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The case of Frictional Torrefaction and the effect of reflux condensation on the operation of the Rotary Compression Unit

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ABSTRACT

This work introduces the process of Frictional Torrefaction and comes as a continuation to the previous work done on Frictional Pyrolysis, which is a novel method of pyrolysis that does not utilize heat but only friction and pressure. Both processes (i.e. Frictional Torrefaction and Frictional Pyrolysis) take place in a Rotary Compression Unit without and with a reflux condenser respectively. Rotating augers are used for the development of friction and the simultaneous increase of pressure. The following types of analysis were performed: TGA, BET, CHNS and HHV. Both products have similar heating values, around 21 MJ/kg. The elemental compositions are comparable but lower hydrogen content (3.5%) was measured for Frictional Torrefaction. BET analysis showed differences on the surface areas and porous sizes of the materials. Frictional Torrefaction has higher fixed carbon (31.23% vs 28.31%), higher surface area (58.16 m^2/g vs 36.88 m^2/g) and higher absorbance (35 cm^3/g vs 26 cm^3/g).

1. Introduction

Recent legislation (European Commission, 2015) have extended the renewable energy integration targets and has set the aim of producing 27% of the total energy from renewables by 2030, which is a significant increase from the initial target of 20% by 2020. These sustainable energy targets, along with the introduction of economic incentives have advanced the utilization of biomass in agricultural and energy production practices. Biomass is a renewable resource and is considered to be carbon neutral from the standpoint that the carbon oxides/emissions that are emitted from the use of biomass had been initially been captured from the atmosphere. Although, biomass based practices are definitely considered as "low-carbon" and sustainable (Gutiérrez et al., 2018), the aspect of carbon neutrality is not a given for all cases (Rabl et al., 2007). For example, Zanchi et al. (2012) highlighted the impact of intensive biomass cultivation on the carbon neutrality of biomass resources. However, the authors suggested that for the case biomass residues there is a better argument to be made in respect to carbon neutrality. European Union is moving towards a similar framework and the recent incentives support next generation biofuels, i.e. fuels from lignocellulosic biomass, algae and waste, and the gradual reduction of conventional food-related biofuels.

A common conversion pathway has been the production of solid carbonaceous products for energy, agricultural or industrial applications. But, according to Mikulandrić et al. (2016), the wide availability of agricultural biomass does not necessarily translate to availability of biomass for energy applications because intermediate processes are necessary in order to increase the bulk density. In principle, thermochemical processing of biofuels can have three main possible upsides; production of an energy dense fuel (Pahla et al., 2017), reduction of the transportation cost (Muazu et al., 2017) and carbon sequestration since according to Gupta et al. (2018) this is considered as an opportunity for carbon dioxide sequestration.

The most common solid product from the thermochemical conversion of biomass is biochar, although this term is overused. Jeffery et al., (2015) denoted that there are some specific prerequisites that should be met in order for this term to hold. The official definition of biochar according to the International Biochar Initiative is that biochar is the product that is "obtained from the thermochemical conversion of biomass in an oxygen-limited condition" (International Biochar Initiative, 2012). The commonly accepted significant parameters that are necessary for biochar definition are the functionality of the material as soil amendment along with the projected low environmental impact (Verheijen et al., 2010). Shackley et al. (2012) made a connection between the term biochar and the aspects of porosity and long-term carbon storage potential. Tan et al., (2017) added that the pH of biochar is expected to be neutral or slightly alkaline and defined the typical carbon composition range between 67.8% and 86.8%. Biochar is used

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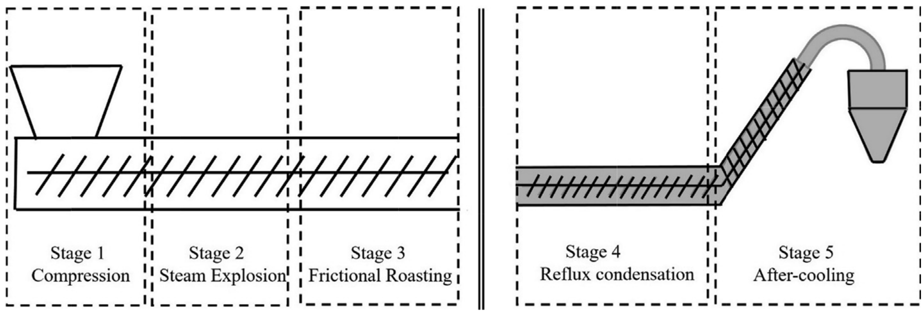

Fig. 1. Frictional Pyrolysis Torrefaction and the potential coupling with a reflux condenser and an aftercooler.

primarily as soil enhancer or as absorption material for pollutants like heavy metals (Wang et al., 2018).

Torrefaction is a form of pyrolysis that takes place under relatively low temperatures, i.e. 200–350 °C, and moderate retention times, i.e. up to 3 h. Temperature and retention time are critical for the quality of the product and the recovered mass yield, therefore biomass is pyrolyzed in “a controlled manner” (Chen et al., 2018a,b). Chen et al. (2015) have emphasized the significant role that torrefaction can have in the upgrading of biomass residues and thus in energy applications like the partial replacement of coal (Proskurina et al., 2017). The reasoning behind the effectiveness of this process is that for a specific range of temperatures and for moderate retention times, a significant fraction of the hemicellulose content degrades and volatilizes (Shen, et al., 2010). The remaining part consists mainly of lignin and cellulose, which have higher carbon and energy content (Da Silva et al., 2016). Torrefied biomass has typically carbon contents higher than 50% and Pahla et al., (2017) reported heating values of up to 26 MJ/kg. Yang et al., (2014) stated the effect of torrefaction on energy densification of low-grade fuels that were pyrolyzed further. The authors showed that torrefaction can be a viable pretreatment method for recovering higher yields of phenols. Thus, torrefaction is a pathway for producing densified fuels with improved properties rather than materials for agricultural or industrial applications.

Vakalis et al. (2016) introduced a novel process, named “Frictional Pyrolysis”, which produces carbonaceous solid biofuels by processing biomass only with pressure and friction (and without the addition of any external heat). The main reactor has been named Rotary Compression Unit, i.e. RCU, and has been patented by Heimann (2013). The process uses the rotation of augers in order to create friction between the sawdust particles and the design along with the evaporation of the gases increase gradually the pressure in the chamber. At a relief point, the pressure drops and this results to steam explosion. The heated steam roasts the material in a process that resembles torrefaction and products from the two processes have some similarities as shown by Vakalis et al. (2016). Initial the sole use of the RCU unit – without the reflux condenser – resulted to auto-ignition of the produced material and this had to be prevented. Thus, the initial/conventional approach after the roasting of the material was the utilization of a reflux condenser for the recapturing of tar compounds and then for cooling down the carbonaceous product. Contrary to the initial design, Talley et al. (2018) used successfully the Rotary Compression Unit without the reflux condenser and the cooling stage for roasting mixtures of wood sawdust and poultry litter. The operation of the RCU solely with woody biomass and without the use of the reflux condenser remained a challenge.

The main scope of the present study was the successful operation of the RCU without the reflux condenser and the comparison of RCU's operation with and without the reflux condenser. The products from the two different processes are expected to have different structures. The difference between the two process flows are shown in Section 2. On the one hand, Section 3 presents the differences in the physical and chemical characteristics between the products from the different configurations. On the other hand, Section 3 discusses the results and argues about the fact that the utilization or not of the reflux condenser results in two distinctive processes. The previously introduced “Frictional Pyrolysis” and the newly developed process without the reflux condenser, which is technically frictional roasting, and in this study is introduced and defined as “Frictional Torrefaction”.

2. Materials and methods

2.1. Background of the process and presentation of the two configurations

As mentioned in Section 1, the process that is presented in this study has been initially defined as “Frictional Pyrolysis” and takes place in an air-tight reactor that has been named by Heimann (2015) as Rotary Compression Unit, i.e. RCU. The process converts biomass into solid carbonaceous products only with the application of friction and pressure, whereas no external heat is inserted in the system. Nonetheless, it is straightforward that heat is produced through rotational fiction and compression. The essence of the RCU is the use of a set of compression screws with 6-inch diameter that rotate within a barrel to compress rapidly the biomass and simultaneously to create friction between the biomass particles. The pressure inside the RCU reaches up to 40 bar. A relief point results to the sudden increase of the barrel diameter and thus, to a significant pressure drop and steam explosion. The steam heats up to 385 °C and roasts rapidly the material. This whole process in the RCU lasts approximately 120 s. The biomass continues to thermally upgrade and carbonize through the Reflux and after 180 s, it exits into the Aftercooler, which is an apparatus that aids the cooling before storage. As mentioned above, the Rotary Compression Unit was initially coupled with a Reflux Condenser and an Aftercooler apparatus in order to control the process but in recent experiments the RCU was used successfully also without the coupling of the RCU with these devices. The two possible scenarios/process flows are shown in Fig. 1.

The temperature and pressure conditions at the relief point are characteristic parameters that define the degree of carbonization. These conditions are influenced primarily by the rotational speed of the augers. The rotational/mechanical energy is provided to the system by a 75 kW Otto engine. The pressure is relatively constant for both scenarios, and around 35–40 bar, depending the intensity of the process. When the RCU was coupled with the reflux condenser, the maximum temperature rotation reached 385 °C but for the case of the sole use of the RCU the process works better with temperatures around 320 °C.

2.2. Analysis and characterization

Corn stover with a heating value equal to 18.23 MJ/kg was utilized as input raw biomass that underwent several different treatments, i.e. Torrefaction, Frictional Pyrolysis and Frictional Torrefaction. An initial analysis, in respect to the heating value of the materials, was done at the laboratories of RE-CORD consortium (Florence, Italy). The products from frictional treatments showed to have almost identical heating values with 21.28 MJ/kg for the product of Frictional Torrefaction and 21.24 MJ/kg for the product of Frictional Pyrolysis. Thus, the analysis