CENTRE FOR RESEARCH IN ENERGY AND ENERGY CONSERVATION

Sludge to Energy Enterprises in Kampala (SEEK)

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Gasification of faecal sludge and biowaste pellets in Kampala, Uganda

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Executive summary

Sludge to Energy Enterprises in Kampala (SEEK) is a project conducted by the Swiss Federal Institute of Aquatic Science and Technology (Eawag), Bioburn AG, the Centre for Research in Energy and Energy Conservation (CREEC), Makerere University and the National Water and Sewerage Corporation (NWSC). This project explores the use of faecal sludge (FS) for electricity production by gasification. As part of the project, CREEC investigated the performance of a conventional 10 kW downdraft moving bed gasifier from All Power Labs, Berkeley, USA, using pellets containing different FS percentages, ranging from 0 wt% to 100 wt%. The pellets were produced with a Bioburn pelletizer and analysed for their heating value and ash content in at Eawag and Makerere University. All experiments were conducted within the specified reactor temperature of 800 °C to 1,000 °C.

Experiments with pellets containing sawdust or coffee husks showed the possibility of gasifying pellets of this size and density produced with the pelletizer. A stable operation of the gasifier over several hours with pellets containing FS was not possible. Operation of the gasifier with pellets from 100% FS was not possible at all due. The formation of agglomerates was a problem in two experiments, probably caused by a quick temperature increase over the sintering temperature of the pellets and not directly related to the composition of the pellets.

The gasification of pellets containing FS is possible, although the high ash content combined with the low heating value makes it difficult. In most of the experiments the produced syngas had an insufficient quality to run the internal combustion engine at a reasonable voltage output. Gasification of pellets containing 65 wt% FS, however, yielded an acceptable quality of the produced gas resulting in a stable voltage output of 220 V.

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List of Abbreviations

APL	All Power Labs
C	Carbon
°C	Degree Celsius
Cm	Centimeter
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CREEC	Centre for Research in Energy and Energy Conservation
Eawag	Swiss Federal Institute of Aquatic Science and Technology
FS	Faecal Sludge
FSM	Faecal Sludge Management
G	gram
H_2	Hydrogen
H_2O	Water
Kg	Kilogram
kW	Kilowatt
kW_{th}	Kilowatt thermal
m^3	Cubic meter
mbar	millibar
min	minutes
MJ	Megajoule
MW	Megawatt
MW_{el}	Megawatt electrical
MW_{th}	Megawatt thermal
NWSC	National Water and Sewerage Corporation
SEEK	Sludge to Energy Enterprises in Kampala Project
V	Volt
wt	Weight

1. Introduction

In most developing countries around the world, poor sanitation cause diseases and are an obstacle for development (Tumwebaze et al., 2013). Furthermore, energy of good quality, i.e. electricity, is an essential factor for development. The energy demand in developing countries increases rapidly and an environmental friendly source should be provided (Ginley et al., 2011).

Over 90% of the energy consumed in Sub-Saharan Africa stems from burning biomass (UNDP, 2013). Only 11% of the Ugandan population had access to electricity in 2010, but it is targeted to increase to 80% by 2040 (Government of Uganda, 2007). To manage this transition from burning biomass to the usage of electricity in a responsible way, renewable energies need to be promoted. Most of Uganda's electricity comes from two hydropower plants along the Nile river with a power of 630 MW_{el} in total and two thermal power plants with 50 MW_{el} each (Apire et al., 2012). A number of small hydropower plants (< 50 MW) and small thermal power plants (< 50 MW) contribute to the electrification of rural areas.

As in many developing countries, a majority of the population in Uganda uses onsite sanitation technologies such as pit latrines and septic tanks. In Kampala, the capital city, only 7% of households are connected to the sewer system, the rest uses onsite sanitation technologies (Muspratt et al., 2014). The faecal sludge (FS) coming from onsite sanitation technologies is often not treated properly. Usually it ends up in poorly managed landfills or is dumped directly into the environment. This jeopardizes the public and environmental health directly and indirectly by contaminating the ground water (Strande, 2011). Therefore, sustainable faecal sludge management (FSM) is essential and can help improving the living standard of the population.

Different approaches for handling FS exist. Beside co-incineration in e.g. cement kilns as it is done in Europe, Japan and in the USA (Strande, 2011; Murakami et al., 2009; Kaltschmitt et al., 2009), anaerobic digestion, pyrolysis or gasification are possibilities to recovery energy from FS (Kaltschmitt et al., 2009). A study performed at the National University of Singapore showed that wastewater sludge can be co-gasified with woody biomass (Ong et al., 2015).

The Sludge to Energy Enterprises in Kampala (SEEK) project conducted by the Swiss Federal Institute of Aquatic Science and Technology (Eawag), Bioburn AG, the Centre for Research in Energy and Energy Conservation (CREEC), Makerere University and National Water and Sewerage Corporation (NWSC) addresses these two major topics. Previous studies showed that FS has an economical value and could be used as a renewable fuel. The calorific value of FS of up to 17 MJ/kg dry mass is comparable with other biomass fuels, e.g. rice husks (Muspratt et al., 2014). By processing FS into fuel pellets and subsequent gasification, a sustainable management of FS could be established.

Although gasification is not a new technology it expanded in the last years due to the increasing cost for fossil fuels. It allows a higher conversion efficiency than conventional coal fired power plants and allows using organic waste such as municipal wastes or biomass (Higman et al., 2008). The thermochemical gasification of biomass takes place at a temperature of more than 800 °C. A gas mixture (so-called syngas) containing mainly H_2 and CO is produced, which can be burned directly, used in an internal combustion engine (including gas turbines) or processed further as a feedstock for the chemical industry (McKendry, 2002-1).

This part of the SEEK project focuses on the gasification of FS pellets. A small 10 kW gasifier from All Power Labs (APL), Berkeley, USA, was used for the tests. Pellets from FS in combination with different other feedstocks, such as coffee husks or sawdust, were produced and tested in the gasifier. The goals were to investigate the feasibility of gasifying pellets containing FS as well as to determine a maximal FS content of the pellets, which allows a reliable operation of the internal combustion engine.

2. Literature review

2.1 Biomass

Several definitions of biomass can be found. The relevant definition used here was formulated by the United Nations Framework Convention on Climate Change:

"Biomass means non-fossilized and biodegradable organic material originating from plants, animals and micro-organisms. This shall also include products, by-products, residues and waste from agriculture, forestry and related industries as well as the non-fossilized and biodegradable organic fractions of industrial and municipal wastes. Biomass also includes gases and liquids recovered from the decomposition of non-fossilized and biodegradable organic material." (UNFCCC, 2005)

Biomass stemming from plants is formed by photosynthesis, involving the interaction between the plant itself, sunlight, water and CO_2 (Basu, 2010). The energy of the sun is stored in the chemical bonds of the organic matter (McKendry, 2002-2). Animals and humans grow by consuming the energy stored in the plants (Basu, 2010).

By burning biomass, no additional CO_2 is introduced into the atmosphere and it is therefore considered as a greenhouse gas neutral energy source (Basu, 2010). Between 10% and 14% of the world's energy consumption stems from biomass (McKendry, 2002-2). The heating value of biomass, however, depends strongly on the kind of biomass used and not all types of biomass are suitable for gasification (Speight, 2014).

2.2 Gasification

The presented summary of the different types of gasifiers is based on information found in various literature (Higman et al., 2008 and Basu, 20110 and Speight, 2014 and Fang et al., 2015 and Stevens et al., 2011).

Gasification in general means the conversion of a solid fuel into synthetic gas (syngas) consisting mainly of hydrogen, carbon monoxide and carbon dioxide. In contrast to pyrolysis, an oxidation medium (air, O_2, H_2O) is needed as well as a source of thermal energy for the endothermic reactions. The heat can come from partial oxidation of the feedstock (auto-thermal gasification) or can be provided externally (allo-thermal or indirect gasification) by a heat exchanger. The most important reactions during gasification are the following:

$$C + H_2O + heat \rightleftarrows CO + H_2 \tag{1}$$

$$C + 2\,H_2O + heat \rightleftarrows CO_2 + 2\,H_2 \tag{2}$$

$$C + CO_2 + heat \rightleftarrows 2\,CO \tag{3}$$

$$C + 2\,H_2 \rightleftarrows CH_4 + heat \tag{4}$$

$$CO + 3\,H_2 + heat \rightleftarrows CH_4 + H_2O \tag{5}$$

$$CO + H_2O + heat \rightleftarrows H_2 + CO_2 \tag{6}$$

The produced syngas can be used as a surrogate for natural gas in different applications. By transforming the syngas into chemical building blocks, a wide range of applications is possible, for example in the textile, food or health industry. By producing liquid fuels from syngas, an application in the conventional transportation sector is possible. By using a renewable feedstock, the produced gas has a low carbon foot print.

The three main gasifier types are: (i) fixed/moving bed, (ii) fluidized bed and (iii) entrained flow. Figure 2.1 depicts these three types. Only the fixed bed gasifier is used for small units with a thermal power input from 10 kW_{th} to 10 MW_{th}. The left of the figure shows two different types of moving bed reactors (updraft and downdraft). Fluidized bed gasifiers are used for 5 MW_{th} to 100 MW_{th} and entrained flow gasifiers for units with a thermal power input > 50 MW_{th}.

According to Higman et al. (2008), the gasification of biomass is considered as especially problematic compared to other feedstocks due to the comparatively low ash melting point and the high tar content.

In general, small-scale gasification appears to be more sensitive to the feedstock characteristics in comparison to large-scale gasifiers. They require a homogeneous fuel size, high calorific value, and low ash and moisture content.

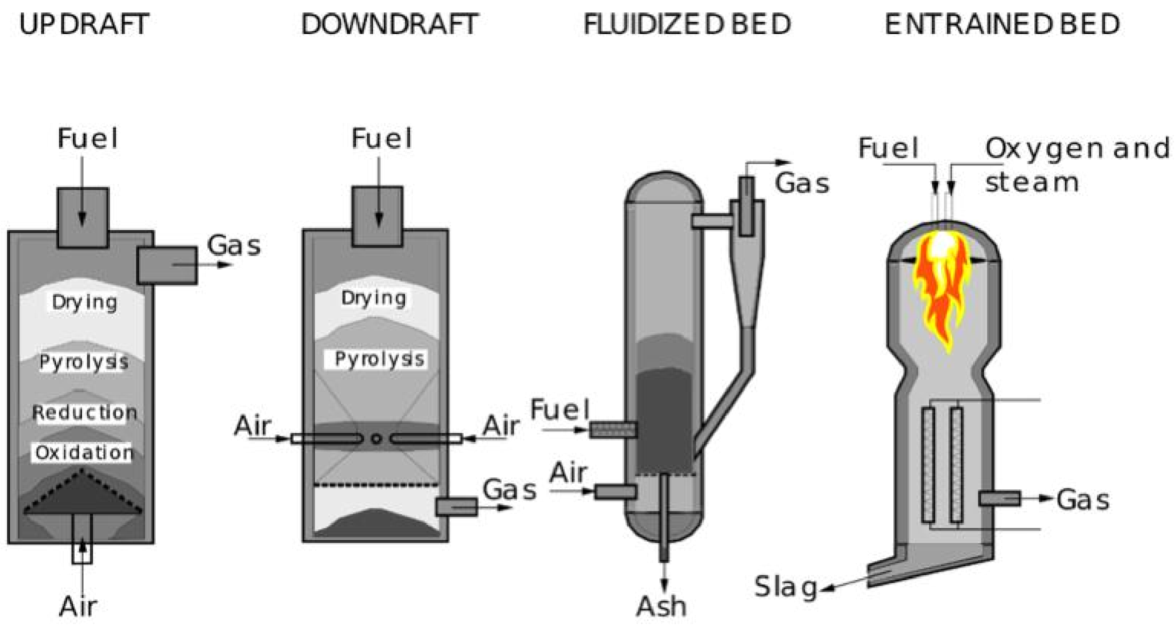

Figure 2.1: Moving bed (updraft and downdraft), fluidized bed and entrained bed gasifiers taken from Le Chien (2012)

Moving bed gasifiers

The moving bed gasifier is the oldest gasifier type. Three different operation modes can be distinguished:

- Co-current or downdraft gasifier
- Counter-current or updraft gasifier
- Cross-current or cross-draft gasifier

These types of gasifiers are cheap to build and therefore used for biomass gasification in small-scale units all over the world, especially in remote areas and in developing countries. Although a number of moving bed reactors were designed for biomass, they usually work only on a specific type of fuel. They are further prone to agglomerations due to the high temperature in the combustion zone, which decreases their reliability.

▪ *Downdraft gasifier:*

In a downdraft moving bed gasifier, the gasification agent is moving in co-current configuration with the solid fuel. Figure 2.2 depicts a schematic of such a reactor. This type of gasifier is easy to control but has higher quality demands on the feedstock than the counter-current gasifier. A moisture content below 25 % is necessary. The biggest advantage of this type is the high tar conversion since the produced gas has to go through the hot zone. This also allows an unproblematic use of the gas in an internal combustion engine. The thermal efficiency is however lower than in a counter-current gasifier due to the high exit temperature of the produced gas. By using a heat recovery unit, a similar thermal efficiency as in a counter-current gasifier can be reached.

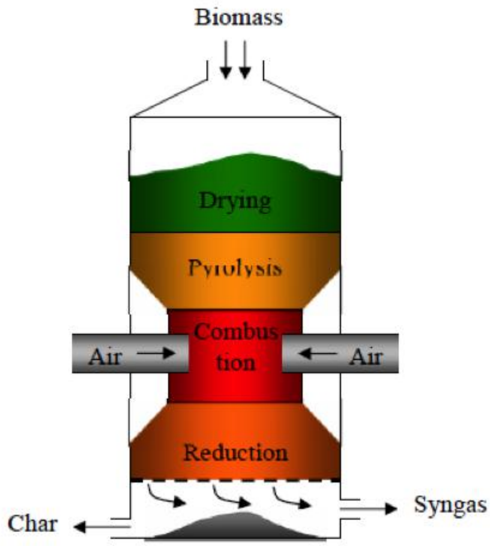

Figure 2.2: Downdraft gasification process
taken from Le Chien (2012)

▪ *Updraft gasifier:*

The feedstock and the gas are moving in a counter-current mode (see Figure 2.1, outer left). The gasifier can be operated with higher moisture contents in the feedstock than in the downdraft gasifier as the feedstock is dried by the hot gas being produced. This results in a high thermal efficiency since the produced gas leaves the reactor at a comparable low temperature. A high moisture content in combination with a high possible ash content of the feedstock makes such a configuration especially favourable for biomass. However, the tar content in the produced gas is considerably higher than in the produced gas from the co-current gasifier.

▪ *Cross-draft gasifier:*

In a cross-draft gasifier the air is injected through nozzles on the side of the gasifier, resulting in a high temperature combustion zone. The produced gas exits on the opposite side of the reactor. Figure 2.3 shows a cross-draft gasification reactor with indicated zones of gasification, pyrolysis and drying of the feedstock. This type of reactor is primarily used for gasification of charcoal with a low ash content but is also used for small-scale biomass units. Due to the low tar production, this reactor can be used in combination with a small internal combustion engine for electricity production. The disadvantages, such as high gas exit temperature, low CO_2 reduction and high gas flow velocity, however outweigh in most cases the advantages of this reactor type.

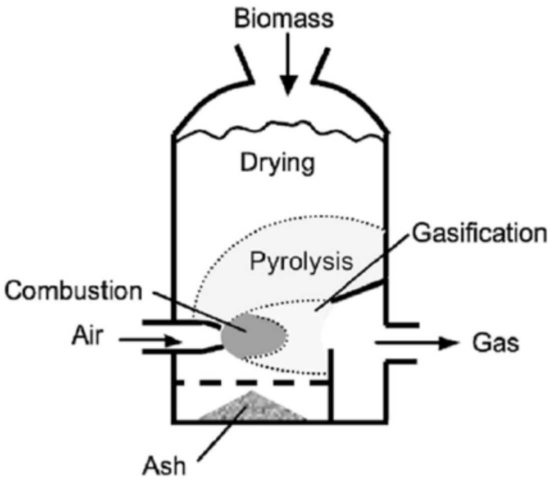

Figure 2.3: Schematic of a cross-draft gasification reactor taken from Basu (2010)

<u>Fluidized bed gasifiers</u>

In a fluidized bed reactor, the gas is flowing with a high superficial velocity in an upward direction through the bed, which is thereby fluidized. These reactors are known for their good mixing characteristics and the uniform temperature distribution in the bed. Although the heat and mass transfer is good, the temperature must be kept below the ash softening temperature to prevent the formation of agglomerates. This reactor type is relatively insensitive to the fuel quality and is therefore often used for the gasification of biomass.

<u>Entrained flow gasifiers</u>

Entrained flow gasifiers are used for large-scale gasification of mainly coal and refinery products with a low ash and moisture content. Finely ground solids or atomized liquids are injected in a stream of air or steam. The operation temperature of these gasifiers are mostly above 1,000 °C which results in a very low tar and hydrocarbon content in the produced gas. Although the operation with biomass is possible, the high cost for the fuel preparation makes this gasifier type less attractive for biomass gasification.

3. Experimental set-up

The design of a gasifier must be adapted to the feedstock properties (Speight, 2014). Biomass is a special gasification feedstock due to the high variability of different properties, such as heating value or moisture and ash content. The suitability of using FS pellets for gasification was assessed using a 10 kW downdraft gasifier from APL. This so-called PowerPallet was designed for remote areas and developing countries with access to biomass. Figure 3.1 shows a flow diagram of the PowerPallet, consisting of a multi-stage downdraft gasifier, a 3-cylinder gas engine from Kubota (Kubota DG 972), a generator head and a process control unit. The latter automatically controls the process and displays all measured values, such as the reactor pressure and temperature, and the pressure in the filter on an LCD screen. Two thermocouples are located at the top and at the bottom of the reduction zone.

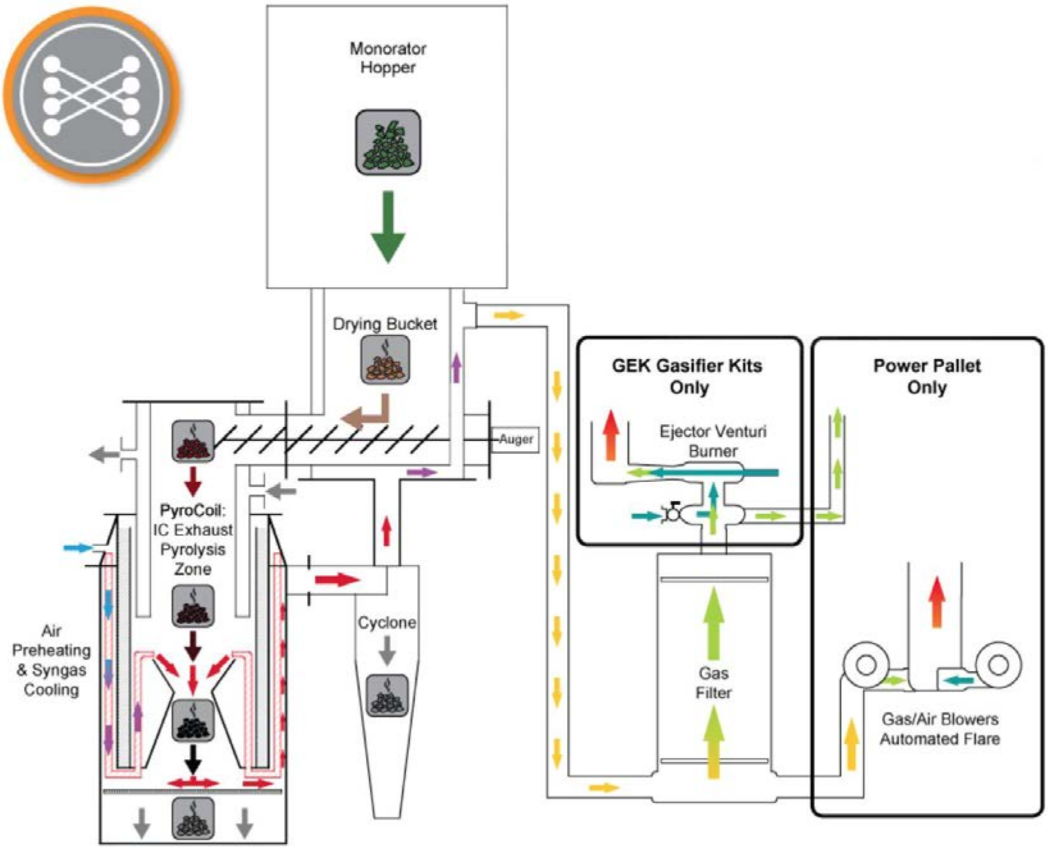

Figure 3.1: Process flow of the 10 kW APL gasifier
taken from APL's technical report 770-00034 "Introducing the power pallet"

The gasifier is designed for carbon-dense fuels such as wood chips or nut shells ranging from 1 cm to 5 cm in size and a moisture content less than 30% (APL, 2012-1). Two gas blowers are installed in series to create a vacuum in the gasifier. This allows an easy start-up without using the engine to create the needed under-pressure in the reactor. The operation temperature should be maintained between 800 °C and 1,000 °C, which is sufficiently below the sintering temperature of the FS pellets (see below in section 3.1). Since the gasifier is designed for a different type of fuel, it is assumed that modifications are necessary for an operation with FS pellets.

3.1 Materials

The fuel pellets used in this study were produced with a Bioburn pelletizer model BPM-X108. A detailed description of this process including a characterisation of the pellets can be found in Englund et al. (2016). The pellets were produced with dewatered FS from the National Water and Sewerage Corporation (NWSC) Lubigi Wastewater and Faecal Sludge Treatment Plant (in the following referred to as NWSC Lubigi).

To increase the calorific value and to decrease the ash content of the pellets, FS was mixed with other biowastes such as sawdust, coffee husks or spent grain and co-pelletized. If necessary, waste cassava flour was used as a binder. The produced pellets had a calorific value between 12.2 and 17.4 MJ/kg dry mass and an ash content between 4% to 44.8% (see also Table 3.1) (Englund et al., 2016). The FS and biowastes were analysed in more detail; a complete characterisation can be found in Gold et al. (submitted) and Byrne et al. (2015).

Important for the operation of the gasifier were especially the sintering temperature, which is the temperature at which agglomerates are formed, and the softening temperature, at which the ash gets sticky and forms agglomerates, which may result in blockages of the bed (Higman et al., 2008). The sintering temperature of 100% FS is around 1,142 °C and the softening temperature at 1,194 °C (unpublished data, Pivot Works). Table 3.1 contains the composition, the moisture content, the calorific value and the ash content of the various tested pellets. Pellets produced from coffee husks (No. 1) were used as a reference fuel.

Table 3.1: Characteristics of the fuel pellets, taken from Englund et al. (2016)

No.	Faecal Sludge (%)	Saw Dust (%)	Fine Saw Dust (%)	Waste Cassava Flour (%)	Coffee Husks (%)	Spent Grain (%)	Moisture (%)	LHV (MJ/kg dry mass)	Ash content (%)
1	0	0	0	10	90	0	10.0	16.1	8
2	0	70	0	30	0	0	10.3	16.9	4
3	45	22.5	22.5	10	0	0	10.6	14.0	19.0
4	50	0	0	0	0	50	10.9	15.8	26.9
5	50	0	0	0	30	20	11.2	16.4	21.7
6	53	0	0	7	40	0	11.2	15.6	21.0
7	65	30	0	5	0	0	11.6	17.4	21.2
8	100	0	0	0	0	0	7.3-10.2	9.9-12.2	30.0-44.8

3.2 Experiments

In a parametric study, the influence of the composition of different fuel pellets on the gasification process was investigated. All experiments were conducted with the pellets listed in Table 3.1. The dried fuel pellets received from the NWSC Lubigi were stored in a dry environment before the tests. Previous tests showed that a moisture content of 20% to 30% is too high for a proper operation of the gasifier. Therefore, prior to each gasification test, the sample pellets were spread on a tarpaulin for open sun drying until the moisture content dropped below 12%, monitored using a hand-held moisture meter (Protimeter mini BLD2000 and Moisture Detector MD).

Before each test, the gasifier was cleaned and all the parts examined for damages and tested for their functionality. For one gasification test, 100 kg of dry pellets were fed into the hopper of the gasifier (see Figure 3.1.). All experiments were conducted by following the "PowerPallet Operation Quick Reference Guide" for a start-up provided (see Figure 3.2). The pressure is given in inches of water column (1 WC = 2.48 mbar). For the start-up, 500 g of charcoal was placed on top of the ash grate to act as starter fuel.

Based on previous experiments, the start-up time of the gasifier to a temperature of 800 °C to 1,000 °C is between 5 to 15 minutes. However, during some experiments minor changes in the proceedings were necessary to reach these temperatures in a reasonable time. This was achieved by increasing the power of the gas blower, resulting in a higher air throughput and a higher temperature. The gas blower in step No. 3 of the guideline was turned on to 3 to 4 WC on P_{react}. Since the temperature of the reactor was still below 100 °C, an increase of the temperature over the sintering temperature of the pellets was not expected. In step No. 6 the gas blower was increased to P_{react} = 6 WC instead of 4 WC. However, the temperature as well as the pressure were monitored during the experiments and no abnormal behaviour was observed.

During the start-up, the time (t_1) needed for the temperature at the top of the reduction zone (T_{tred}) to increase to 100 °C were recorded since this is the highest temperature measured. Additionally, a time (t_2) was measured indicating the time needed from T_{tred} = 100 °C until the produced syngas could be lighted in the flare. These times were recorded to allow a comparison of the performance of the gasifier with different fuel pellets.

The total time the engine was running during an experiment was measured and is labelled as t_e. Furthermore, the number of cranking times to start the engine (N) was counted as well as the stable voltage output at idle speed of the engine (V_1) and the stable generator terminal voltage (V_2) at full throttle. The number of cranking times as well as the measured voltage outputs indicates the quality of the produced gas. A low number of N indicates a high fuel quality. A voltage over 220 V is considered as good and sufficient.

PowerPallet Operation Quick Reference Guide

Start-up Check List

- Charcoal in the GEK reactor
- Filled feedstock hopper
- Gas filter & air filter
- Air tight seals & connections
- Engine oil/coolant
- Battery Charged
- Thermocouples
- System pressure drop
- O2 sensor
- CO meter
- Biomass auger feed
- Clearance around system (ie: flare and exhuast stack)
- CO meter
- Recommended tools

Before proceeding: Please read the *PowerPallet Operation Manual 10kWPP & 20kWPP* and *PowerPallet Setup, Maintenance, and Troubleshooting* documentation for complete operation details and guidance.

For further information, visit our website www.gekgasifier.com. For technical assistance, please contact *support@allpowerlabs.org.*

Quick Start-up Instructions

Start-up:

1. Turn power On
2. Open Flare Gas Valve
3. Turn on Gas Blower for 1-2 WC on P_react
4. Light Reactor w/ propane torch through Ignition Port
5. Cap Ignition Port when T_tred is climbing and >60C
6. Increase Gas Blower to 4 WC
7. Increase Air Blower until the flare lights and the flame is pulled down into the burner and not seen above the top of the Flare Stack.
8. Increase Gas Blower to reach >800C but <1000C. Adjust air blower as needed.
9. Turn off blowers, close Flare Gas Valve, and open Engine Gas Valve.
10. Crank the engine. Engine will start when air is purged from the gas line.

Shutdown:

1. Turn off engine, or turn off Air and Gas Blowers
2. Close Engine and Flare Gas Valves
3. Make sure Air Inlet on the GEK Gasifier is closed.

Figure 3.2: Instruction for a quick start of the APL Power Pallet gasifier, taken from the PowerPallet Operation Manual (APL, 2012-2)

4. Results and discussions

4.1 Behavior of different fuel pellets

The experiments were conducted by CREEC at Makerere University in Kampala. A list of experiments containing measured values can be found in Table 4.1 below.

Fuel pellets no. 1 (reference)

The reference experiment was performed with the fuel pellets no. 1 (see also Table 3.1), containing 90 wt% coffee husks and 10 wt% waste cassava flour (WCF). The pellets had a moisture content of 10%, a relatively low ash content of 8 wt% dry mass and a calorific value of 16.1 MJ/kg dry mass. Although this experiment was stopped due to rainfall (the experiments were conducted outdoors without a canopy), the best performance of the gasifier was attained in comparison to the other fuel pellets (see below). After only 4.5 minutes the top reactor temperature T_{tred} reached 100°C and after another 4.5 minutes the produced gas could be lit. The resulting flame was consistent and strong, indicating that the produced gas was of high quality. This is further supported by the performance of the engine. The engine started after only one crank and an acceptable voltage at full throttle of V_2 = 225 V was measured. No agglomerations of pellets nor of ash were observed.

This experiment showed that pellets produced with the Bioburn pelletizer can perform well in the 10 kW PowerPallet. During the experiment, no clinkers were produced, which leads to the assumption, that the gasifier could have been operated for a longer period of time with this fuel type. After the experiment, it was observed that most of the pellets in the reactor were crushed by the auger but, again, it is assumed that this did not affect the performance of the gasifier.

With 346 kg/m^3 (Englund et al., 2016) the bulk density of these pellets is in the same range as that of the other pellets containing FS. A sufficient gas circulation in the bed as well as a similar temperature distribution for the different pellets can be assumed, since a comparable moisture content was measured for the different pellet compositions.

Fuel pellets no. 2

The performance of the gasifier with the fuel pellets no. 2 containing sawdust and waste cassava flour was comparable to the reference experiment. The measured times as well as the number of cranks of the engine and the resulting voltages are similar. These pellets showed a slightly higher calorific value of 16.9 MJ/kg dry mass and an ash content of 4 wt% dry mass. The lower bulk density of 177 kg/m^3 (Englund et al., 2016) for these pellets seems to have a negligible influence on the performance of the gasifier.

The additional crank of the engine can be explained by the leakage of the gas pipe observed between the gas filter and the engine. This leakage also caused an early shutdown of the gasifier due to safety concerns. As in experiment no. 1, no agglomerates were formed, indicating that the fuel pellets have a sufficient high sintering temperature of over 1,000 °C.

Fuel pellets no. 3

The pellets with a FS content of 45 wt% and in total 45 wt% sawdust performed considerably poorer than the pellets containing only coffee husks or sawdust in combination with waste cassava flour. Although the time to start the gasifier is comparable, the engine needed 4 cranks to start and the resulting voltage of 207 V at full throttle was below the acceptable voltage of 220 V. During the experiment, the engine slowed down and the voltage kept reducing. No extensive tar production was observed, nor formation of clinkers.

This can have several reasons. The calorific value with 14 MJ/kg DM was lower than in the above discussed experiments and the ash content with 19 wt% DM considerably higher. However, it is not possible to make a definite statement if one or both of these facts are the reason for the poorer performance. In case of a comparable pellet consumption it is probable that the lower heating value results in an insufficient power output of the gasifier.

Another reason for the engine to slow down could be a high tar production which can reduce the cross section of the pipes, and therefore limit the fuel supply to the engine. Furthermore, depositions of tar in the intake manifold and at the valve seat can disturb the flow pattern and reduce the performance of the engine. However, no extensive tar production was observed.

Fuel pellets no. 4 and 5

Both types of pellets containing 50 wt% FS performed similar. The calorific values were with 15.8 MJ/kg DM (no. 4) and 16.4 MJ/kg DM (no. 5) in the same range and similar to the values reported for the pellets containing 90 wt% coffee husks (no. 1). The gas production was consistently of an acceptable quality in both experiments, indicated by the revolutions the engine needed to start. This is also supported by the voltage V_2 at full throttle, which in both cases was around 220 V. As in the experiment with pellets no. 3, no unusual high tar production or formation of clinkers was observed.

Fuel pellets no. 6

During the experiment with fuel pellets no. 6, containing 53 wt% FS and 40 wt% coffee husks, an intermitted gas production was observed, which can explain the difficulties to start the engine as well as the poor performance with only V_2 = 198 V at full throttle. An insufficient gas production probably caused the engine to stop working after only 37 min. The reduced gas production can be explained by the formation of a clinker (see Figure 4.1), which was observed after the experiment.

The formation of a clinker can cause an intermitted gas production due to blockages of the gas path. It can further reduce the temperature in the reactor by clogging the air nozzles resulting in an insufficient air supply to the combustion zone. This means that the temperature decreases rapidly and no syngas is produced.

However, the formation of agglomerates in the reactor indicates that the temperature exceeded the ash melting temperature or at least the sintering temperature at some point during the experiment. By maintaining the operation temperature of the reactor between 800 °C and 1,000 °C, agglomerations should not form since FS pellets have a sintering temperature of 1,142 °C. Furthermore, no agglomerations were formed during the experiments with pellets no. 1 containing 90 wt% coffee husks nor with pellets no. 2.

Possible reasons for an increased temperature in the reactor resulting in clinker formation could be an incorrect temperature measurement due to tar deposition on the reactor walls covering the thermocouple, local hot spots in the oxidation zone or an operating error. It is most likely that the temperature increased for a short period of time over the sintering temperature of the pellets, which was not noticed.

Figure 4.1: Clinker formed during an experiment with FS

Fuel pellets no. 7

Despite the higher FS content, pellets no. 7, containing 65 wt% FS and 30 wt% sawdust, performed considerably better than the test with pellets no. 6. Although the time needed for lighting the gasifier was longer than usual, the resulting voltage V_2 reached the desired 220 V. However, not all of the produced gas did burn and the engine stalled after 77 min of operation.

During the experiment no agglomerations were formed. This indicates that the clinker formation does not only depend on the composition of the pellet and supports the assumption that technical problems or operating errors caused the clinker formation in experiment no. 6.

Fuel pellets no. 8

The experiment with pellets no. 8 containing 100 wt% FS was repeated twice, showing consistent failures. After lighting the gasifier, no combustible gas was produced. A sustainable combustion of the pellets was not possible, probably caused by the low calorific value and high ash content of the pellets.

Table 4.1: Summary

No.	t_1 (min)	t_2 (min)	N (-)	V_1 (V)	V_2 (V)	t_e (min)	Observations
1	4.5	4.5	1	200	225	48	▪ No clinker formation ▪ Auger crushed most of pellets ▪ Consistent gas, strong flame
2	5	3	2	196	223	90	▪ No clinker formation ▪ Small gas leakage between filter and engine ▪ Strong flame with strong flare burning sound
3	6.5	6	4	185	207	54	▪ No clinker formation ▪ Engine slowed down ▪ Voltage kept reducing
4	6.4	5.5	2	198	221	40	▪ No clinker formation ▪ Consistent gas production ▪ Engine operated for 40 min. only due to rain
5	6.5	5	3	197	218	20	▪ No clinker formation ▪ Consistent gas production
6	6.8	5.5	4	178	198	37	▪ Clinker formation ▪ Intermittent production
7	8	6	3	173 - 190	220	77	▪ No clinker formation ▪ Part of gas did not burn ▪ Engine stalled after about 1 hour running
8	13	-	-	-	-	-	▪ Clinker formation ▪ Poor gas ▪ Repeated twice, consistent failure

4.2 Challenges

Several challenges arose during the operation of the APL gasifier using pellets containing FS. A steady operation over several hours producing electricity was not possible.

The syngas production was insufficient in most of the experiments to run the engine on a reasonable load at a voltage of minimum 220 V. The low quality of the gas can have several reasons. Part of the syngas may have been oxidized immediately in the oxidation zone, causing a high temperature zone which favours the formation of agglomerations. As mentioned above, clinkers were formed in two of the experiments. It lies in the nature of a fixed bed reactor that heat transfer is poor and can cause local hot spots (Speight, 2014). Removal of clinkers requires the gasifier to be disassembled, a time consuming procedure where most of the gaskets have to be replaced.

The formation of tar may cause additional problems. Although a gas filter is installed, some of the components can pass and condense in the pipes between the filter and the engine or even cause damages to the engine (Klotz, 2014). In addition, tarry residuals can stick to the walls of the reactor preventing a smooth operation of the gasifier (Le Chien, 2012). As soon as pellets cannot move downwards freely, the process is disturbed.

A minor problem in these experiments was the high ash content of the pellets containing a high FS percentage. Due to the comparable short operation times of the gasifier, the ash content did not cause any major challenges. If, however, a long term operation of the gasifier is achieved, the high ash content may require changes to the ash grate. Modifications to the gasifier were not possible as part of this project.

5. Conclusions and recommendations

Within the framework of the SEEK project, CREEC investigated the gasification of FS pellets produced with a Bioburn pelletizer in a 10 kW gasifier from APL. Different pellets containing FS, ranging from 0 wt% to 100 wt%, were tested. Additional pellet components were either sawdust, coffee husks or spent grain. If necessary, waste cassava flour was used as a binder.

The experiments with pellets no. 1 and 2, containing no FS, showed the feasibility of gasification of the pellets produced.

The experiments conducted with pellets containing FS yielded mixed results. The formation of agglomerates was a problem in two of the experiments: pellets containing 53 wt% (no. 6) and 100 wt% (no. 8) FS respectively. However, no agglomerates were formed in the other experiments conducted with pellets containing FS. It is assumed that the clinker formation is not related to the FS but resulting from technical failures such as a wrong temperature measurements or local hot spots in the combustion zone, or operation errors.

Operation of the gasifier with pure FS pellets was not possible and is unlikely due to the low heating value of FS. However, operation with a high FS percentage is possible as shown by the experiment with pellets containing 65 wt% FS (no. 7), achieving a voltage of 220 V.

Therefore, from this study it can be concluded, that gasification of pellets containing FS is possible, but it is assumed that the gasifier from APL has to be modified for a trouble-free operation.

Further experiments could systematically investigate the influence of the share of FS in the pellets, i.e. using only pellets of different mixtures of FS and sawdust. This would enable determination of the maximum FS percentage in pellets, that still allows a stable operation.

To investigate the influence of the different calorific values of the pellets, a feedstock with a different pellet size could be used to increase/decrease the volumetric energy content and therefore the available energy in the reaction zone.

The gasifier may be modified for an operation with FS pellets. By introducing water in the combustion zone, the temperature is reduced which prevents the formation of agglomerations, especially if the water introduction is done automatically after reaching a specific temperature. It would further favour the water-gas shift reaction (Equation (2) in Section 2.2) which would increase the calorific value of the produced gas by increasing the H/CO ratio (Basu, 2010 and Speight, 2014).

Further recommendations of FS gasification are:

- Co-pelletizing with other waste streams in ratios of less than 25% FS
- Further reduction in ash content (e.g. FS from source separating toilets with high calorific value and low ash content)
- Redesign in feeding system to stop auger from crushing pellets
- Chemical treatment (additives) into FS pellets to curb clinker formation
- Large scale gasifiers probably of different type (other than downdraft) should be experimented with (e.g. Xylowatt Belgium, www.xylowatt.com)

Any further experiments done in line with above recommendations should include the characterization of the producer gas.

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