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The conversion of anaerobic digestion waste into biofuels via a novel Thermo-Catalytic Reforming process

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ABSTRACT

Producing energy from biomass and other organic waste residues is essential for sustainable development. Fraunhofer UMSICHT has developed a novel reactor which introduces the Thermo-Catalytic Reforming (TCR®) process. The TCR® is a process which can convert any type of biomass and organic feedstocks into a variety of energy products (char, bio-oil and permanent gases). The aim of this work was to demonstrate this technology using digestate as the feedstock and to quantify the results from the post reforming step. The temperature of a post reformer was varied to achieve optimised fuel products. The hydrogen rich permanent gases produced were maximised at a post reforming temperature of 1023 K. The highly de-oxygenated liquid bio-oil produced contained a calorific value of 35.2 MJ/kg, with significantly improved fuel physical properties, low viscosity and acid number. Overall digestate showed a high potential as feedstock in the Thermo-Catalytic Reforming to produce pyrolysis fuel products of superior quality.

1. Introduction

The G8 communique, in 2008 declared the goal of reducing greenhouse gas emissions by 50% by 2050 from 1990 levels. To reach this objective the energy supply is directed towards renewable energy systems such as wind, solar and biomass (thermo-chemical and biological systems). Wind and solar power combined cannot guarantee a stable supply of energy generation due to fluctuation of wind and sun. Therefore, in order to improve the reliance of renewable energy supplied, thermo-chemical conversion of biomass must make up for the fluctuations and unreliability of supply. In 2012 biomass had a share of 1.5% of world electricity generation (IEA, 2014), but the potential for cultivating lignocellulosic biomass for energy production is limited due to the availability of land which must also be used to cultivate food crops.

A more attractive option is to utilise organic wastes like residues from anaerobic digestion (AD) plants. However as the total energy content of the original biomass entering an AD plant cannot be fully broken down by microorganisms, significant quantities of organic digestate residues remain after the process. More than 7800 AD plants operate in Germany and produce over 60 million tons of digestate every year (approximately 10 wt% dry matter) (Biogas Association, 2014). The majority of this waste is disposed of by landspreading depending on local regulations. Due to these regulations, the management of the residues from biogas fermenters is carried out in different manners. The way digested has to be treated dependents on the region and current state of the fertilizer saturation of the agricultural sites. In Southern Germany for instance, the situation is the following, that digestate is allowed to be brought out to agricultural fields, whereas in Northern Germany, the situation is complete different as digestate must not be spread on agricultural fields due to an over saturation of phosphorus and nitrates on the fields. The situation is similar in Europe, so that the application of digestate as fertilizer depends

Abbreviations: TCR®, Thermo-Catalytic Reforming; CHP, combined heat and power units; AD, anaerobic digestion; TAN, total acid number; HHV, higher heating value; LHV, lower heating value.

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from region to region. But as digestate contains a residual calorific value (approximately 14 MJ/kg) (Kratzeisen et al., 2010) there is a potential for further energy to be extracted before it is disposed of.

In thermal conversion processes such as gasification and fast pyrolysis, organic waste residues such as digestate cannot be utilised due to its high residual moisture content, low heating value and low ash melting point (Kratzeisen et al., 2010). High moisture contents gives rise to handling and processing difficulties with high energy inefficiencies, since the majority of energy input into the process is required to evaporate water. Low ash melting points, can cause ash slagging, sintering and agglomeration at temperatures above the ash softening point. Low calorific values, lead to poor product quality and inefficient gasification. Furthermore fast pyrolysis of biomass can produce high amounts of liquids which are highly oxygenated, corrosive and viscous, making them unsuitable for use as fuels without significant catalytic upgrading (Meier et al., 2007; Luo et al., 2004; Zhang et al., 2007).

Pyrolysis can be characterised into three main groups, fast, intermediate and slow depending on the temperatures, heating rates and vapour residence times which are applied. Each can also be characterised in terms of its product distribution to form solids, permanent gases and liquids (aqueous and organic). Intermediate pyrolysis of digestate for energy generation is of interest as intermediate pyrolysis operates at relatively moderate temperatures (673–773 K) and heating rates (minutes) in the complete absence of oxygen, with vapour residence times in seconds. This produces fuels with a higher energy density than the original biomass making them easier to transport and store. Thus producing storable fuel energy carriers in the form of permanent gases, liquid bio-oil and solid char makes it easier to produce on demand energy and heat in combined heat and power (CHP) units, higher energy dense fuels also have higher conversion efficiencies to electricity in CHP units. Processing digestate in this way can have a positive effect for the reduction of greenhouse gas emissions whilst simultaneously reducing waste to landspread/landfill as well as contributing towards a stable supply of renewable energy.

In literature little has been reported on the pyrolysis of digestate (Neumann et al., 2015), although some research exists on the intermediate pyrolysis of other organic wastes (Hornung et al., 2009, 2011; Mahmood et al., 2013; Ouadi et al., 2013; Samanya et al., 2012). The most relevant to this work is the batch intermediate pyrolysis and subsequent post reforming of brewers spent grain for the production of hydrogen rich syngas (Mahmood et al., 2013). The results showed that downstream reforming of the pyrolysis products up to 1123 K with the use of external steam and catalyst increased H_2 yields above 50 vol% in the product gas. Sattar et al. (2014) investigated the steam gasification of four intermediate pyrolysis biochars (sewage sludge, wood pellets, rapeseed and miscanthus) for hydrogen rich syngas production. The results show hydrogen yields increased to approximately 59 vol% at gasification temperatures of 1023 K when using rapeseed bio chars. The pyrolytic conversion with more than one reactor was done by other groups. Adrados et al. (2013, 2015) has published several results for the production of high quality char and hydrogen rich gas, within a two step pyrolysis process. With low heating rate of 3 K/min and pyrolysis temperature of 1023 K and a catalytic treatment at 1173 K of the vapours, gases with more than 50 vol% hydrogen could be produced from olive tree cuttings. A yield of 21–26 wt% char was produced. The low heating rate has a positive effect in terms of a low tar production. Liu et al. (2014) demonstrated the conversion of water hyacinth in a two-stage fixed bed reactor with catalytic pyrolysis. In the first stage they added a catalyst to the feedstock and within the second stage they reformed the pyrolysis vapours on a nickel-based catalyst. The result was a gas yield up to 48.5% with a Hydrogen content of up to 77.2 vol%. Demirbas (2001) showed for different feedstock with a catalytic pyrolysis at 1025 K that a gaseous yield of more than 50% with a hydrogen content up to 70% can be produced. Ni et al. (2006) and Balat (2008) give a brief overview of hydrogen production via pyrolysis reactors for different feedstock. Gases with more than 60 vol% hydrogen can be produced with pyrolysis processes. Further research for producing high grad biodiesel was demonstrated by Noureddin et al. (2014) and Mahdi et al. (2013).

Fraunhofer UMSICHT has implemented a Thermo-Catalytic Reforming TCR® process in a novel patented TCR® reactor (Hornung et al., 2014a). The TCR® technology can be applied for all kind of residues with a HHV higher than 8 MJ/kg and a water content lower than 20 wt% due to the economy of the process, whereas the evaporation of water inside the reactor at high temperatures lowers the thermal efficiency of the process. Therefore material pre-drying at significant lower temperatures is recommended as the process can supply sufficient low temperature heat from the downstream components like heat exchangers. However technologically it is possible to process materials with a water content up to 70 wt%.

Projects on TCR® are also carried out on the conversion of plastics e.g. from WEEE (electronic scrap). Within this paper only the results of biomass conversion, in particular digestate, are presented.

The technology is based on the intermediate pyrolysis and subsequent downstream post reforming of pyrolysis products into a hydrogen rich synthesis gas, a fuel biochar with similar properties to anthracite coal and a bio-oil with significantly improved liquid fuel physical and chemical properties. The TCR® is able to process biomass with high ash and moisture contents and low ash melting points. The reforming step which is achieved at elevated pyrolysis temperatures above 773 K optimises the production of hydrogen synthesis gas in the process.

The TCR® is part of the bio-battery concept developed by Fraunhofer UMSICHT (Hornung, 2014b) for the delivery of energy to balance and stabilise the electrical supply from renewable sources. Fig. 1 shows the conversion step of the bio-battery concept. After the anaerobic digestion the digestate is further treated in the TCR® plant. The TCR® technology applied to residues of biogas plants contributes to the financial outcome of a biogas plant significantly and increases the economic benefit of biogas plants by the generation of additional heat and power out of the biogas residues in a range of up to 20%. In addition the residues from biogas plants are classified as problematic compounds (depending on the region) due to an oversaturation of agricultural sites by mainly nitrates and phosphates. The benefit of the TCR® technology for a biogas plant is therefore an improved economy of the overall biogas plant and a smart solution for the disposal of the biogas residues from which new products are produced. The Oil for example can be stored and used as fuel for power production while other renewables like photovoltaic or wind power do not produce energy.

The aim herein was to test and characterise the TCR® process and its variable parameters for the feedstock digestate and its products for syngas applications and decentralized power production.

2. Materials and methods

2.1. Raw materials

For the TCR® test runs digestate obtained from a wet AD plant in Northern Germany was used. The AD plant processes a mixture of animal and plant wastes for the production of methane rich biogas for CHP generation. The residual digestate leaving the digesters