangular air inlets.

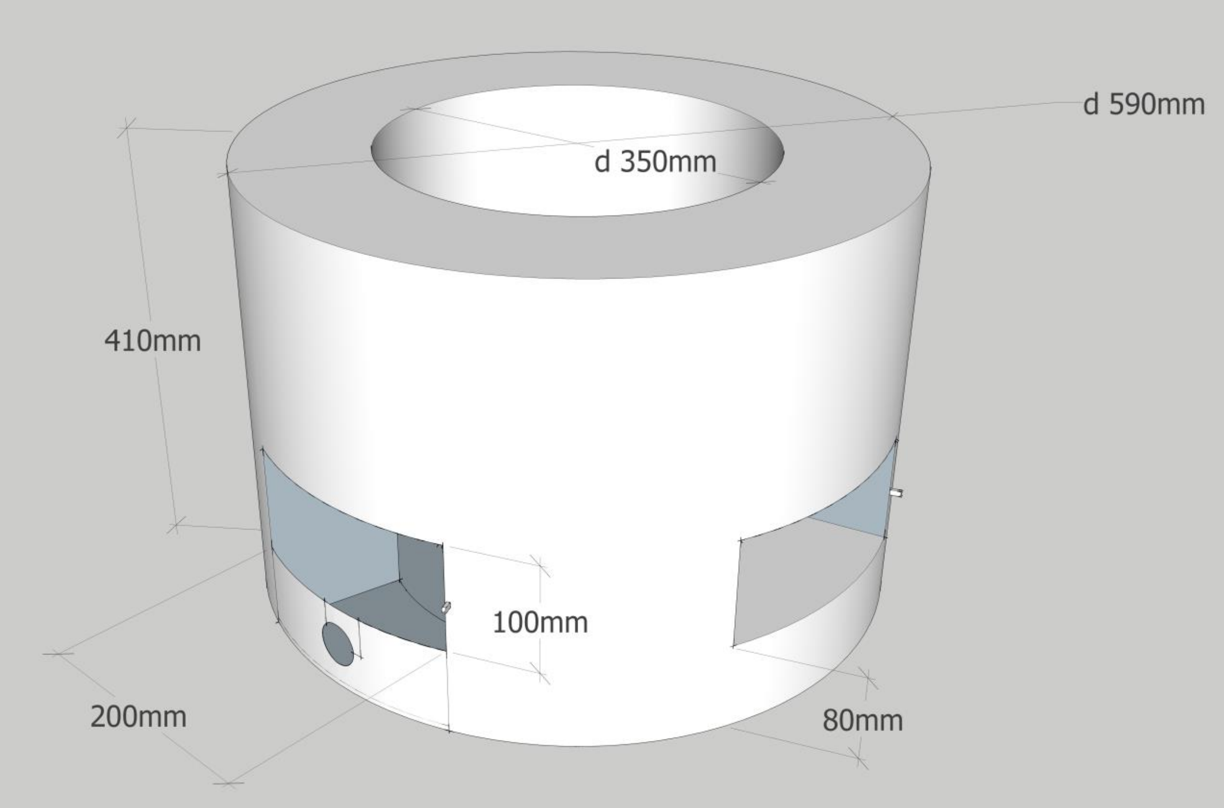


Figure 13: Blueprint with the external dimensions of the furnace (mm)

2. Insulation

The insulation consists of a wall of bricks and mortar. Split the bricks into half to fit the round interior surface of the drum. Make the mortar of cement and sand mixed in a 1:1 ratio. The mortar can also be used to smoothen the surface of the insulation (Figure 14). Also around the air supply inlets, except for the air inlet where the gas burner was later installed (see blueprint).

In order to reduce heat loses, the area of the air inlets facing the exterior of the furnace was smaller than that facing the interior (Figure 15).

Figure 14: Insulation of the furnace made with bricks and mortar.

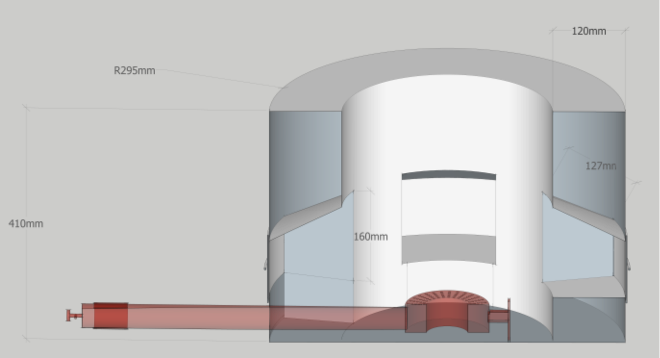


Figure 15: Blueprint of transversal cut of the furnace

1. Air shutters

The air shutters (together with the chimney) allow controlling the amount of secondary air that enters into the furnace. This has an impact on two of the key combustion parameters: time and turbulence.

Cut the shutters for the air inlets out of a metal sheet and bent them into the right shape so that they fit to the round outer surface of the furnace. They are slightly bigger (ca. 10 %) than the inlets to make sure they completely close the air inlets. Weld the shutter plates to a metal bar which is previously bent in the right shape. The shutters attached to the bar are thus movable by a handle and allow controlling the airflow and thereby the oxygen needed for the combustion of the pyrolysis gases.

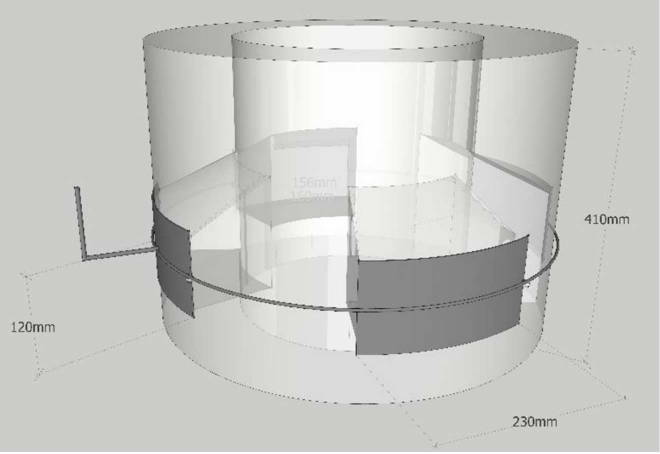


Figure 16: Blueprint with the dimensions of the air shutters attached to the metal bar and the handle.

2. Installing the gas burner

The gas burner shown in Figure 17 and Figure 18 was bought from stock. A metal extension pipe was added to prolong the distance between the burner ring and the gas/air inlet so that the connection to the hose and the inlet slot for the primary air could be located outside the combustion chamber. A cylindrical metal cover was put over the gas/air inlet to control the amount of oxygen provided into the gas burner which allows to control the conditions of the flame.

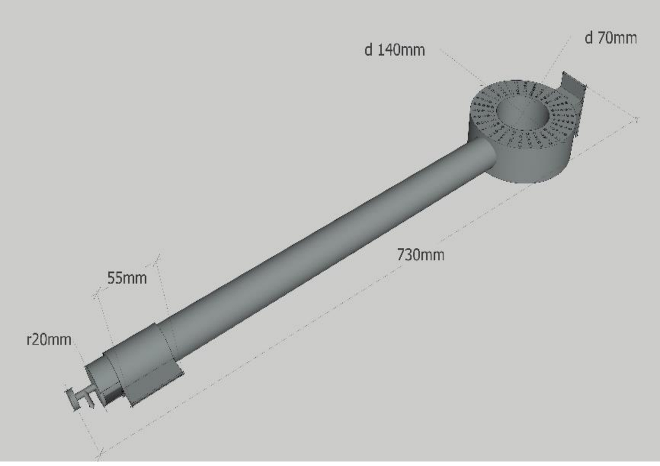


Figure 17: Blueprint with the dimensions of the burner

Once the burner is insterted into the furnace, it should be located in the center.

Figure 18: Photo of the burner, with welded extension

Figure 19: Top view of furnace

4.2.Reactor barrel

The reactor system consists of two reactor barrels which contain 7 metallic tubes each. The feedstock is inserted into these tubes which are later closed with lids. The reactor barrels are stacked on the furnace and on top of each other. The lower barrel serves to carbonize the feedstock while the upper barrel makes use of the waste heat and dries raw wet feedstock. Figure 20 shows an overview of one barrel and the 7 tubes.

Understanding the heat transfer from the hot combusted gases to the walls of the tubes where the feedstock is contained and ultimately to the feedstock itself, is therefore crucial.

This heat transfer is mainly affected by several factors, namely, the nature and thickness of the materials used to contain the feedstock, the specific surface area of the feedstock exposed to high temperatures, the heat losses through the barrel walls and the speed with which the hot gases cross the barrels upwards before they dissipate into the atmosphere.

Figure 20: Overview of one oil barrel and its seven tubes.

Criteria for construction

When constructing the barrels, the following objectives need to be considered:

- Locally available and standardized oil barrels (208 L)
- High thermal conductivity of materials that contain the feedstock like steel
- Low thermal conductivity of materials of the external wall of the barrel or insulation around it to avoid heat loses (e.g. mud bricks)
- Heat resistance of all materials of the reactor that are exposed to high temperatures (e.g. metals such as copper and aluminium are not recommended since they deform and melt at 600°C respectively)
- High surface area for heat transfer to the feedstock
- Trigger turbulence of the draft
- Ensure that the release of the pyrolysis gas occurs close to the combustion area and make use of its heat most effectively as possible
- Robust. The barrels must be able to hold the weight of a loaded upper barrel and a chimney (empty barrel weights around 40 – 50 kg)

- Safe and user-friendliness: the reactor needs to be easily filled and emptied

Materials and labour needs for construction

Table 3 present the materials needed for the construction of the two reactor barrels.

Table 3: Materials and labour required to construct two reactor barrels. Prices given are Tanzanian prices in 2016.

Amount	Material	Costs in USD
2	208 L standard oil barrel	36
4	Steel plate (1200 mm x 2500 mm)	130
2	Steel rod Ø 16 mm, 2350 mm	32
2	Chain min. 1020 mm, chain link Ø= 8 mm	6
2	Insulation material	5
4	Shackle	4
2	Barrel strap (needed for using the reactor)	4
Labour costs (1 person, 64 hours = 8 days)		60
Total costs two reactor barrels		**277**

Constructing the reactor barrels

In the coming lines, the required adaptations and construction steps are covered. The same steps need to be followed for both reactor barrels that are needed for the reactor system.

External barrel

The use of standardized 208L oil barrels is recommended due to their widespread availability and cheap cost.

Three main adaptations are required:

1) The bottom plate of the barrel must be removed and an insulation system needs to be installed.
2) A grid that will sustain the weight of the tubes needs to be welded.
3) Finally, two brackets need to be attached for lifting purposes.

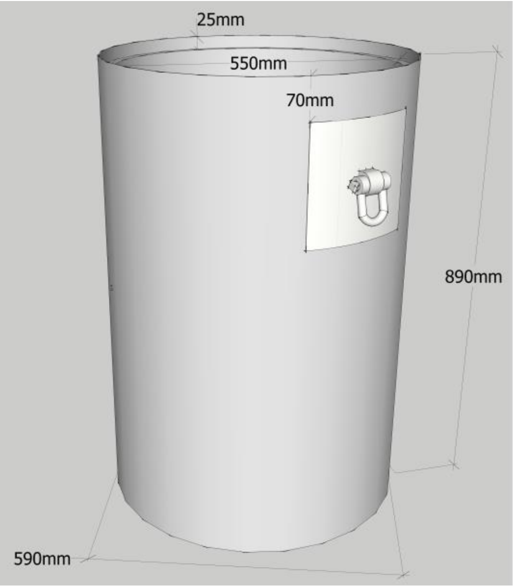


Figure 21: Blueprint with the dimensions of the barrel

1) Installing the insulation

Cut out the lower and upper cover plates with the electric cutting disk, keeping attention not to damage the rim. Once the barrel consists of a hollow cylinder the insulation can be installed. There are two different ways to install the insulation: internally or externally.

Internal insulation: The internal insulation consists of inserting a hollow pipe of a smaller diameter within the barrel. The empty space that remains between the wall of the oil barrel and the inserted cylinder is filled with an insulating material, e.g. stone wool or glass wool. *Note: this is the model shown in the pictures of this report.* However, this space could also be left empty, as air also acts as a good insulator.

As show in Figure 21, the diameter of the oil barrel is of 590 mm. The inner cylinder could then have a diameter of 550 mm. That leaves a cavity of 20 mm between both walls which could be filled with the insulation material. This inner cylinder can be made cutting a rectangle of 1727 mm x 865 mm from a 2 mm thick steel plate (Figure 22). Along the long sides of the rectangular plate, 50 mm long cuts are done every 50 mm. These small lashes could later be bent and welded along the rim of the oil-barrel.

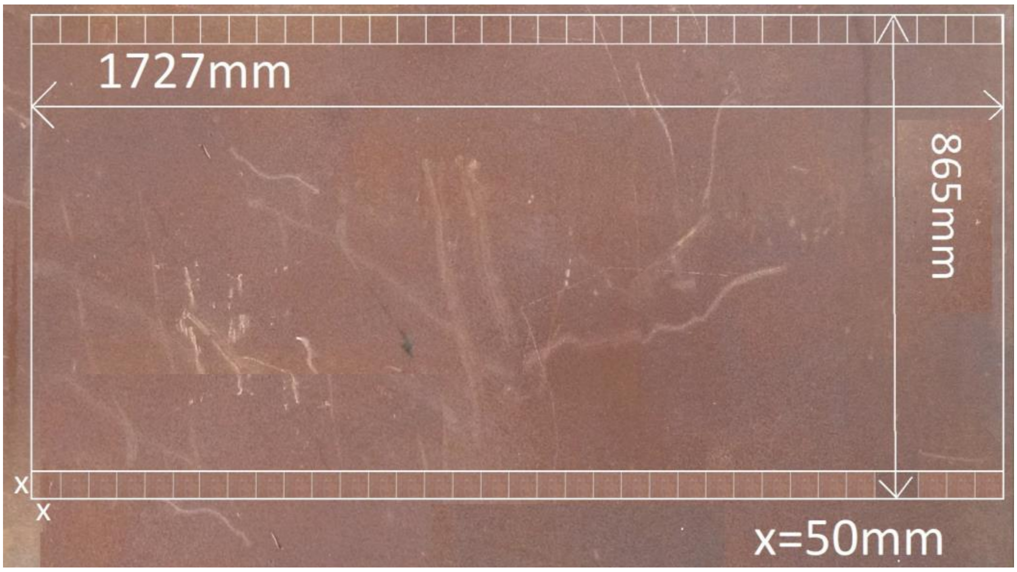


Figure 22: Dimensions of the metal plate of the inner cylinder used for insulation

Then the plate is bent until the rims of the short sides touch each other and are spot welded, creating a hollow cylinder. The insulation cylinder can then be inserted into the oil-barrel and positioned exactly at the centre. The lashes are then bent evenly below the rim of the oil-barrel and attached by spot welding. After checking correct alignment the cuts and gaps are closed by welding. Continuously, turn the barrel so that the welded rim is facing downwards. Insert the insulation material from the side that is still open. Finally bend evenly the lashes of that side and weld them to the rim of the reactor.

The drawback of this material is that part of the volume in the interior of the oil-barrel is used for insulation, reducing the volume of feedstock that can be inserted per batch. Furthermore, if the insulation material is damage or degraded, it cannot be substituted without opening the reactor.

External insulation: the external insulation consists of the opposite operation. A metallic cylinder is attached externally around the oil barrel. The cavity between both cylinders is filled with the insulation material. The advantage of this approach is that the volume within the oil-barrel can entirely be used to contain the cylinders and therefore, feedstock. There is no need to compromise a fraction of the volume for insulation. Consequently, an adequate thickness of insulation can be used.

2) Installing the holding grid

A metal grid needs to be installed at the same location where the bottom plate used to be. The main purpose of the grid is to hold the tubes containing the feedstock and at the same time allow the hot combustion gases produced in the furnace to easily pass heating up the tubes and ultimately the feedstock.

The grid has to hold the whole weight so it is recommended to weld it tight and thoroughly. The type of metal used should cope with high temperatures (steel).

The grid costs of 5 bars of 16 mm diameter. The best order to install the bars corresponds to the numbering shown in Figure 23.

The external diameter of the barrel is 590 mm. Bar 1 (570 mm length) should be welded first. Then bars 2 and 3, with an approximate length of 500 mm, are welded, with a 150 mm separation from bar 1 to both sides.

Bars 4 and 5 are also approximately 500 mm long and are separated 300 mm from each other.

Figure 23: Overview of the metal grid.

3) Installing shackles and chain

The operation of the reactor system requires lifting and moving the reactor barrels. Each loaded reactor barrel can weigh up to 100 – 120 kg. This arduous task can be eased by a lifting mechanism (see section crane in page 44). In order to lift the reactor barrels, two shackles and a chain need to be attached per barrel, which serve as lifting mechanism. The shackles are attached to the exterior wall, in opposite sides of the reactor barrel (Figure 24).

First, cut a metal plate (approximately 215 mm x 215 mm) and bend in the right shape. It is either welded or attached with bolts to the reactor barrel. Weld a 30 mm long piece of an iron bar (d=25 mm) at the centre of each plate. Drill a 10 mm wide hole in the middle of the iron bar to install the shackle and the chain. The chain has an approximate length of 1020 mm. The chain must be long enough to fit over and lift the reactor barrel. The chain also needs to be strong enough to hold the weight of the reactor barrel filled with the feedstock (approximately 100-120 kg depending on the density of the feedstock). Figure 25 shows the dimensions of the brackets.

Figure 24: Overview of the bracket and the chain.

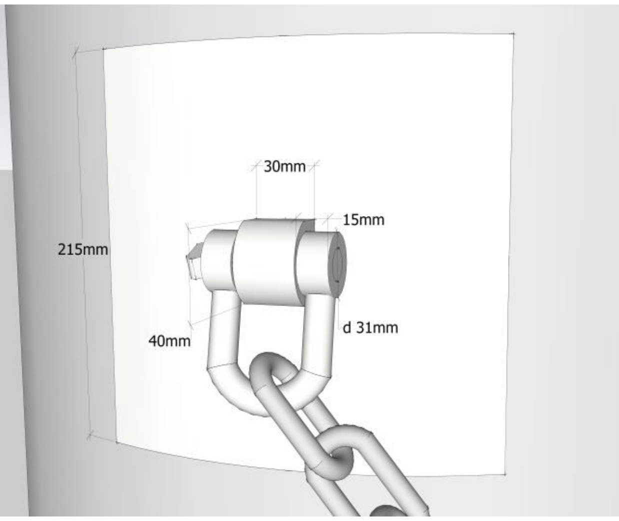


Figure 25: Blueprint with the dimensions of the shackle and plate.

Tubes and lids

In order to increase the surface area of feedstock exposed to higher temperatures, the volume of the barrel was divided into cylindrical compartments. A set of tubes presented an optimal relation between reactor volume and feedstock volume.

Each tube has a volume of 16.45 L and the seven tubes together have a total volume of 115.15 L. At the one end the tubes are closed while at the other end a removable lid allows to open and close the tubes. The tubes are separated from each other by a 10 mm gap, and attached through short metal bars to each other, which ensures a homogeneous heat distribution between the tubes. The gap between each tube allows enough space for the pyrolysis gases to mix with air, combust and ascend towards the chimney.

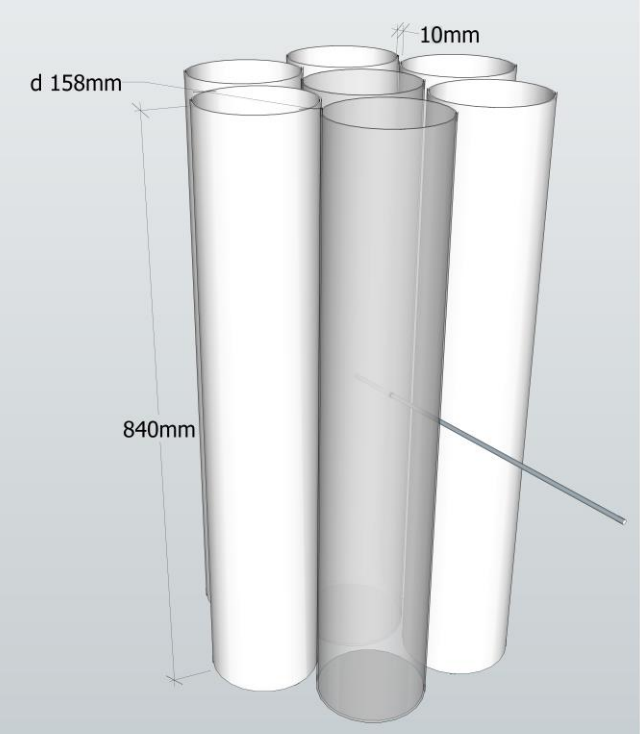


Figure 26: Blueprint with the dimensions of the 7 tubes.

The gap also allows to fit a thermocouple between them and measuring the temperature inside the centre tube as shown in Figure 26 and explained in Appendix A and Appendix B.

The lids must fit tightly over the tubes. This avoids air entering the tubes during the cooling phase but it should allow the pyrolysis gases to exit when there is an overpressure within the tube. During the development process different types of lids were tested. Exterior lids provided the best conditions for the pyrolysis gas discharge and the flames of the burning gases. The flames exit the tubes in a vertical direction, combusting immediately after exiting the tube, which contributes optimize the use of the heat by exposing the feedstock to higher temperatures (Figure 27). The dimensions are given in Figure 28.

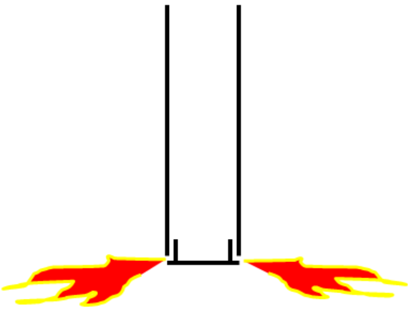


Figure 27: Impact of lids on the flame direction. Left: interior lids. Right: exterior lids.

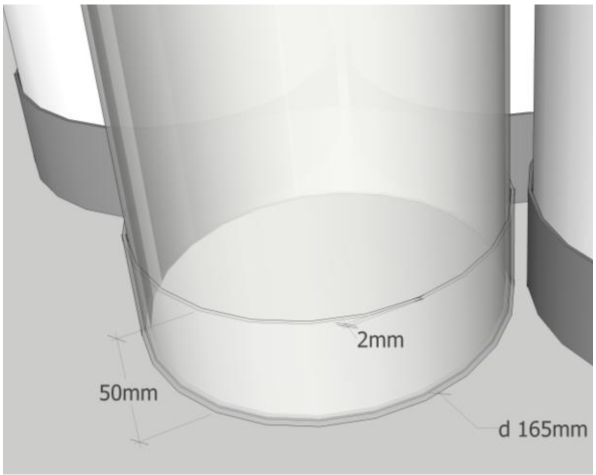


Figure 28: Blueprint with the dimensions of the lids

The lids, such as the one shown in Figure 29, can be constructed from a single metal sheet (Figure 30).

1. Purchase a 2 mm thick steel plate.
2. Draw and cut seven circular plates with a diameter of 158 mm (marked with "B" in Figure 30 and corresponding with "B" in Figure 29).
3. Cut seven long rectangular strips (510 mm x 50 mm, marked with "C" in Figure 30).
4. Spot-weld the metal strips to the outer rim of the round plates.
5. Check for proper alignment and remove any protruding material.
6. Weld along the outside rim and make sure the welding is air tight.

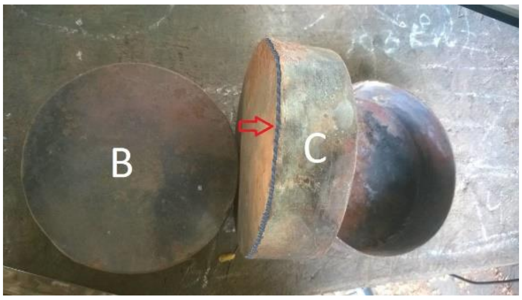


Figure 29: Overview of the lids

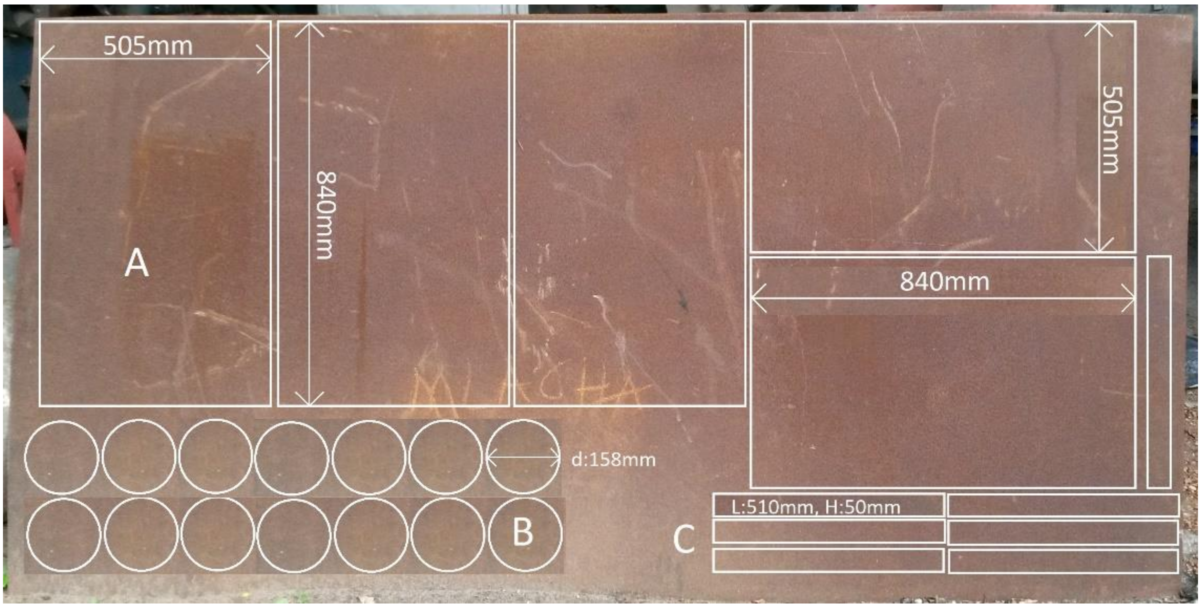


Figure 30: Overview of the pieces required to build the seven lids and five tubes (an extra sheet will be required to build two extra tubes).

The tubes can be produced either from standard steel pipes or from rolled steel sheets which are welded together. If they are produced from standard steel pipes, the method is simple.

1. Purchase 158 mm diameter steel pipes (if available). Check what lengths are available and purchase whatever is most convenient to transport. Ideally 4 m long so that the seven pipes can be cut from only 2 pipes.
2. Cut 840 mm long pipes using an electric grinder, equipped with a cutting disc.
3. One of the ends of the tubes must be hermetically closed, for which a metallic circular plate, with a diameter of 158 mm and a thickness of 2 mm, needs to be cut and spot-welded.

If the pipes need to be produced out of a flat metal sheet, the process is more laborious, however these pipes tend to be thinner, are therefore lighter and are heated faster- This implies that less heat is consumed for rising the temperature of the metallic structure and more heat can be used by the feedstock.

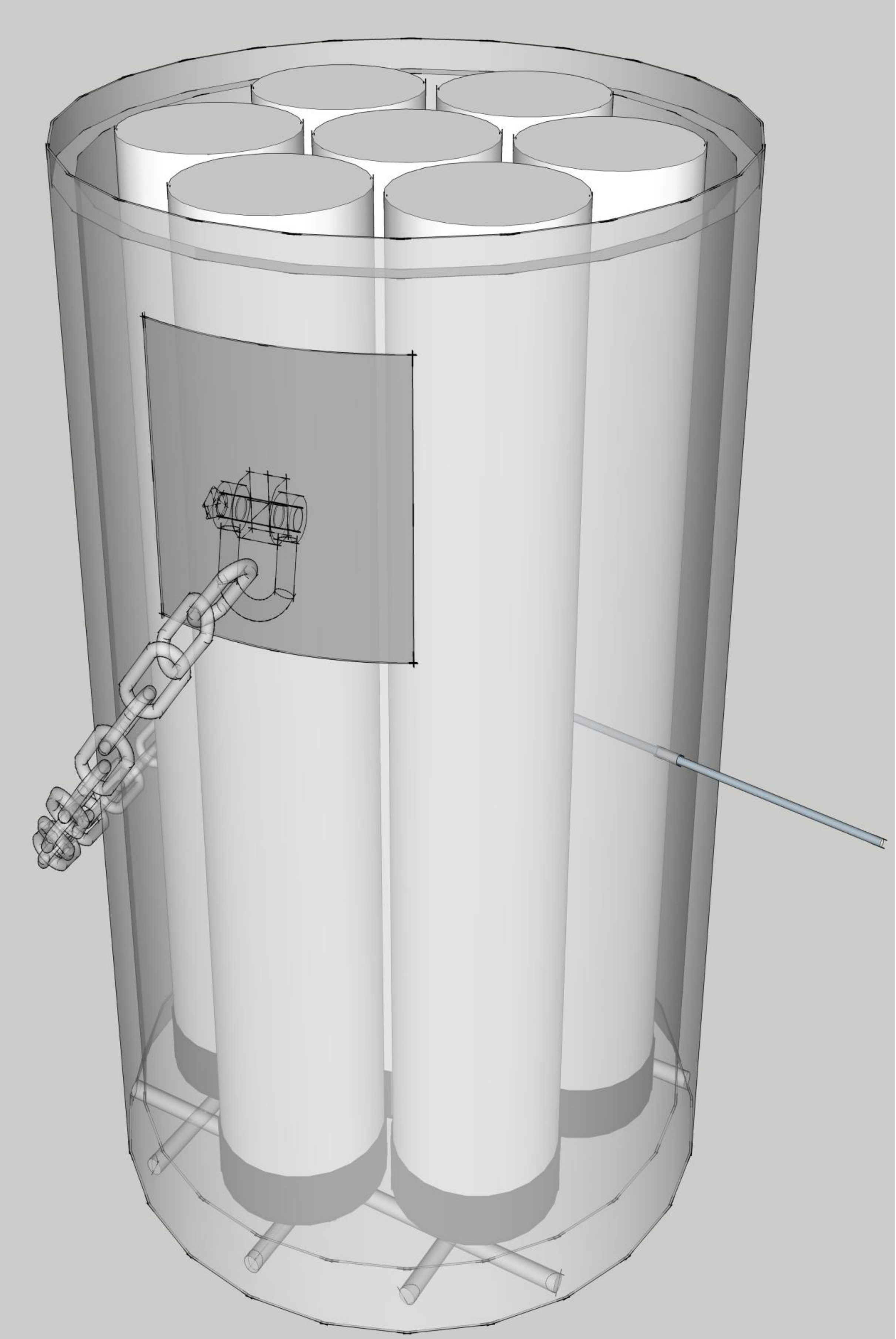
1. Purchase two 2 mm thick steel plates.
2. Draw the pieces that need to be cut on the plate as shown in Figure 30.
3. Cut the parts with an electric grinder equipped with a cutting disc.
4. The plates marked with an A in Figure 30 need to be rolled into a cylindrical shape using a roll bender. The tube is rolled on their short side (550 mm), keeping a length of 840 mm.
5. The lids can then be used to hold the tubes in a rolled position as shown in Figure 31. For that, first roll the plate so that one of the 840 mm sides will roll underneath the other side. Then fix two lids, one on each end to hold the plate rolled. Both 840 mm long edges will overlap in a straight line.
6. Weld both sides to each other along the overlapping edge. Once solidified, remove the lids.

7. Weld one of the bottom plates (marked as B in Figure 30) to one of the ends of the tube. Make sure that the welding is air tight.
8. Once all 7 tubes are ready, identify which lid fits best to each tube and number them accordingly. This can be done by spot welding as shown in Figure 32.
9. Finally all tubes need to be linked to each other by welding a small steel rod (d= 10 mm, L = 20 mm) between each tube and the middle tube.


Figure 31: Lids used to hold the rolled plate before welding.


Figure 32: Numbering used to identify best fitting lids and tubes.

The picture on the next page provides a blueprint with the general overview of the reactor with all components.



4.3.Chimney

The chimney element is an important part of the system since it is the one in charge of creating and controlling the upward draft. In the model proposed in this manual, the chimney consists of a part of an oil barrel, an exhaust pipe and a movable shutter.

Criteria for construction

The chimney had to fulfil the following objectives:

- Locally available and standardized oil barrels (208 L)
- Create an upward airflow to make the combustion gases exit from the top and to suck fresh air into the combustion chamber of the furnace.
- Control the draft in order to influence the 3T-s needed for good combustion.
- Heat resistance. Gases passing through the chimney are still several hundred degrees and the material must be able to withstand these temperatures.
- Airtight fit with the reactor. Avoid leakages as much as possible
- Operating the chimney needs to be safe and user-friendly.

Figure 33: Overview of the chimney

Materials and labour needs for construction

Table 4 present the materials needed for the construction of the chimney.

Table 4: Materials and labour required to construct the chimney. Prices given are Tanzanian prices in 2016.

Amount	Material	Costs in USD
1	Upper part of 208 L oil barrel(200mm)	-
1	Steel plate (1000 mm x 1000 mm)	10
Labour costs (1 person, 8 hours = 1 day)		7.5
Total costs chimney		**35**

Constructing the Chimney

In the coming lines the steps followed to construct the furnace will be explained. The chimney consists of three main parts: the chimney drum, the exhaust pipe and the shutter system. These are shown in Figure 34.

For the construction of these parts, the left overs of the oil-drum used to build the furnace as well as a 2 mm thick steel plate are needed. All the required parts were first drawn on the steel plate as shown in Figure 35 shows all the required parts drawn on a steel plate and which need to be cut with an electric grinder.

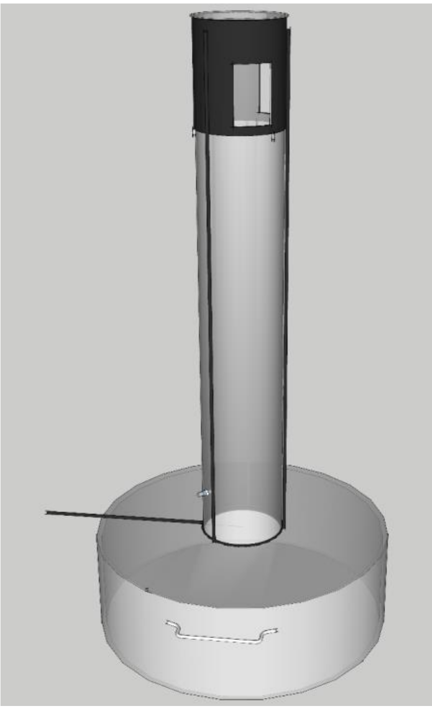


Figure 34: Blueprint with the three components of the chimney.

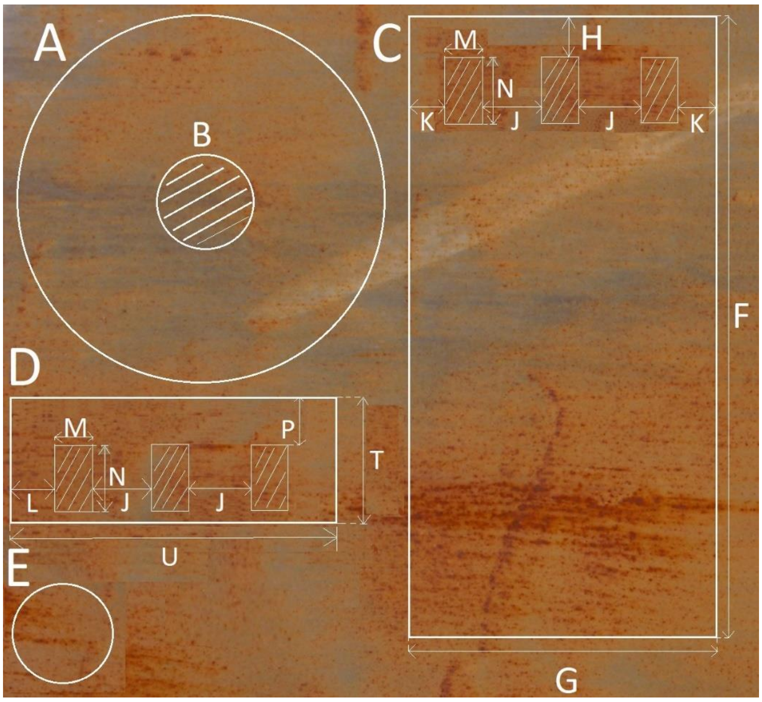


Figure 35: Overview of the pieces required to build the chimney (drawn on a steel plate): A: Plate for chimney drum, d=610mm, B: hole for chimney pipe, d=160mm, C: chimney pipe, F=1000mm, G=503mm, H=70mm, J=103mm, K=51.5mm, M=65mm, N=100mm, D: shutter element L=53mm, P=50mm, T=190mm, U=507mm, E: chimney pipe top plate, d=170mm

Chimney drum

The chimney drum can also be built with an oil-drum.

1. First cut the upper part of the barrel (with a lid). This piece should have a height of 200 mm and it will have the same diameter as the reactor barrel.
2. Remove the lid and face this side of the cut drum to the floor. The rim of the lid will be used to connect the chimney to the upper barrel with a metallic belt.
3. Then weld the big round steel plate, marked with "A" in Figure 35, to the drum. The diameter of the plate "A" must be slightly bigger than the drum`s diameter (610 mm vs 590 mm) which allowed to weld the parts together easily.
4. Remove the smaller circle "B" (Figure 35) out of plate "A". This hole determines the diameter for the chimney pipe (approx. 160 mm).
5. Finally, weld two metallic handlebars to the sides in order to allow lifting the chimney easily by hand.

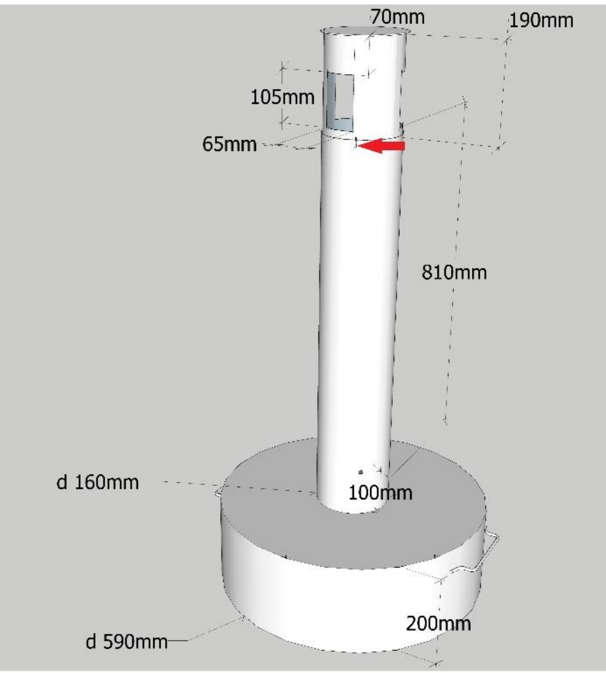


Figure 36: Blueprint with the dimensions of the chimney drum and the exhaust pipe.

Exhaust pipe

The steps for the construction of the exhaust pipe are as follows:

1. First cut the big rectangle from the steel plate (marked as "C" in Figure 35).
2. Next, cut the small three rectangles of the plate C.
3. Afterwards roll the sheet using a roll bender.
4. Weld the pipe's edges together.
5. Position the pipe in the centre of plate "A" over the hole "B". Attach the pipe by spot welding from the outside and continuously checked for straight alignment.

Shutter system

The shutter is one of the main parts to control the pyrolysis conditions inside the reactor barrel. The shutter element contains three parts:

a) the shutter part, which consists of the main part and it is built from the same steel plate,
b) the steel bars, which consist of the skeleton of the shutter system and allow turning the shutter radially and
c) the shutter holders, which are small metal pieces welded to the exhaust pipe. They hold the shutter element at the right height and reduce friction.
d) the handle stops, which stop the shutter at the fully open and the fully closed positions.

The shutter pipe and the bars are all welded to each to other forming one single moving unit. The steps required to build the shutter system are as follows:

Shutter pipe:

1. Cut the "D" and "E" parts from the steel plate (Figure 35).
2. Cut out the three rectangles drawn in the "D" element.
3. Using a roll bender, roll the "D" part into a small pipe. Before welding the edges of part "D" note: It is also important that the diameter of the shutter pipe is not too big because this would lead to a gap between the shutter pipe and the chimney, which would lead to a not proper closing of the chimney. If needed, part D has to be adjusted to the chimney pipes outer diameter. The shutter plate`s inner diameter (d = 163 mm) must be slightly bigger than the outer diameter of the chimney pipe (160 mm) so that it fits properly over the chimney pipe.
4. Weld the edges of part "D" together.

Steel bars:

5. Next, cut three steel bars (930 mm long) and weld them to the left-hand side of the shutter pipe's rectangles in the rolled "D" (see "Y" in Figure 33).
6. Bend another steel bar in a circle with a diameter of 165 mm, slightly bigger than the exhaust pipe and weld both ends. The exhaust pipe should fit through this ring.
7. Weld the ring to the bottom end of the three steel bars as shown at the bottom of Figure 37.
8. Weld a straight bar (330 mm) to the ring. This bar serves as a handle of the shutter element.

Shutter holders:

9. Cut 4 small metal pieces (10 mm x 10 mm) out of the steel sheet.
10. Locate the shutter element around the exhaust pipe and align the rectangles in the exhaust pipe with those of the shutter element so that they match as accurately as possible.
11. While holding the shutter element at this position, draw a line on the exhaust pipe marking the lower end of the shutter pipe (see "X" in Figure 33). It is in this lines where the shutter holders will be welded and will hold the shutter element on the right height.

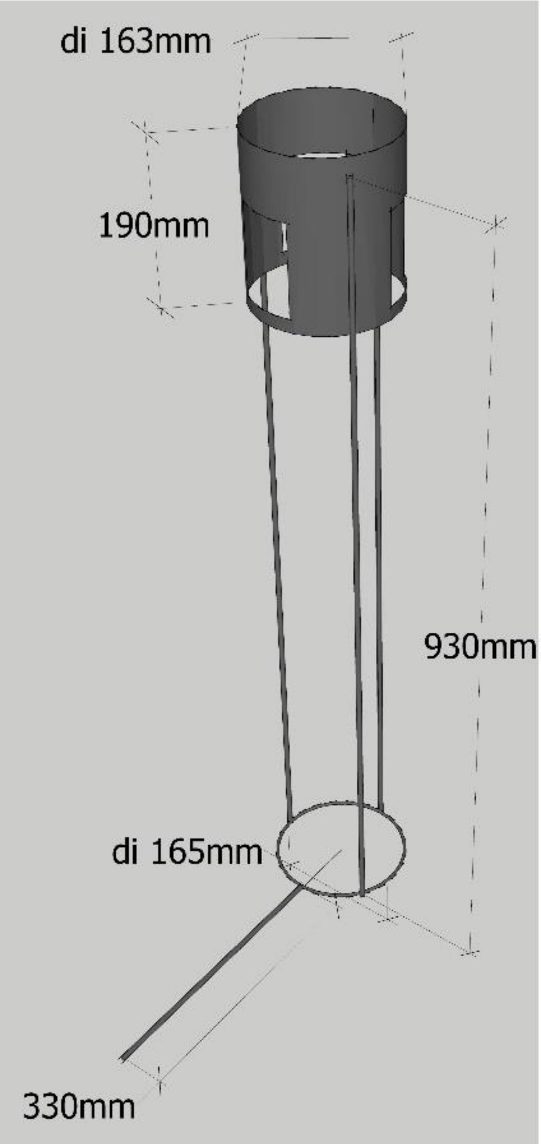


Figure 37: Blueprint with the dimensions of the shutter system

12. The 4 shutter holders should not interfere with the movement of the shutter element. They should be located in such a way that the rectangular openings can completely overlap (fully open chimney) or do not overlap at all (fully closed chimney).
13. Once the right locations are identified and marked, lift the shutter element and weld the shutter holders. Do not remove the shutter element entirely otherwise, once the holders are installed, it will not be possible to put it back.

Handle stops:

1. Cut 2 small metal pieces (10 mm x 25 mm) out of the steel sheet.
2. Using the handle observe which are the fully open and fully close positions. Mark the position of the handle in each location on top of the chimney drum (piece "A").
3. Weld the two pieces.

As a final step, weld the plate "E" (from Figure 35) to the top of the exhaust pipe. This plate closes the upper end of the exhaust pipe leading the exhaust gases to exit through the rectangular openings.

4.4.Crane

Criteria for construction

Since manual handling of the heavy reactor barrels is physically very demanding, a crane is needed. The crane must be high enough to accommodate two reactor barrels and a chimney underneath, and still have enough space to lift them on top of each other.

It is important to calculate or measure the total height of the reactor setup (including chimney) before constructing the crane. Apart from the hoist, the crane can be built from simple and readily available parts. The crane and hoist are an important part of the equipment, so the material must still be of good quality, so that a safe operation of the system is possible at any time.

Figure 38: Overview of the crane

Materials and labour needs for construction

Table 5 present the materials needed for the construction of the crane.

Table 5: Materials and labour required to construct the crane. Prices given are Tanzanian prices in 2016.

Amount	Material	Costs in USD
1	Chain block	81
2	Bolts (M16)	4
8	Bolts (M12)	9
4	Bolts (M14)	6
2	Black pipe 2"	41
1	MS Channel 100x55x6mm	52
4	Flanges	36

4	Rollers with bearings	27
Labour costs (1 person, 16 hours = 2 days)		15
Total costs crane		**271**

Constructing the crane

The total height of the reactor system is around 3390 mm: chimney 1200 mm, each reactor barrel 890 mm and the furnace 410 mm. To this height, it is required to add a safety distance of 100 mm. The total height of the crane was then almost 3500 mm.

The model shown in this manual considers a distance of 2000 mm between each pole on the ground (see Figure 41), so the length of the poles should be 3640 mm.

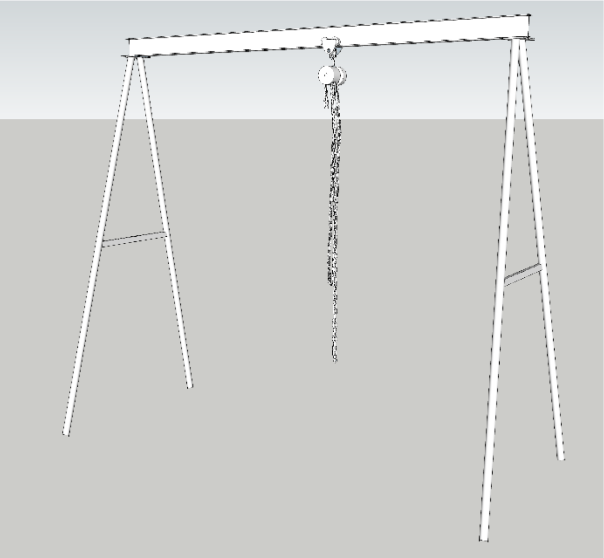


Figure 39: Overview of the crane

1. Choose a standard wide flange beam (4000 mm length) allows the hoist to move easily along the crane.
2. Weld a 5 mm thick steel plate (150 mm x 200 mm) at both ends of the beam (Figure 40).
3. Drill four holes (d=10 mm) in each plate 20 mm distance from the edges (Figure 40).
4. Next, cut the four poles with a length of 3640 mm, and laid them on the ground pairwise. The rear ends of the poles were set in the distance of 2000 mm.
5. Weld a rectangular bar (1000 mm x 50 mm x 30 mm) in the middle of the two poles to hold the poles in position and to reinforce the crane construction (see Figure 41).
6. Cut the poles at the upper end so that a horizontal steel plate can be welded on top (exact the same size like the steel plate welded to the wide flange beam). Cut the pole with a 2° inclination so the plate is positioned orthogonal on the front view but with a 2° inclination on side view. As a result, the ends of the poles are obliquely outward of the beam, thus ensuring a secure stand of the crane.
7. Attach the wide flange beam with four bolts on each side to the poles.
8. Paint the crane with a protective coating against corrosion.
9. Once the coating is dried, install the trolley for the hoist.
10. Finally hook the hoist into the trolley and adjust the length of the chain.

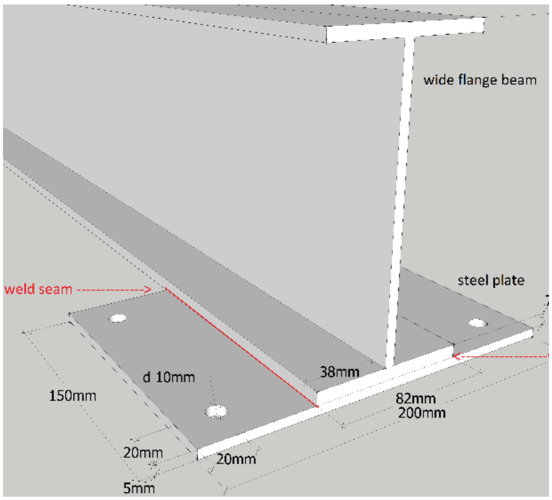


Figure 40: Blueprint of the end of the beam with the dimensions

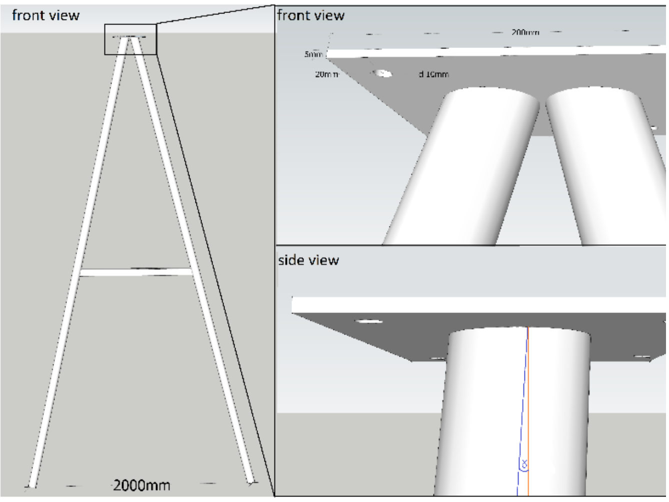


Figure 41: Blueprint of the top of the poles. Left: transversal sight of the crane. Right: zoomed view of the link between the plate and the poles.

5. OPERATING THE DOUBLE BARREL REACTOR SYSTEM

This section explains the practical daily tasks of operating a biochar processing facility. It is divided into several subchapters based on the different phases of the process: preparing the batch, running the carbonization process and emptying the reactors. Each activity includes the equipment needed, the individual work tasks, protective measures for workers and points of monitoring and data collection. In this manual, the steps are given for the case of using liquefied petroleum gas (LPG) as fuel.

5.1.Preparing the batch

Step 1 – Preparing the equipment and filling the feedstock

The barrels are prepared and filled with the feedstock to be pyrolyzed.

Equipment needed in this step:

Figure 42: Left: Biomass. Middle: electric scale. Right: A square shaped log.

Figure 43: Left: Crane with hoist Middle: Ladder to install the upper barrel and the chimney. Right: Dust mask

Figure 44: Left: gas cylinder and rotameter. Right: three barrel straps to fix the barrels.

Figure 45: Left: furnace with gas burner. Middle: set of barrel, tubes and lids (reactor barrel). Right: chimney with lambda sensor

Location:

There are a few aspects to be considered when it comes to the location of the reactor system.

- Roofing: the reactor system itself does not need to be protected from the rain. However, if monitoring electronic equipment is used (lambda sensor, thermocouples, etc.), this should be protected from the rain.
- Power connection: providing electronic equipment is foreseen, the site should have a power connection.

- Exhaust gases: keep in mind that the slow pyrolysis process generates a lot of exhaust gases. Therefore, it is a must to locate the reactor system in a well ventilated place.
- Wind exposure: the performance of the furnace and the heat distribution among the pipes can be altered if the reactor system is exposed to the wind. Consequently, either the reactor system is located in a wind free area, or some wind shields are installed.
- Storage: the site should also allow storing both the feedstock to be pyrolyzed and the produced char. It is important not to moisten any of these materials. Estimate beforehand the amounts that will be pyrolyzed on a weekly basis in order to estimate the space required for storage.
- Accessibility: the site should be accessible by whatever means of transport is used to carry the feedstock and to export the char.

Tasks:

T1.1: **Set up the LPG installation:** connect the LPG cylinder to the rotameter (if available), and this to the burner. Check the connections for leakage. Test if the LPG-burner works properly before setting up the reactor. Once checked, disconnect the gas cylinder from the rotameter and weigh the LPG cylinder with the scale and note the weight to calculate later the amount of gas consumed in the run. Reconnect the gas cylinder.

T1.2 **Prepare the feedstock:** check the feedstock you want to carbonize. If this feedstock will be inserted in the lower barrel, the moisture content should not be higher than 20%.

A cheap and simple pre-drying method could be to expose it to the sun as shown in Figure 46. Some big pieces of feedstock might need to be chopped in order to insert them into the tubes

Box 1: Maximum moisture content in lower barrel

Moisture Content

Maximum moisture content in lower barrel 20%

Figure 46: Sun pre-drying sawdust.

T1.3: **Fill the reactor:** Insert the feedstock into the tubes. If possible, compress the biomass with a square shaped log (or alike). Paper can be used to fill the gaps between the tubes to avoid feedstock from falling in the gaps. Once filled, remove the paper. Weigh the tubes with the scale to check how much biomass was filled in the tubes (the tare weight of the tubes must be known). Afterwards close the tubes with the lids and clean up the spilled biomass.

Figure 47: Filling, compressing the feedstock in the tubes (T1.3)

Box 2: Understanding the effect of particle size

Particle Size

Keep in mind that when a feedstock with small particle size is compressed, the pyrolysis process lasts longer since the biomass acts then as an insulator, slowing down the heating up rate of the material. Besides, in very densely loaded batches, the layer of feedstock closest to the wall of the tube is often pyrolyzed and the interior remains untouched. In these cases, the carbonized layer functions as an insulator, and hinders radial front of the process.

Consequently, it is recommended to leave some air cavities within the tubes. This can easily be obtained by making sure that the particle size of the feedstock is above 1 cm. Sawdust for instance, performed generally well. However, much better performances are observed with briquetted sawdust. Not only were the amount of inserted feedstock, and consequently, the generated char bigger, but also the energy performance of the process was much more efficient.

Figure 48: Raw and carbonized sawdust briquettes

T1.4: Assemble the barrel and the tubes: the process of inserting the tubes in the barrel is as follows.

- First lift the barrel with the crane by hooking it to the middle bar of the metal grid (Figure 49 left).
- Locate the barrel over the tubes and smoothly let it drop, leaving the tubes inside (Figure 49 middle).
- Carefully turn the reactor barrel upside down by hand. The lids of the tubes should be facing the floor.

Figure 49: Assembling the reactor barrel: bringing the barrel and tubes together (T1.4)

Before releasing the hook from the crane make sure the reactor has a proper stand on the furnace (Figure 49 right). Attach the barrel strap to secure the reactor barrel to the furnace and release the chain from the hook of the crane.

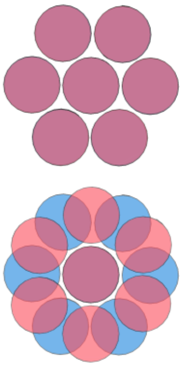


Figure 50: Top: top of view of reactor tubes aligned to each other. Down: lower barrel tubes (blue) and upper barrel tubes (red) do not overlap.

T1.5: **Prepare upper barrel:** for the second barrel repeat tasks T1.2 to T1.4. Use a ladder when setting up the upper barrel on top of the lower barrel. Make sure the ladder has a safe stand before it is used (Figure 51). The alignment of both barrels is very important. The tubes of both barrels should not be perfectly aligned to each other. Otherwise the hot gases would quickly scape through the chimney. This negatively affects two of the 3 combustion requirements: time and turbulence (see section "Combustion" in page 21). In order to enhance these two aspects, the reactor barrels should be located in such a way that the inter-tube cavities of the lower barrel are blocked by the tubes of the upper barrel. (below image in Figure 50).

Figure 51: Locating upper barrel and chimney with ladder (T1.5 and T1.6)

T1.6: **Install the chimney:** lift and locate the chimney on the upper barrel. Once located, attach the barrel strap (Figure 51).

T1.7: **Place the wind shields:** set the wind shields around the furnace, especially if the reactor system is located outdoor and is exposed to the wind.

Protective measures for workers:

- Pay attention to hands and feet when working with the heavy parts and avoid injuries through squeezing.

- Use dust mask when filling the tubes with biomass

Attention when operating with LPG cylinders:

The reactor described in this manual is operated with liquid petroleum gas (LPG). Always follow the correct procedures for assembling and disassembling liquefied gas equipment. Check that all the connections are clean and do not leak before using the reactor.

- Store gas cylinders in cool, dry, well-ventilated areas, away from incompatible materials and ignition sources. Ensure that the storage temperature does not exceed 52°C (125°F).
- Store, handle and use compressed gas cylinders securely fastened in place in the upright position. Never roll, drag, or drop cylinders or permit them to strike each other.
- Leave the cylinder valve protection cap in place until the cylinder is secured and ready for use.
- Discharge compressed gases safely using devices, such as pressure regulators, approved for the particular gas.
- Never force cylinder’s valve connection or use homemade adaptors.
- Always ensure that equipment is compatible with cylinder pressure and contents.
- Carefully check all cylinder-to-equipment connections before use and periodically during use, to be sure they are tight, clean, in good condition and not leaking.
- Carefully open all valves, slowly, pointed away from yourself and others, using the proper tools.
- Close all valves when cylinders are not in use.
- Never tamper with safety devices in cylinders, valves or equipment.
- Do not allow flames to contact cylinders and do not strike an electric arc on cylinders.
- Always use cylinders in cool well-ventilated areas.
- Handle "empty" cylinders safely: leave a slight positive pressure in them, close cylinder valves, disassemble equipment properly, replace cylinder valve protection caps, mark cylinders "empty" or "MT," and store them separately from full cylinders.

Points of monitoring and data collection:

- Weighing the gas cylinder allows to calculate the energy used for the production of the char. The value is also needed to calculate the efficiency of the run and allows to spot weaknesses in operating the pyrolysis process.
- Measure the weight of each filled tube unit before and after pyrolysis. This numbers are needed to calculate the efficiency of the reactor and properties of the char that was produced.

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5.2.Running the carbonization process

Operating the pyrolysis reactor is a versatile challenge in which the directly occurring parameters such as the size of the flame, the colour of the smoke, etc., must be observed. All these parameters must be interpreted quickly and the pyrolysis process must be controlled so that in the end the biomass is completely pyrolyzed.

Step 2 - Heating up and drying phases

Equipment needed:

Apart from the reactor and the technical equipment prepared in the previous steps the following equipment is needed.

Figure 52: Left: lighter or matches. Middle1 : Mirror with handle. Middle 2: Thermoresistant gloves. Right: Rotameter. Model: Wagner, C_4H_{10}, 2-19l/min

If a gaseous fuel is used to heat up the reactor system, a rotameter can be very handy to control the flow rate. For the reactor system presented in this manual, the LPG flow rate was set at 6 - 6.5l/min by using a rotameter. This flow rate was found to be optimal. The burner cannot handle more LPG and the flame is big enough to touch the bottom of the reactor. A rotameter costs around 240 USD.

Tasks:

T2.1: **Set the shutters:** fully open the shutter at the furnace and close the shutter at the chimney.

T3.2: **Ignite the LPG:** open the valve of the LPG cylinder and then slightly open the valve at the LPG burner and ignite the gas with a lighter.

HINT: use a long match or a piece of paper fixed to the end of a stick to ignite the flame in the furnace to prevent burns.

T2.3: **Adjust the flows:** adjust the gas flow with the valve at the LPG burner until the rotameter shows a gas flow of 6 l/min (Figure 53). Use then the small black cover at the LPG burner to adjust the primary air flow through the burner.

This allows to change and adapt the flame`s properties manually (check Box 3). The closer the flames get to the tubes, the better the heat transfer into the inside of the tubes and therefore the better the efficiency of the whole reactor system. The flames start heating up the outer surface of the tubes, gradually reaching the feedstock through the metal walls Use the mirror to check the flame properties.

Figure 53: Valve of burner to adjust LPG flow (lower red arrow). Black cover to adjust primary air entering the burner (upper red arrow).

T2.5: Heating up phase: the temperature inside the tubes increases from the outside to the centre ***("Heating up phase")***. The temperature is rising slowly up to 100°C, and remains there until the water contained in the feedstock has evaporated. This represents the "***Drying phase"***. Since the tubes are closed with lids the vapour is pushed out the small gaps between the tubes and the lids through the increase in partial pressure created by the water vapour. This is showed in blue in Figure 54. Depending on the moisture content this can take up to 60 minutes or even longer.

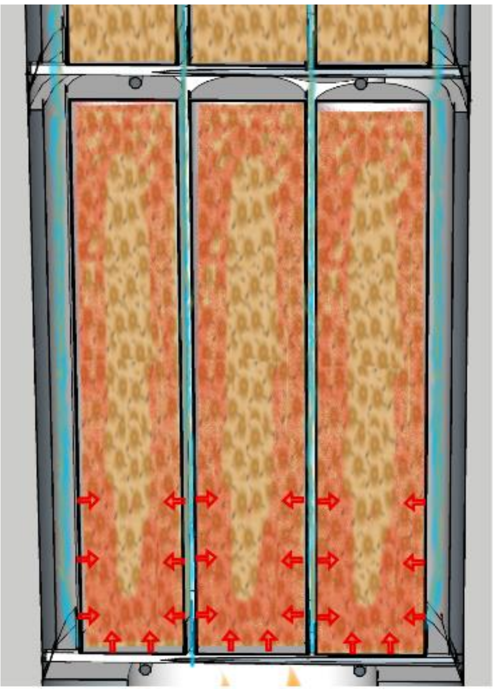


Figure 54: Gradual heating up phase – from the walls to the centre.

T2.4: Monitor combustion conditions: once the flame is ignited, the oxygen content in the reactor will drop. When operating a reactor without technical equipment (i.e. lambda sensor, thermocouples, etc.) the main indicator of the process is the flame coming out of the tubes and the smoke released from the chimney (see Box 3 and

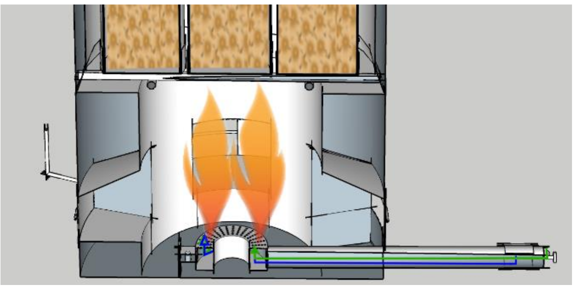


Figure 55: Blueprint of well-adjusted flames (T2.3).

Box 4 in the next section).

Step 3 –The slow pyrolysis process within the reactor system

The temperature of the lower barrel rises once the drying process in the lower barrel has ended. The type of biomass will determine the temperature at which pyrolysis will start. Normally, this happens at around 200 - 300°C.

Equipment needed: same as step 2 and scale from step 4.

Tasks:

T3.1 **Manage the temperature:** the temperature in the reactor is the most important operational control variable for pyrolysis processes Three ways to control the heat conditions of pyrolysis reactors are:

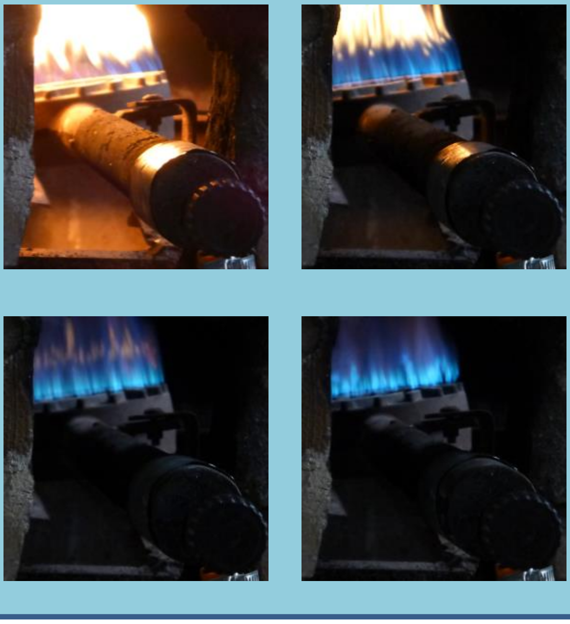
1) to observe the colour of the flames (Box 3),
2) to observe the colour of vapours produced (Box 4), and
3) to measure and control the temperature inside the reactor using standard feedback control systems such as thermocouples (see Appendix A and Appendix B).

T3.2: **Notice the generation of pyrolysis gases**: when the feedstock starts pyrolyzing it goes through a complex thermochemical decomposition in which part of the volatile components are emitted as pyrolysis gas. Similar to the water vapour before, the pyrolysis gases are driven out of the tubes through the cavities in the lids pushed created by their own pressure. Due to their high temperature and flammable composition, they ignite at the flames of the gas burner, providing additional heat to the process, increasing the temperature inside the tubes even further. Use the mirror to check if the pyrolysis gases already ignited.

Box 3: Understanding the flame as indicator

Flame Colour

If a pyrolysis reactor is operated without technical equipment (temperature sensor, lambda sensor), the combustion can be optimized by observing the colour of the flames of the burning LPG and pyrolysis gases. The colours of the flames give an indication of the temperature of the flames. Figure 56 shows the colour range that the LPG flame can present. A dark yellow to orange flame indicates a rather low combustion temperature (top left). The reason for this is usually a lack of oxygen in the combustion, which implies too little primary air. Often a lot of soot is formed, which clearly shows as black smoke in the exhaust gases. If the flame is blue and jagged (bottom right), it implies that it has excessive primary air.



T3.3: **Observe exhaust gases:** at this time the colour of the smoke slowly turns to yellowish (see Box 4). This is a clear indication that pyrolysis is taking place, but also of incomplete combustion. In this case, considering the increase on available fuel (LPG and increasing amounts of pyrolysis gases), incomplete combustion is most likely due to a lack of oxygen. However, the fulfilment of the 3T-s (time, turbulence and temperature) should always be ensured.

As a general rule, the exhaust gases coming out of the chimney should be transparent. That is an indication that all the fuel is being burnt and that the combustion products are only CO_2 and water vapour. If the supply of oxygen is not increased by opening the shutters of the furnace, the exhaust gases coming out of the chimney will slowly turn darker, clear indication that soot is being produced: a sign of incomplete combustion.

Box 4: Understanding the exhaust gas as indicator

Exhaust gas colour

Control by observation of vapour colour is an approach typically used with low-cost carbonization reactors without heat or bio-oil recovery. Due to the high water content of the smoke leaving the chimney, the smoke has a white colour during the drying process. A yellow/brown smoke is typically associated with pyrolysis. As pyrolysis continues, the smoke becomes more and more transparent and finally turns bluish if part of the char begins to combust.

Drying and pyrolysis can however occur simultaneously. Parts of the feedstock at the lower part of the tube can start to pyrolyze since they are closest to the furnace and therefore, exposed to the hottest part of the reactor (500°C). These might result in some yellowish colour during the

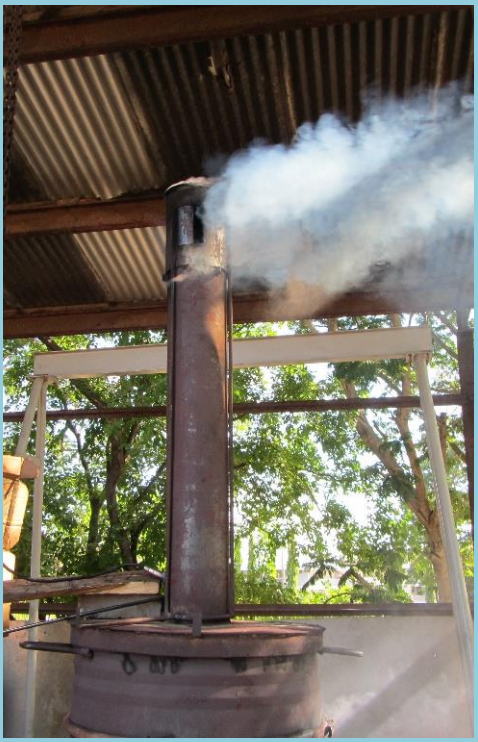


Figure 57: White colour leaving the chimney

T3.4: Manage the secondary air: as soon as the pyrolysis gases start to burn, it is important to manage the flow of secondary air (blue arrows, picture left) by adjusting the opening angel of the shutters. In principle, the shutters should preferably be closed rather than open. Keep in mind that the air entering through the shutters is at ambient temperature. The more air you let into the reactor, the bigger temperature drop that occurs within the reactor, jeopardizing one of the prerequisites for good combustion: temperature. However, due to the reasons explained before, it is important to adjust the shutters in order to supply the required amount of oxygen, otherwise the combustion is suffering and producing dark smoke (i.e. soot).


Figure 58: Schematic of the carbonization process in the lower barrel: heat distribution, combustion of the pyrolysis gases and supply of secondary air.

This represents a source of air pollution and consequently a health threat for operators working in the vicinity of the reactor. Furthermore, not combusted all pyrolysis gases generated is a loss of fuel and reduces the efficiency of the system. A too high airflow can, however, lead to a cooling down of the reactor and to the end of the pyrolysis process. The temperature in the tubes should rise constantly. At this time the process still needs energy provided from the furnace.

T3.5: **Identify strong pyrolysis:** by observing the flames with the mirror, you will notice that their intensity increases and after a while, most of the tubes are generating intense flames. Providing a thermocouple is installed, it can be observed how the temperature rises to 650 - 750°C in the middle tube. The production of pyrolysis gases is at the maximum point.

At this point, the reactor produces its own energy and is thus self-sustaining. The LPG supply can be switched off completely to save fuel and keep the process as efficient as possible. Adjust accordingly the position of the shutters, and consequently the supply of secondary airflow to the new conditions. The average LPG consumption observed was 1.5 – 3 kg per run, depending on nature of feedstock, moisture content and quality of the LPG (see "Observations" in section "-Operational costs").

Depending on the type and the amount of feedstock, the pyrolysis in one barrel can last for up to 90 minutes. Consider that at this time the outer surface of the barrel can be as hot as 400°C. Always wear gloves and pay attention to hot surfaces when checking pyrolysis conditions. Gradually, the feedstock in the lower barrel is turned into char. The volume inside the tube has reduced by about one third (Figure 59).

T3.6: **Heating up and drying the upper barrel**: like the lower barrel, the upper barrel goes through the drying and the heating up process. The pyrolysis of the lower barrel provides the necessary energy.

T3.7: Pyrolysis in the upper barrel: if the original moisture content of the upper barrel is lower than 35%, the waste heat from the lower barrel is enough to dry and reach pyrolysis conditions in the upper barrel (i.e. temperature of 300°C, no oxygen and no water). The pyrolysis process in the upper barrel starts once the pyrolysis process in the lower barrel has already exceeded its pyrolysis peak and starts reducing its pyrolysis gas production and slowly the temperature. The pyrolysis gases from upper barrel combust and provide the required heat to continue drying and pyrolyzing the upper feedstock (Figure 59). When the secondary air enters the reactor is pre-heated and leads to a more efficient combustion process of the pyrolysis gases of the upper barrel.

When pyrolysis is strong in the upper barrel, the strong flames can reach up to the top of the chimney and might flicker out through the openings (Figure 60). Open all shutters to provide maximum airflow at this moment.


Figure 59: Schematic of the pyrolysis process. Lower barrel fully carbonized. Upper barrel: beginning of the pyrolysis process

T3.8: Manage the secondary air during transition from lower to upper reactor: in this transition phase from the pyrolysis process of the lower to the pyrolysis process of the upper barrel smoke is a very important indicator. If the shutters are too wide open, the secondary air flow will increase, which leads to an increase in the oxygen supply but a temperature drop of the reactor which might lead to an incomplete pyrolysis in the upper barrel. Closing the shutter too much leads to a suffering combustion and the production of smoke and soot. As a general rule, the shutter of the chimney should preferably be rather close. Except when dark smoke is produced, then open the shutters gradually until the smoke


Figure 60: Strong pyrolysis in the upper barrel with flames coming out of the chimney.

turns again transparent.

The secondary air slowly cools down the lower barrel. After a certain time the flames at the lower barrel extinguish due to the lack of temperature and combustible gases.

T3.9: **End of pyrolysis:** at the end of the process, maintain the shutters closed. After a while, the oxygen content in the exhaust gases will rise. This is the end of the pyrolysis process and the reactor enters the cooling phase, which takes several hours. Do not empty until the reactor has reached ambient temperature, otherwise, the produced char might combust due to its high temperature and its contact to oxygen.

Figure 61 shows the temperature recordings of the thermocouples throughout a standard experiment (note: the temperature of the lower barrel is around 200°C in minute 1, which indicates that the thermocouples started recording slightly after the burner was switched on). The following conclusions can be drawn:

- In 50 minutes the lower barrel reaches its maximum temperature (around 750°C) and after drops slowly.
- In 120 minutes, the chimney reaches its maximum temperature (450°C) and then drops.
- The upper barrel gradually increases its temperature until it starts producing pyrolysis gases (min 130) when the temperature increase is much faster. It reaches its maximum temperature of 750°C in min 150 and min 167. Then drops fast.
- The maximum temperatures of the upper are reached 100 minutes later than in the lower barrel.
- A big part of the heat is dissipated through the walls since the chimney never exceeds 450°C.

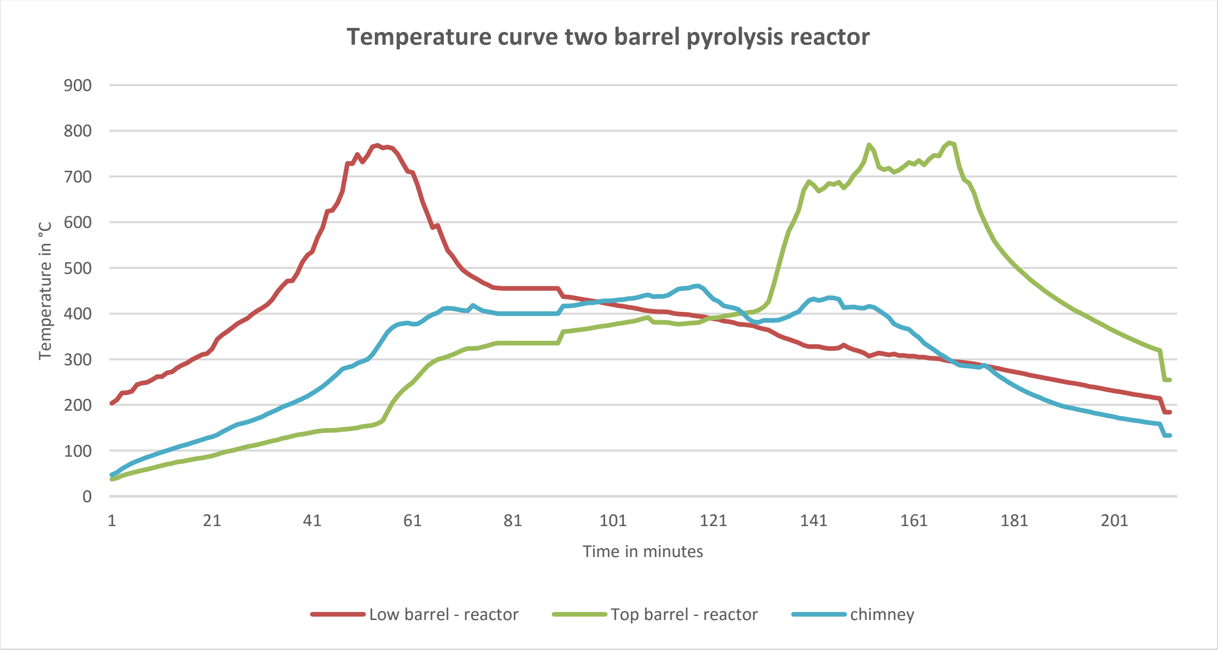


Figure 61: Temperature recordings of the thermocouples during a standard experiment.

Protective measures for workers:

Note that during operation of this reactor, components can reach temperatures above 350°C. Therefore, there is a considerable risk of burns. Wear the necessary protective equipment when operating the reactor. Toxic gases can be generated during operation. Avoid inhaling smoke and wear a mask while operating the reactor. Use the reactor only in well-ventilated areas.

- Use leather gloves when working on the hot reactor to prevent burns
- Know all of the hazards (fire/explosion, health, chemical reactivity, corrosion, pressure) of the materials you work with.
- Wear the proper personal protective equipment for each of the jobs
- Know how to handle emergencies such as fires, leaks or personal injury.

Points of monitoring and data collection:

- Watching the flames and smoke during the pyrolysis and its use as indicator to maintain the pyrolysis process is of great importance.
- Weighing the gas cylinder allows to calculate the energy used for the production of the char. The value is also needed to calculate the efficiency of the run and allows to spot weaknesses in operating the pyrolysis process.

5.3.Emptying the reactor system

Once the pyrolysis process is finished, the reactor needs to be cooled down, disassembled, the char needs to be harvested and finally the equipment cleaned. In this section the steps of this phase are explained.

Step 4 - Dismantle the reactor, emptying the tubes, clean the reactor

In this last step the process of dismantling and emptying the reactor is explained.

Equipment needed:

Figure 62: From left to right: crane with hoist, wire Bruch, dust mask and rag or towel.

Figure 63: From left to right: ladder, scale, storage bag or storage container and dust pan with brush.

A scale is required to measure the weight of:

- Tare weight of empty tubes
- Weight of filled tubes to calculate the weight of the feedstock.
- If LPG is used as a fuel for the furnace, the consumption of LPG per batch can be calculated by weighting the LPG cylinder before and after the experiment. This allows to calculate the energy used for the production of the char. The value is also needed to calculate the efficiency of the run.

Tasks:

T4.1: Calculate consumed fuel: disconnect and weigh the gas cylinder to calculate the gas consumed in the run. Put the gas cylinder in a safe place.

T4.2: Remove the chimney: once the reactor has cooled down to ambient temperature, remove the chimney. Again two people are recommended for this step. Place the ladder close to the reactor. One person stands on the ladder and is holding the chimney while the second person is removing the barrel strap. Lift the chimney form the upper barrel and put it aside.

T4.3: Observe the soot: examine the inside of the chimney. Normally a light coating of soot is visible. If the inside area of the barrels and the chimney are completely covered with thick soot, the process was suffering from bad combustion. This can either be because of lack of oxygen or because the 3T-s where not fulfilled (see section "Combustion"). Use this as indicator for the next run and consider that the airflow has to be bigger. Clean the soot in the inside area with the wire brush.

T4.4: Remove upper barrel: attach the hook of the crane to the chain of the upper barrel. Lift it from the reactor and put it on the ground. Clean the soot and other impurities with the rag. Release the crane and turn the barrel upside down by hand.

T4.5: Weight the char: attach the hook to the barrel's metal grid and lift the barrel leaving the tubes on the floor. Put the barrel aside. Remove the lids from the tubes. At this point, the volume reduction of the biomass after pyrolysis is best seen. In general the volume of the biomass has reduced by one third (Figure 64). Put the tubes on the scale and note the weight of the tubes with the char inside to calculate the mass loss.

Figure 64: Volume loss of the feedstock after pyrolysis process.

T4.6: Empty the upper barrel: empty the tubes by pouring the char carefully on a container (make sure that the char is at ambient temperature, otherwise, use a thermoresistant container). If necessary the char can now be examined and samples can be taken for further analysis. Put the char then in a storage bag or container for post processing (e.g. briquetting).

T4.7: Repeat steps T4.3 to T4.6 for the lower barrel.

T4.8: Clean the tubes and the lids with the wire brush so that they can be used for the next run. Clean the work space with the broom and the dustpan and dispose the waste in the dustbin.

Figure 65: Left: produced char emptied on a plastic or cardboard sheet (T4.7). Right: Clean chimney after removing the soot with the wire brush (T4.9)

Protective measures for workers:

- Pay attention to hands and feet when working with the heavy parts and avoid injuries through squeezing.
- Use dust mask when empting the tubes and cleaning the reactor parts with the wire brush

Points of monitoring and data collection:

- Measure the weight of each filled tube unit before and after pyrolysis. This numbers are needed to calculate the efficiency of the reactor and properties of the char that was produced

5.4. Calculating the energy efficiency

The energy efficiency of a run is an important parameter, especially if the char produced is meant to be used as fuel (i.e. energy carrier) rather than as a soil amendment (biochar). The energy efficiency is calculated with Equation 6.

$$ER = \frac{mass_{char(db)} \cdot HHV_{char\,(db)}}{mass_{LPG} \cdot HHV_{LPG}}$$ **Equation 6**

Where:

- $mass_{char(db)}$: is the dry mass of all char produced. This can be weighted using the scale.
- $HHV_{char\,(db)}$: is the high heating value of the char produced (see Equation 7).
- $mass_{LPG}$: is the mass of LPG consumed. This can be weighted by calculating the weight difference of the LPG cylinder before and after an experiment.
- HHV_{LPG}: is the high heating value of the LPG. Normally around 50 MJ/kg.

The high heating value (HHV) of the char can be calculated in two different ways. HHV can be measured using a calorific bomb. However, these equipment is expensive and not always available. Another simpler and cheaper approach is to calculate the HHV based on the proximate analysis using Equation 7 (Parikh et al., 2005). Proximate analysis of char can be measured according to the standard ASTM D1762 – 84, available online.

$$H\mathrm{HV} = 0.3536 \cdot \mathrm{FC\%_{db}} + 0.1559 \cdot \mathrm{VS\%_{db}} + 0.0078 \cdot \mathrm{ASH\%_{db}}$$ **Equation 7**

Where:

- $FC\%_{db}$: is the fixed carbon content in percent of total solids.
- $VS\%_{db}$: is the volatile solid content in percent of total solids.
- $ASH\%_{db}$: is the ash content in percent of total solids.

Energy ratios of a run should ideally be higher than 1. Otherwise, the run consumed more energy than the one it generated as char.

5.5. Continuous system

Often the reaction process does not provide enough heat to first dry and then pyrolyze the upper barrel. This particularly occurs when the moisture content of the upper barrel exceeds 30 - 35%. The process is sufficient to heat up and dry the feedstock in the upper barrel, but not to pyrolyze it. Consequently, the sequence of tasks explained in Step 3 only applies when the moisture content in the lower barrel is below 10% and in the upper barrel below 30%.

If these conditions are not met, the process needs to be adapted slightly. The reactor system needs to be operated as a continuous system. This implies having at least three reactor barrels. The tasks are the same as the ones explained in Step 3 until the point when the lower barrel ends its pyrolysis process. Then this barrel is removed and put aside to cool down, and the already heated up upper barrel is shifted to the position of the lower barrel and a new barrel with fresh feedstock is added on top. This process can be perpetuated for many repetitions. In next lines the task required for three barrels will be explained:

1. Monitor pyrolysis in the lower barrel: keep an eye to the pyrolysis process in the lower barrel. This can be done by observing the flames with the mirror (Box 3), by checking the colour of the exhaust gases as explained in Box 4, or by checking temperature recordings if thermocouples are used (see Appendix A, Appendix B and Appendix D). Turn off the LPG after ensuring strong pyrolysis in the lower barrel.

   If thermocouples are available, keep an eye to the recordings from the upper barrel. When the temperature remains at around 100°C it means that the feedstock is being dried. It is important to reach this stage since the upper barrel should be dried before shifting it to the lower position.

2. Shifting reactor barrels: once the pyrolysis process is over, the reactor barrels need to be shifted. This needs to be done with caution since the barrels are at very high temperatures. Please use all protective measures.
   a. Remove the chimney (ideally with two people) and leave it aside for a moment.
   b. Lift the upper barrel with the crane and leave it on one side of the furnace for a moment. If the feedstock has already started to pyrolyze, the external wall of the barrel could reach a temperature of 400°C, so a shield might be required to protect the operator form such high temperatures.
   c. Lift the lower barrel with the crane and leave it on the opposite side of- and separated from- the furnace, so that it can start cooling down. If the pyrolysis is over, the temperature will be lower.
   d. Lift the former upper barrel with the crane, and locate it on top of the furnace (if required, use a shield to protect from the high temperatures).
   e. Lift the third barrel and locate it on top of the "new" lower barrel.
   f. Finally add the chimney.
3. Supply of extra heat: during the shift of the reactor barrels, the temperature of the entire reactor system will drop and consequently, the pyrolysis reactions will most likely reduce in intensity and the generated pyrolysis gases will not be combusted. Once the reactor barrels are shifted, additional heat needs to be supplied through the furnace. The LPG required in this second round is much lower since both the furnace and the "new" lower barrel are already preheated and the feedstock in the lower barrel is dried.
4. Monitoring pyrolysis in the "new" lower barrel: this step is again the repetition of step 1. This sequence of steps can be repeated as many times as desired.

Keep in mind that the barrels with the pyrolyzed feedstock need to be cooled down before being emptied. Cooling them down is important, otherwise, the hot char will combust when entering into contact with the ambient oxygen. A good method for a quick reduction of temperature is to hang the reactor barrels from the crane and to let the wind pass through the cavities between the tubes.

6. FINANCIAL ANALYSIS

In this chapter we provide an approximate calculation of the financial viability of such a carbonization reactor. The figures report the costs of materials and labour in Dar es Salaam in 2016.

6.1.Investment costs

Table 6 provides the investment costs of the material used to construct the reactor system whereas Table 7 gathers the time and labour costs of construction.

Table 6: Investment costs of materials to construct the reactor system

Component	Amount	Material	Unit cost (USD)	Total Costs (USD)
Furnace	1	208 L standard oil barrel	18	18
	15	Bricks	0.2	3
	10 kg	Cement bag (10kg)	6	6
	1	Steel rod Ø 8 mm, 2500 mm	5	5
	1	Ring burner	50	50
	1	Steel pipe Ø 40 mm, 300 mm	5	5
	1	Steel plate (1200 mm x 2500 mm) For wind shields and shutters	1	32.5
	Total costs furnace			**134.5**
2 Reactor barrels	2	208 L standard oil barrel	2	36
	4	Steel plate (1200 mm x 2500 mm)	32.5	130
	2	Steel rod Ø 16 mm, 2350 mm	16	32
	2	Chain min. 1020 mm, chain link Ø= 8 mm	3	6
	2	Insulation material	2.5	5
	4	Shackle	1	4
	2	Barrel strap (needed for using the reactor)	2	4
	Total costs 2 reactor barrels			**217**
Chimney	1	Part of 208 L oil barrel(200mm) (leftover from furnace barrel)	-	-
	1	Steel plate (1000 mm x 1000 mm)	10	10
	1	Steel rod Ø 8 mm, 6500 mm	17.5	17.5
	Total costs chimney			**27.5**
Crane	1	Chain block	1	81
	2	Bolts (M16)	2	4
	8	Bolts (M12)	1.125	9
	4	Bolts (M14)	1.5	6
	2	Black pipe 2"	20.5	41
	1	MS Channel 100x55x6mm	52	52
	4	Flanges	9	36
	4	Rollers with bearings	6.75	27
	Total costs crane			**256**
Consumables	3	Boxes, welding sticks	7.5	22.5
	2	Grinding disk	2.5	5
	10	Cutting disks	2.5	25
	5	Sandpaper for metal, 100 grain	0.2	1
	Total costs consumables			**53.3**

TOTAL	**Total costs reactor**	**688.3**

Exchange rate used: 1 USD = 2222 TZS

Table 7: Labour costs for constructing the reactor system

Component	Hours - days required	Unit cost (USD/h)	Total Costs (USD)
Furnace	16 hours = 2 days	0.9375	15
2 Reactor barrels	64 hours = 8 days	0.9375	60
Chimney	8 hours = 1 day	0.9375	7.5
Crane	16 hours = 2 days	0.9375	15
TOTAL	**104 hours = 13 day**		**97.5**

*The labour costs shown here are based on the salary of a technician in Dar es Salaam in 2016.

The previous tables do not consider the costs of safety equipment (i.e. goggles, ear protection and dust mask), or other required tools (i.e. electric grinder, ruler, ladder, scratcher and welding machine) and transportation costs. The total costs of constructing a reactor system are around 790 USD (785.8 USD). These costs could be considerably reduced if the reactor system would be produced in chain production.

6.2.Operational costs

During the process of carbonization we distinguish three elements which contribute to the operational costs: accessing and transporting feedstock to the treatment unit, labour costs and fuel costs of running the batch reaction.

No costs associated to biowaste are considered in this exercise. Table 8 below considers all the other operational costs.

Table 8: Operational costs of the pyrolysis process

	Element	Value	Unit
Fuel costs	Energy type	**LPG**	
	Energy content	46	MJ/kg
	Fuel consumption per run	2 – 3	kg
	Energy unit cost	1.35	USD/kg
	Energy cost per run with two barrels	**2.7 – 4.05**	**USD**
Labour costs	Run duration with double barrel	250 - 350	min
	Daily working hours	8	hours
	# of runs per day	1 - 2	batch/day
	# of workers	1	person(s)
	Salary per hour and person	0.9375	USD/h.
	Total salary costs per run	**3.9 – 5.5**	**USD**
Total Costs	**TOTAL PROCESS COST (per run)**	**6.6 – 9.5**	**USD**
	TOTAL PROCESS COST (per day with 2 runs)	**11 - 15**	**USD**

Observations:

- **LPG Consumption**: it is obvious that the amount of LPG consumed depends on the nature and moisture content of the feedstock in the upper and lower barrels, the combustion efficiency and insulation. However, it was observed that the brand of the LPG cylinders and the fact whether the LPG cylinder was new or not had also a strong influence on the amount of LPG consumed. The first runs with a cylinder always consumed less fuel. This leads us to think that the proportion of gases mixed in such cylinders is not always the same, and that either the gases with a higher HHV are consumed first, or that the cylinders also contain a proportion of low HHV gases which reduce the HHV of posterior runs. Any improvement on those aspects reduces the LPG consumption and consequently the operational costs.
- **Run duration**: the run duration also depends on several aspects such as the nature and moisture content of the feedstock, the calorific value of the fuel, the efficiency of combustion and insulation. Any improvement on those aspects reduces the LPG consumption and consequently the operational costs.

6.3.Revenues

The produced char represents the revenues of such a treatment plant. The revenues depend on the amount of char produced and its market value. The price of charcoal is prone to sudden fluctuations in Tanzania. Between March and November 2017, prices have risen by half in Dar es Salaam, costing around 70,000 TZS per 100 kg bag in November 2017 (Zacharia et al., 2017). The following calculations were therefore done based on three different prices: 400 TZS/kg (0.18 USD/kg), 600 TZS/Kg (0.27 USD/kg) and 800 TZS/kg (0.36 USD/kg), which are based on the lower and higher price estimates for charcoal provided in the Tanzania Biomass Energy Strategy and Action Plan (Camco, 2014).

The table is also calculated for different amounts of input waste. The amount of mass that can be inserted into the reactor depends on the density and particle size of the feedstock. Medium particle size and dense materials (i.e. mango seeds, wood blocks, crashed coconut shells, etc.) enable a higher loading rate than low density materials (i.e. sawdust, cardboard, bagasse, etc.). The biowaste-to-char conversion rate ranges between 30% - 35%. In the table below a value of 32.5% was applied. The HHV of the char briquettes ranges between 25 -28 MJ/kg.

Table 9: Calculation of mass of char output per batch

Parameter	Amount 1		Amount 2		Amount 3	
	Value	Unit	Value	Unit	Value	Unit
Input mass per barrel	20	kg	40	kg	60	kg
Input mass per run (two barrels)	40	kg	80	kg	120	kg
Moisture content	10	%	10	%	10	%
Mass (dry weight)	36	kg	72	kg	108	kg
Mass of char output per batch (two barrels)	13	kg	26	kg	39	kg

Table 10: Potential revenues based on three different amounts and market prices.

			Amount char 1		**Amount char 2**		**Amount char 3**	
			Value	*Unit*	*Value*	*Unit*	*Value*	*Unit*
			13	*kg*	*26*	*kg*	*39*	*kg*
Price 1	*0.18*	*USD/Kg*	2.34	USD	4.68	USD	7.02	USD
Price 2	*0.27*	*USD/Kg*	3.51	USD	7.02	USD	10.53	USD
Price 3	*0.36*	*USD/Kg*	4.68	USD	9.36	USD	14.04	USD

The comparison of Table 8 (operational costs) and Table 10 (revenues) shows that the financial feasibility of the treatment installation is only possible when the charcoal can be sold at the highest price and the reactor is filled with at least 60 kg in each barrel. This poses several challenges as these amounts are not possible with feedstocks with low density. Furthermore, the amortization costs of the installation have not being considered. This would add an additional cost. In the coming lines we propose several adaptations for anyone willing to construct such a treatment plant with the aim of making profit.

7. RECOMMENDATIONS

1) **Adjusting the design of the reactor**: a trade-off between the following two parameters should be found: increasing the reactor capacity and increasing the heat exchange surface of the feedstock.
    a. **Reactor capacity: t**he financial analysis shows that the more dry mass that can be included in the reactor improves the financial profitability.
    b. **Heat exchange area:** the bigger the heat exchange surface, the faster the material will be pyrolyzed. New designs with a bigger number of tubes could be tested. The challenge is finding a design that optimizes both the reactor capacity and the heat exchange area.
2) **Reduce fuel consumption:**
    a. **Insulation:** improving on the efficiency of the insulation system could contribute considerably to reduce the duration of each run and the fuel consumption, ultimately reducing the operational costs.
    b. **Choice of good fuel:** choosing a feedstock will contribute to reach the pyrolysis conditions faster, and switching off the fuel supply sooner. The most desired characteristic for the feedstock is to have an as low moisture content as possible. Getting rid of the water contain in the feedstock consumes a big part of the energy. Furthermore, other ideal characteristics are having a high fixed carbon content, and consequently a high heaving value (HHV).
    c. **Alternative fuels:** alternatively, other fuels could be used. It is worth exploring other furnace designs which enable accommodating part of the generated char or even dried biowastes as fuels. This could considerably reduce the fuel expenses. For such purpose, a new furnace would have to be constructed. A grid to hold the char should be mounted above the secondary air inlets, 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 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.

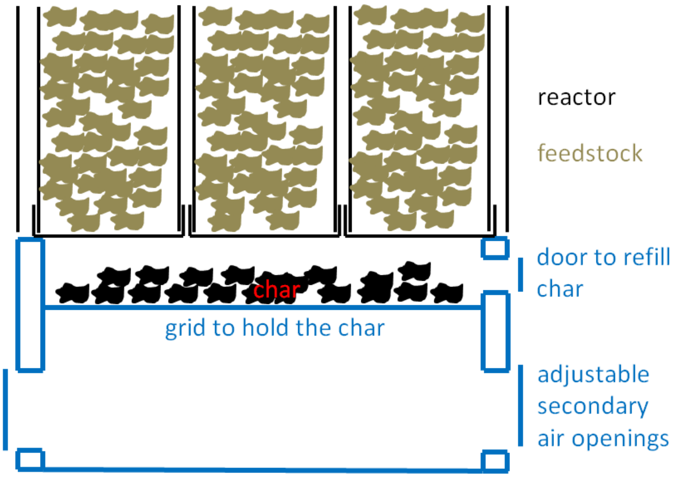


Figure 66: furnace fired with char

3) **Insulation:** using insulation presents advantages and disadvantages.
   a. **Reduce fuel consumption:** as mentioned above, the use of insulation increases the efficiency of the process, reducing the needs for fuel consumption.
   b. **Increase number of runs per day:** as mentioned, the duration of each run could be reduced by improving on the efficiency of the insulation system, allowing running more than one run per day. This increases the yield of each unit of salary costs invested and therefore the profitability of the treatment process.
   c. **Reduce lifetime of reactor system:** the use of insulation increases the temperatures achieved, consequently reducing the lifetime of the barrels if the reactor system is built with standard oil barrels. The metal starts presenting cracks and holes after 10 rounds, whereas without insulation it could last at least 50 rounds. This has a direct impact on the investment costs and payback durations. An alternative would be to build a reactor with more durable materials such as stainless steel.
4) **Combustion conditions:**
   a. **Reactor design:** rethinking the design of the reactor in order to fine tune the three important combustion characteristics 3T-s (time, temperature and turbulence) can also be considered.
   b. **Heating up secondary air:** options to heat up the secondary air before injecting it in the furnace could increase the efficiency of the system.

5) **Better handling:**

   a. **Procedure of loading and unloading** a reactor could be facilitated by adding two handles on both sides of the barrel. 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.

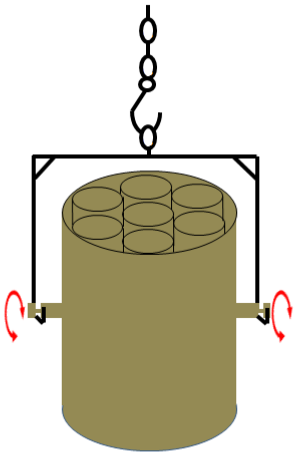


Figure 67: sketch for new reactor, improving the handling

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Appendix A: Additional technical equipment

The additional equipment explained in this annex is not essential for the operation of the reactor system. However, its use can improve the overall efficiency of the pyrolysis and combustion process. This equipment is recommended whenever the pyrolysis conditions and combustion process need to be monitored. This might be the case if the reactor is used for experimental purposes.

LambdaCheck®

The lambda sensor serves to monitor the residual oxygen in the exhaust gas in the chimney, which serves as important indicator of the combustion conditions in the reactor. If the residual oxygen in the exhaust gas is lower than 4 – 6% there is not enough air (oxygen) for a complete combustion, and consequently, harmful gases such as CO and volatilized tars are generated.

If the percentage is higher, the volume of secondary air is higher than the required. Every volume unit of secondary air in excess consumes heat that will not be used to heat up, dry and pyrolyze the feedstock. Instead it drops the temperature of the combustion zone, affecting negatively to one of the 3T-s required for good combustion conditions (i.e. temperature), and should therefore be avoided.

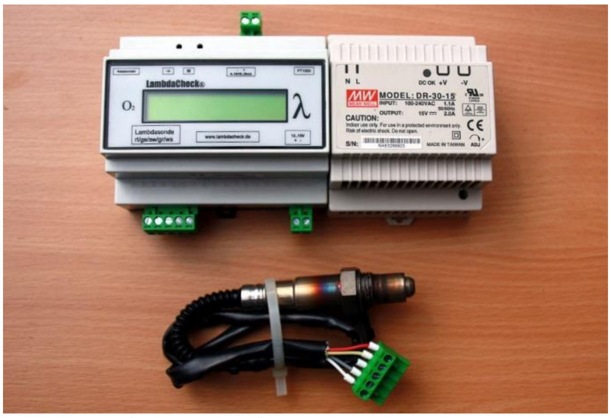


Figure 68: Overview of the lambda sensor

The LambdaCheck unit is a simple set made of a lambda sensor, the LambdaCheck-Module and 230 V to 12 V power converter. It costs around 235 USD.

Thermocouples

The information about the temperature of the feedstock is the key element of running a successful pyrolysis process. Thermocouples are temperature measuring gadgets. They are connected to the PicoLog hub (Figure 70) and the computer. The collected data allows visualising the pyrolysis process with graphs and figures.

Figure 69: Overview of the thermocouples used.

The thermocouples shown here are type K thermocouples which belong to the thermoelectric sensors. Each of these thermocouple costs around 55 USD. However also other thermocouples (analog) can be used, making sure they can withstand temperatures up to 800°C.

Data logger


Figure 70: PicoLog data logger

A data logger is only needed when using thermocouples to measure the temperature. The data logger records the data over time and allows visualizing the data via an external instrument. The data logger used in this guide is a PicoLog and runs with the PicoLog software on a computer. Appendix C and Appendix D detail how to install and operate the software. This model costs around 400 USD.

Laptop

A laptop is needed when using thermocouples combined with a data logger (like PicoLog) and software. In general it is not necessary to have a laptop to run the reactor. But it is very helpful to visualize the pyrolysis process with the temperature data and spot weaknesses in operating the process by analysing the date and figures (figure C2-4)

Appendix B:

Setting up measurement equipment and data logger

Providing the equipment explained in appendix A is used, two main aspects of the reaction can be monitored: the temperature and the residual oxygen in the exhaust gas. Three thermocouples can be used to monitor the temperature. One is located at the lower end of the chimney exhaust pipe. The other two are located each in the centre tube of the tube unit of the upper and the lower reactor barrel. At least one thermocouple per central tube in each reactor barrel is recommended.

This section explains how these monitoring gadgets are installed.

Equipment needed:

Figure 71: Left: PicoLog hub with USB-cable. Middle: Laptop with PicoLog software. Right: LambdaCheck unit (top) and the sensor (bottom) to measure the residual oxygen.

Tasks:

T1: **Construction hints:** when constructing the reactor system, a few additional steps need to be added if thermocouples and a lambda sensor are to be used. First a hole should be drilled through the wall of the reactor barrel, which should be aligned with a second hole, previously drilled in the middle tube. A thermocouple will be inserted, through this wall, between two of the tubes (see Figure 73) into in the middle tube. This enables monitoring the temperature of the feedstock in the middle tube of the reactor barrel.

Figure 72: Insertion of the thermocouple through the barrel wall

Figure 73: Thermocouple in the interior of the barrel.

Furthermore, two additional holes need to be drilled in the lower end of the chimney. One will be used for the lambda sensor and the other one for a thermocouple (see Figure 74). If a lambda sensor is installed, this should be done without interfering with the movement of the shutter element. Drill a hole of 20 mm of diameter in the exhaust pipe, 100 mm above plate "A". A nut (M18x1.5) was welded in a 15° angle on top of the hole allowing installing the lambda sensor with its head pointing downwards. Install the lambda sensor in such a way that the sensor head is well exposed to exhaust gases to be measured in the interior of the chimney. The connection of the sensor should be so tight that no false air can be sucked in (measurement falsification).

T2: **Mounting the reactor system:** the thermocouples of the barrels should be inserted before mounting them on top of the furnace, as shown in Figure 72. Then, when mounting both barrels and the chimney on top of each other, it is recommended to turn them until the thermocouples point in the direction where you have your computer. Once the reactor system is mounted, insert the last thermocouple in the chimney (see Figure 74).

Note: two people are required to install the chimney if a lambda sensor is used. One person is lifting the chimney on the upper barrel while the other person makes sure the Lambda sensor is in the right position to connect it to the LambdaCheck unit (Figure 74).

Figure 74: Connecting the Lambda sensor and the thermocouple to the chimney.

T3: **Connect the Lambda sensor**: after inserting the lambda sensor in the chimney, it now needs to be connected to the LambdaCheck unit. The cable of the sensor is not long enough and it is of upmost important to keep the cable and the LambdaCheck unit far from the hot reactor wall. A solution is to hang the LambdaCheck unit from the hook of the crane and connect the lambda sensor plug to it (see Figure 75). Plug in the 230 V plug for power. The Lambda sensor is now heating up for 30 seconds and after that ready for use.

Figure 75: LambdaCheck hanged from the crane (S2-1)

T2: **Connect the PicoLog to the computer:** Place the PicoLog hub and the laptop on a table. Ensure that the table is sufficiently distant from the reactor, since the heat radiation might damage the electronics of the equipment.

T3: **Connect the thermocouples to the PicoLog hub:** make sure the larger pins are on the left hand side of the plug when plugging in the thermocouples. Pay attention to the cable of the thermocouples and check they are not touching the reactor barrels. Connect the PicoLog hub with the USB cable to the laptop.

Figure 76: Connecting thermocouples to PicoLog hub (T2.3)

T4: **Set up the PicoLog recorder for the new run**: a detailed step by step installation and set-up for the PicoLog reader is described in Appendix C and Appendix D. After setting up the PicoLog reader the reactor is ready to be operated.

Operating the lambda sensor

The lambda value has to be maintained between 4 % and 6 % oxygen to run the pyrolysis process most efficiently. There are a few critical moments where special attention needs to be given to the Lambda sensor:

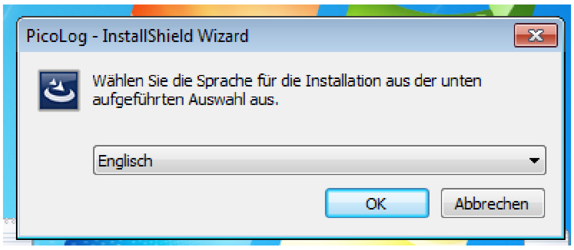
- **First ignition of flame (fuel):** oxygen within the reactor is probably high at the beginning. Therefore, watch the LambdaCheck monitor and slightly open the shutters of the chimney and close the shutter at the furnace until the oxygen content is drops to 4% and 6%.
- **Drying phase:** in this phase the lambda sensor value fluctuates and needs to be adapted by adjusting the shutters so that it remains between 4% - 6%. By rule of thumb the shutters have to be more open the closer the drying process is to end.
- **Transition from lower to upper reactor:** in this transition phase from the pyrolysis process of the lower to the pyrolysis process of the upper barrel the lambda value is a very important indicator. If the shutters are too wide open, the secondary air flow will increase, which leads to an increase in the lambda value and a temperature drop of the reactor which might lead to an incomplete pyrolysis in the upper barrel. Closing the shutter too much leads to a suffering combustion and the production of smoke and soot. In the transition phase the lambda value should be maintained at 6 % oxygen and therefore, constantly adjusted since the conditions vary continuously.

At the end of a run, disconnect the PicoLog from the laptop and the LambdaCheck from the electricity. Pack and store the equipment before starting to dismantle the reactor system.

Appendix C: Installing PicoLog Software

1. Double click on the PicoLog-Icon to start the installation Wizard.

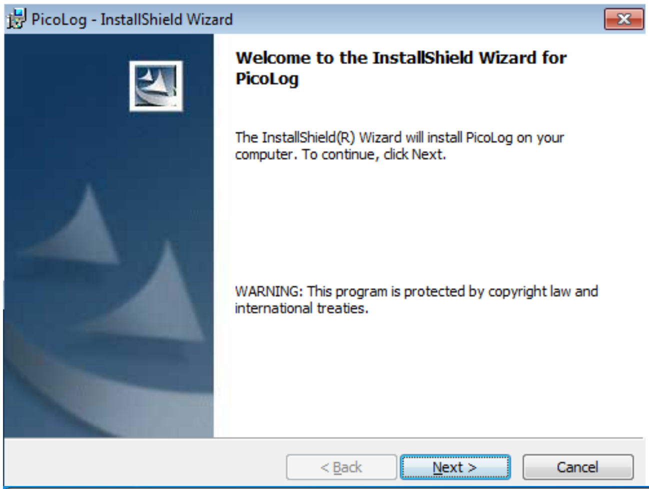
2. Choose the preferred language (English is recommended) and click "OK".



Wählen Sie die Sprache für die Installation aus der unten aufgeführten Auswahl aus.

Englisch

3. Now the "PicoLog-InstallShield Wizard" opens. Click "Next".

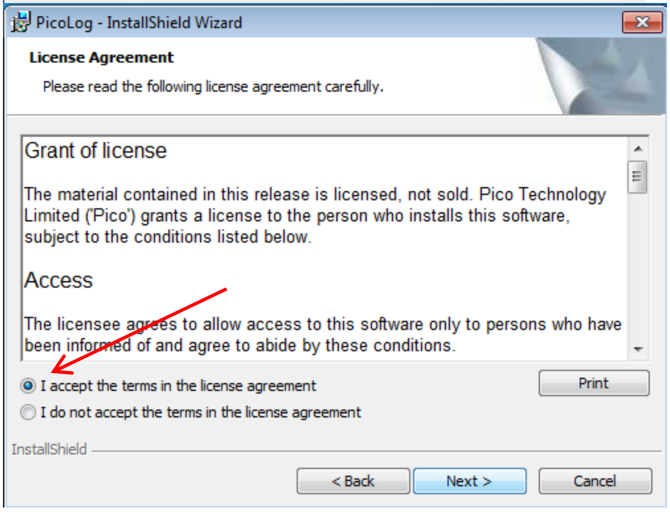


Welcome to the InstallShield Wizard for PicoLog

The InstallShield(R) Wizard will install PicoLog on your computer. To continue, click Next.

WARNING: This program is protected by copyright law and international treaties.

4. As next accept the terms in the license agreement and click "Next".



License Agreement

Please read the following license agreement carefully.

Grant of license

The material contained in this release is licensed, not sold. Pico Technology Limited ('Pico') grants a license to the person who installs this software, subject to the conditions listed below.

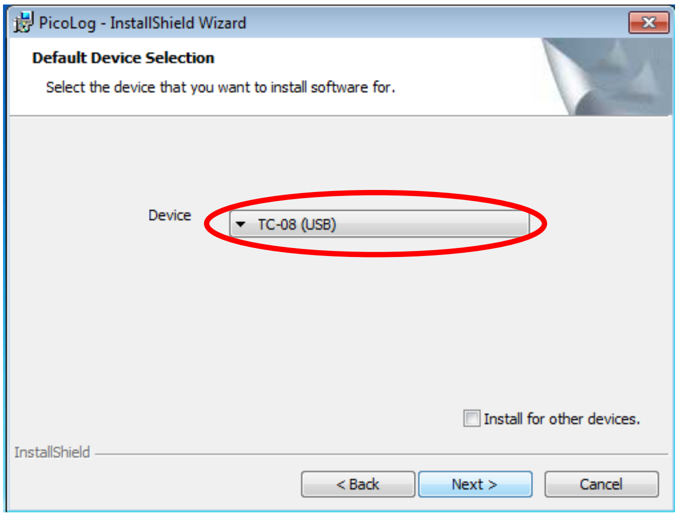
Access

The licensee agrees to allow access to this software only to persons who have been informed of and agree to abide by these conditions.

● I accept the terms in the license agreement

○ I do not accept the terms in the license agreement

5. Now chose the right software. In our case it is the **TC-08 (USB).** Click therefore on the small arrow in the drop down menu and select the **TC-08 (USB)** and click "Next".



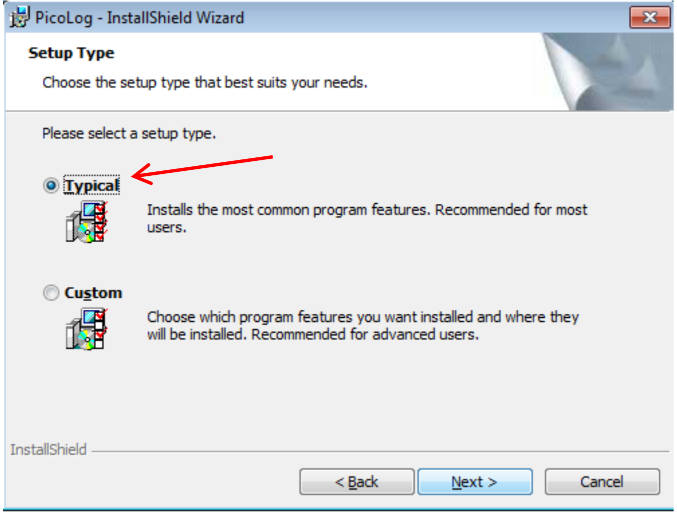
Default Device Selection

Select the device that you want to install software for.

Device: TC-08 (USB)

☐ Install for other devices.

6. Choose the setup type. Here "**Typical**" is recommended. Click "Next".



Setup Type

Choose the setup type that best suits your needs.

Please select a setup type.

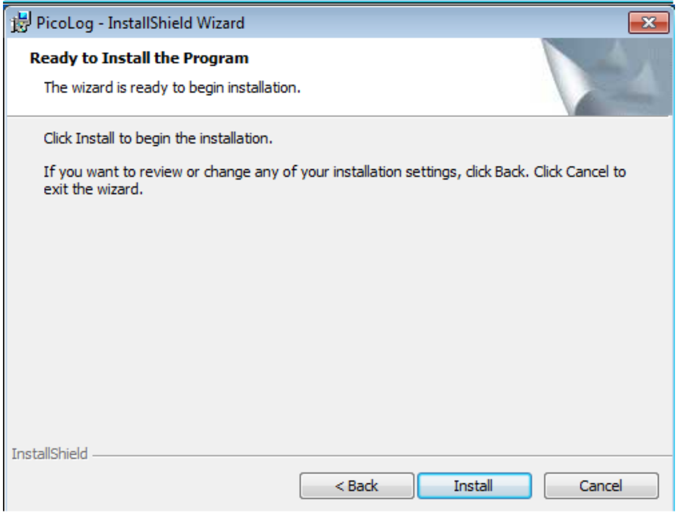
● **Typical**

Installs the most common program features. Recommended for most users.

○ **Custom**

Choose which program features you want installed and where they will be installed. Recommended for advanced users.

7. Now click "**Install**" to start the installation of the PicoLog software. After the installation click "**Finish**" and the InstallShield Wizard will automatically close.



Ready to Install the Program

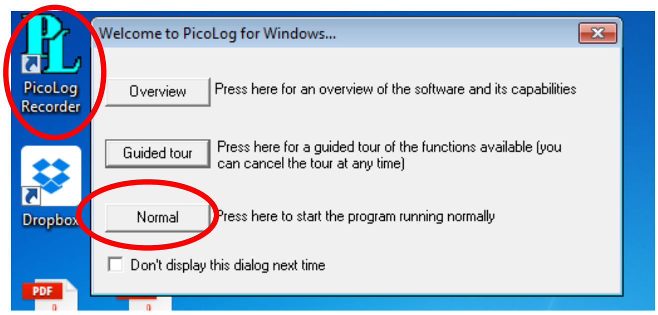
The wizard is ready to begin installation.

Click Install to begin the installation.

If you want to review or change any of your installation settings, click Back. Click Cancel to exit the wizard.

Appendix D: Using PicoLog recorder

1. To open the PicoLog recorder double click on the PicoLog icon on the desktop. Then click on the button “**Normal**” to start the program.



Welcome to PicoLog for Windows...

Overview: Press here for an overview of the software and its capabilities

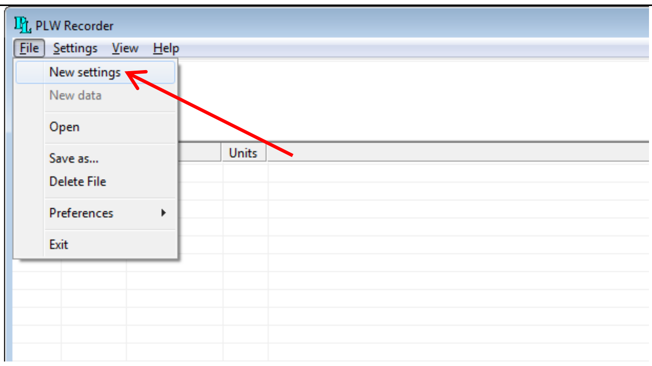
Guided tour: Press here for a guided tour of the functions available (you can cancel the tour at any time)

Normal: Press here to start the program running normally

☐ Don't display this dialog next time

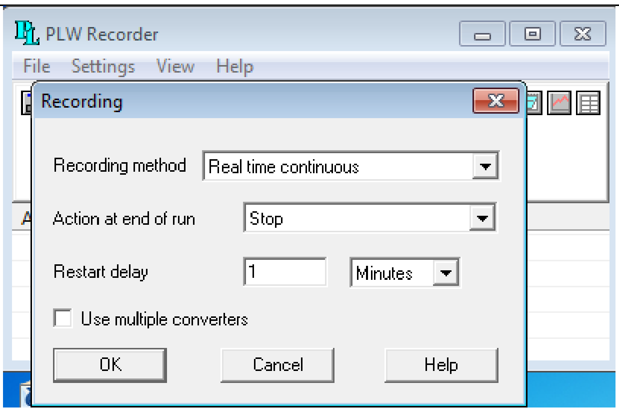
---

2. The Window “PLW Recorder” appears which is the regular PicoLog recorder. To set up a new experiment go to File→ **New settings**



---

3. Then the Window “Recording” appears. Chose the settings seen in the picture and click “**OK**”.



Recording

Recording method: Real time continuous

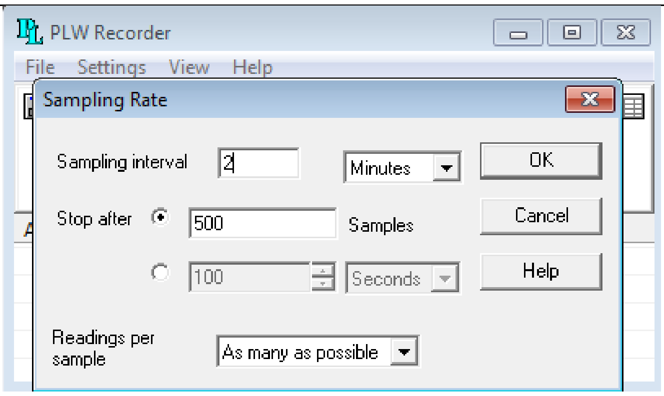
Action at end of run: Stop

Restart delay: 1 Minutes

☐ Use multiple converters

---

4. Automatically the Window “Sampling Rate” appears. Chose the settings seen in the picture and click “**OK**”.



Sampling Rate

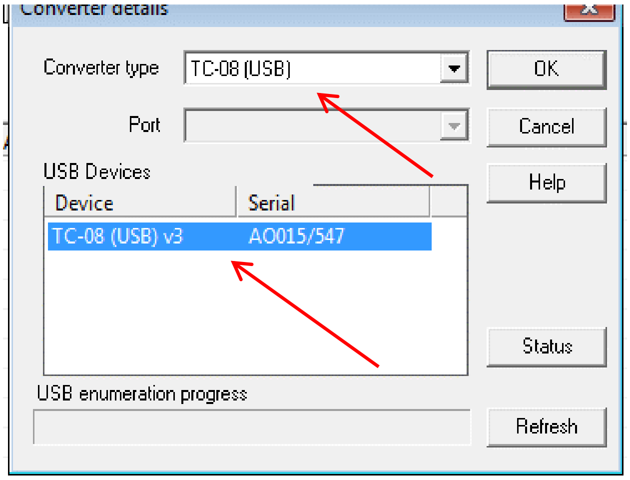
Sampling interval: 2 Minutes

● Stop after 500 Samples

○ 100 Seconds

Readings per sample: As many as possible

5. Automatically the Window "Converter details" appears. In the drop down menu choose the settings seen in the picture. It is important that the correct driver is selected (USB). Click "**OK**" to continue.



Converter details

Converter type: TC-08 (USB)

Port:

USB Devices

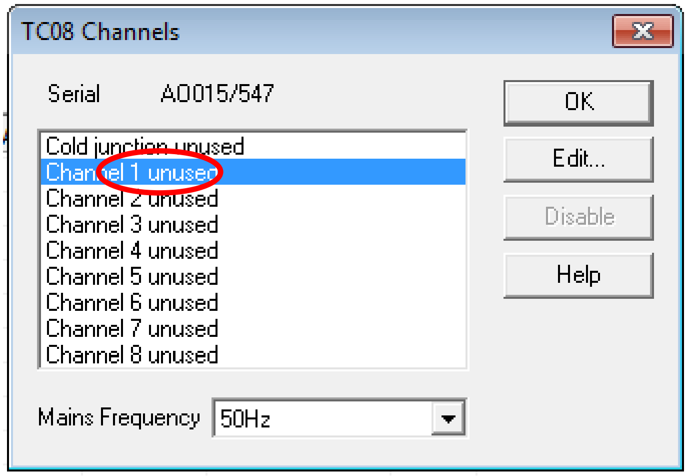
Device	Serial
TC-08 (USB) v3	A0015/547

USB enumeration progress

---

6. Now the window "TC08 Channels" opens. Choose the channels where the thermocouples are plugged in. Click "**Edit**" to do the necessary settings.

7. Note: in this window all the channels have status "unused" even if there is a device plugged in or not!



TC08 Channels

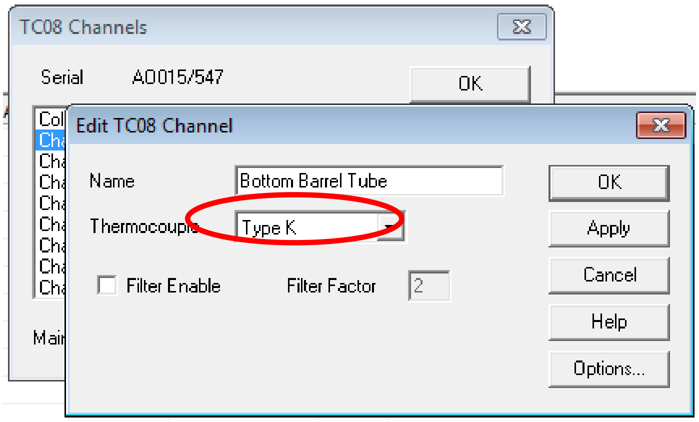
Serial A0015/547

Cold junction unused
Channel 1 unused
Channel 2 unused
Channel 3 unused
Channel 4 unused
Channel 5 unused
Channel 6 unused
Channel 7 unused
Channel 8 unused

Mains Frequency: 50Hz

---

8. Name the channel in the "Edit-Window". For this reactor it is recommended to call the channels after the position the temperature is measured.
9. As next choose the type of the thermocouple. We use **Type K** thermocouples.
10. Press "OK" to return to the previous window to edit the other channels.



Edit TC08 Channel

Name: Bottom Barrel Tube

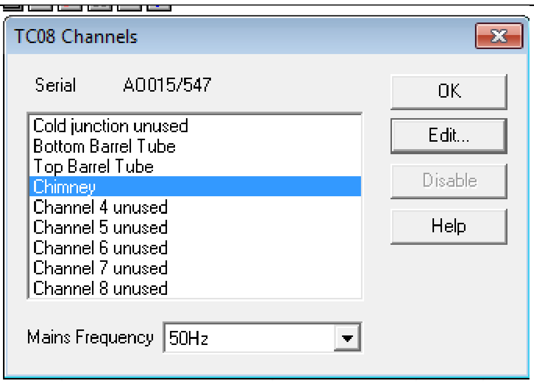
Thermocouple: Type K

☐ Filter Enable

Filter Factor: 2

---

11. After editing the channels click "**OK**" to close the Window and return to the PLW Recorder



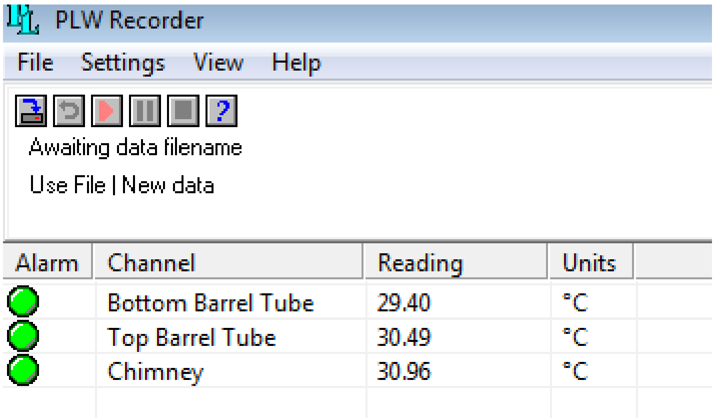
TC08 Channels

Serial A0015/547

Cold junction unused
Bottom Barrel Tube
Top Barrel Tube
Chimney
Channel 4 unused
Channel 5 unused
Channel 6 unused
Channel 7 unused
Channel 8 unused

Mains Frequency: 50Hz

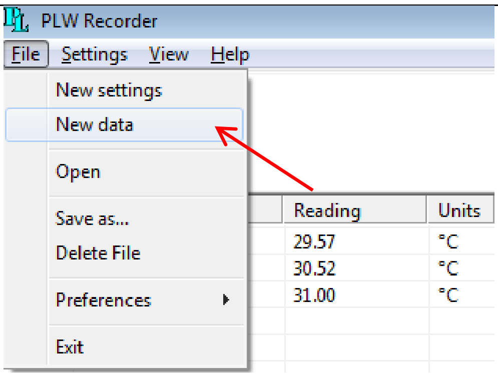
12. Now the previous edited channels should be seen in the exact order and with the names that have been given before.



Awaiting data filename
Use File | New data

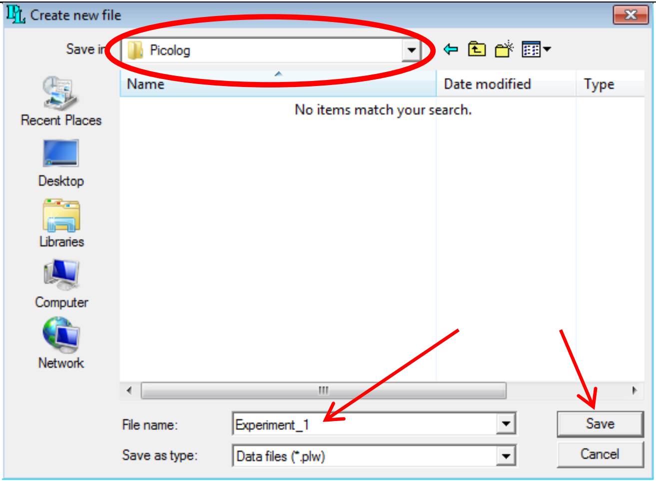
Alarm	Channel	Reading	Units
●	Bottom Barrel Tube	29.40	°C
●	Top Barrel Tube	30.49	°C
●	Chimney	30.96	°C

13. Create a new data file to run an experiment. Therefore go to **File→ New data**



Reading	Units
29.57	°C
30.52	°C
31.00	°C

14. The window "**Create new file**" appears. Select or create a path where the PicoLog-file should be stored. Name the file and click "**Save**" and automatically return to the PLW Recorder.



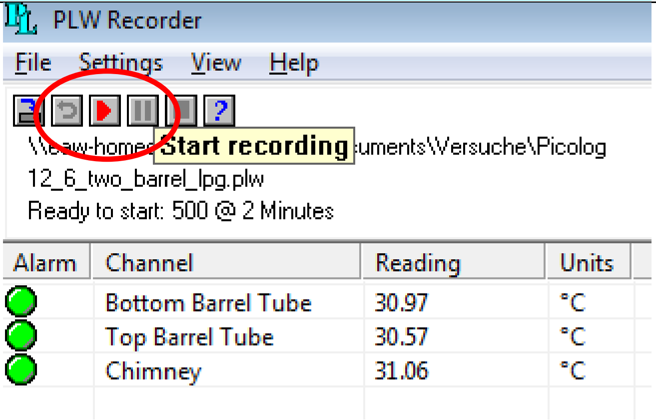
Save in: Picolog

No items match your search.

File name: Experiment_1

Save as type: Data files (*.plw)

15. To start the experiment and the recording just click on the **play button**.



\\[illegible]aw-home[illegible]uments\Versuche\Picolog
12_6_two_barrel_lpg.plw
Ready to start: 500 @ 2 Minutes

Alarm	Channel	Reading	Units
●	Bottom Barrel Tube	30.97	°C
●	Top Barrel Tube	30.57	°C
●	Chimney	31.06	°C

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We start from the premise that creating value from biowaste can trigger improvements in sustainable waste management practices and impact of the well-being of dwellers in low- and middle-income settings.

This publication provides knowledge on a low-tech and cheap technology alternative for slow pyrolysis. There are numerous ways to design and operate a slow pyrolysis unit. Typically it requires a single, homogenized and dry material as feedstock. The primary goal of this manual however, is to show that urban biowaste can be used. The output, the char, can be used as renewable fuel but also as soil amendment (biochar) given its beneficial impacts on the soils and their fertility.

This manual is for practical use. It lists all materials, equipment and actions that are required to build and operate a reactor. The design of the reactor is based on using locally available construction material and equipment and relies of human labour instead of automation.

This manual targets readers with little basic knowledge of waste management in general and slow pyrolysis in particular, but who have the willingness to work with waste and to implement and operate such a facility.