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Production and characterization of a new quality pyrolysis oil, char and syngas from digestate – Introducing the thermo-catalytic reforming process

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ABSTRACT

A 2 kg/h laboratory scale thermo-catalytic reforming (TCR®) unit was designed and commissioned at Fraunhofer UMSICHT to convert digestate into enhanced pyrolysis products. The TCR® reactor is an intermediate pyrolysis screw reactor connected to a reformer. In the experimental series reported, digestate pellets were used as feedstock. The aim herein was to test and characterize the TCR® reactor for the feedstock digestate and its products for syngas applications and decentralized power production. Prior to the pyrolysis experiments thermal gravimetric analysis was used to analyze the weight loss over temperature. The digestate was pyrolyzed at a constant temperature of 400 °C, whereas the reformer temperature was varied between 500 and 750 °C. Following the cooling and condensation of pyrolysis vapors, these separated into bio-oil, an aqueous phase and permanent gases. Hydrogen concentration increased together with increased reforming temperatures and reached a maximum of 35 vol% at 750 °C. The bio-oil generated at 750 °C had a higher heating value of 33.9 MJ/kg, 1.7 wt% water content and a total acid number of 4.9 mg KOH/g. It was possible to convert over 91% of the energy content of the biomass into usable products. These results are analyzed together with the extensive feedstock and product characterization and the experimental parameters and discussed.

1. Introduction

Bioenergy will play a significant role in the future energy supply [1–3]. The expansion of bio-fuels produced from biomass residues has been deemed essential to meet sustainability and cost criteria [4]. The existent competition of energy crops with food and feed production makes the utilization of agricultural waste streams like straw or digestate necessary. It has therefore emerged as one of the favored future strategies for the bioenergy sector, which is confirmed by the increasing number of residue- and waste-to-energy projects [5,6]. Digestate is the residue following anaerobic digestion of biodegradable feedstock for the production of biogas. In Germany alone, more than 7800 anaerobic digestion units produce over 60 million tons of digestate every year (at approximately 10 wt% dry matter) [7]. As the total energy content of corn or other energy crops, being the main feedstock for agricultural anaerobic digestion units in Germany, cannot be fully used in the digestion process, making use of these residues for power production is an important step to improve overall economics. For example, digestate with a dry matter of 90% still has a heating value of 15.8 MJ/kg [8]. However due the high ash content, low ash melting point and slagging, digestate is not a favorable fuel for incineration and necessitates special furnace designs [8–10]. Therefore biomass pyrolysis is a promising conversion technology for the production of biofuels from residue. Moreover, energy from biomass and its residues has the potential to be CO_2 neutral and can therefore have a positive effect on the reduction of greenhouse gas emissions [11].

In the presented work dried and pelletized digestate was processed in a recently developed thermo-catalytic reforming (TCR®) reactor with the objective of quantifying and characterizing the products [12]. The TCR® is an enhanced intermediate pyrolysis screw reactor combined with a reforming process as a part of

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Table 1
Composition of primary feedstock of the anaerobic digestion plant.

Component	wt%
Cattle slurry	17
Pig slurry	17
Corn silage	62
Others	4

Fraunhofer UMSICHT's concept of the 'Biobattery' [13–16]. Within this concept bio-oil and gas from TCR® will be used for engine applications for combined heat and power. The utilization of TCR® bio-oil blended with biodiesel has been successfully proven in a diesel engine already [21]. Further the char is of interested as potential fertilizer and soil conditioner.

2. Materials and methods

2.1. Raw material

For the experiments pre-conditioned digestate from an anaerobic digestion plant operated by Neue Energie Steinfurt GmbH, Germany (NESt) was used. Chemical composition and physical properties of digestate are dependent on the blend of substrates used as feedstock for biogas production. The feedstock composition used in the NESt anaerobic digestion (AD) plant from which the pellets were acquired is shown in Table 1. For a better homogenization inside of the AD plant the feedstock has been chopped prior to the input. During the fermentation process the primary anaerobic feedstock is converted to biogas for power generation and digestate as the residue.

Fresh digestate has a high moisture content of approximately 90 wt% which can be reduced down to 60–70 wt% by mechanical de-watering and reduced further to 10–20 wt% by drying. 1000 kg of homogenized digestate were mechanically de-watered, dried and pelletized by NESt. The pellets had a diameter of 6 mm and about 15–30 mm length (Fig. 1).

2.2. Feedstock characterization

Volatiles and fixed carbon of the digestate were measured by Thermo Gravimetric Analysis (TGA) in a Netzsch STA 409 PC Luxx TGA device. Prior to TGA, samples of digestate pellets were milled and homogenized with a Fritsch pulverisette 23 ball-mill. Approximately 25 mg of dried digestate was filled into a crucible and pyrolyzed under an inert atmosphere of Argon at a flow rate of 100 ml/min, to a maximum temperature of 1000 °C, with a heating rate of 20 °C/min.

Fig. 1. Digestate pellets (as received).

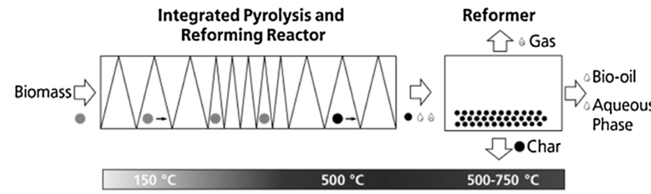

Fig. 2. Schematic drawing of the thermo-catalytic reforming reactor.

Ash content at 575 °C and total moisture content at 105 °C of the feedstock was determined in a muffle furnace according to ASTM E1755-01 and ASTM E1756-08.

Ultimate analysis was carried out by an external analytical laboratory using a Leco TruSpec CHN analyzer and a Leco SC-144DR for sulfur. The higher heating value in MJ/kg of the digestate was determined with an IKA C5000 bomb calorimeter.

2.3. Thermo-catalytic reforming (TCR®) experiments

The TCR® plant is installed at the laboratory of Fraunhofer UMSICHT Institute Branch Sulzbach-Rosenberg, Germany. The TCR® unit is an intermediate pyrolysis reactor connected to a reformer [12,14–16]. A schematic of the thermo-catalytic reforming is shown in Fig. 2. A picture of the plant is shown in Fig. 3. The reactor is a multi-zone auger pyrolysis reactor which can process a feed in an inert atmosphere of nitrogen at a rate of up to 2 kg/h. The lab-scale reactor is heated externally by electrical heating bands. The feed moves through the different zones of the screw conveyor system and can be heated using a specific temperature profile. On the downstream side of the auger reactor, resulting intermediates are conveyed into the electrical heated reformer, where a reforming between char, vapor and gases takes place, resulting in an upgrading of all phases which can be performed at lower temperatures as described in conventional catalytic coal gasification research [17,18]. The big variability in process control gives the plant a wide range of options regarding gas composition and amount, oil quality and char stability.

The experiment was conducted with a total of 5 kg pelletized feedstock with a mass flow of 1.6 kg/h and an average residence time of 5 min. Three different temperature zones made up the temperature profile used for the TCR® reactor. Temperatures increase from 150 °C at the inlet to 500 °C at the outlet with a constant temperature in the central pyrolysis zone of 400 °C. The temperature in the reformer was varied between 500 °C and 750 °C. The reactor was heated for 80 min prior to the introduction

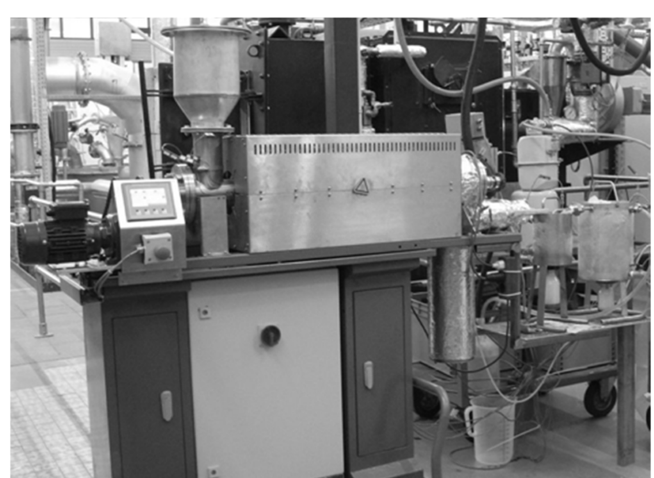

Fig. 3. Laboratory scale TCR® reactor installed at Fraunhofer UMSICHT.

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