MASS AND ENERGY BALANCES FOR A STAND-ALONE TOMATO PEELS TORREFACTION PLANT

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Abstract

Torrefaction is an emerging thermal pretreatment of biomass, which produces a solid biofuel having superior handling, milling, storage and co-firing properties compared to raw biomass. During the process a combustible gas ('torgas') consisting of different organic compound is also produced in addition to the torrefied solid product. In a properly designed and operated torrefaction system the torgas may be combusted to generate heat for the drying and torrefaction steps, thus increasing the overall process efficiency. In this paper, a simple process simulation of a stand-alone torrefaction plant with internal heat integration was performed to assess whether autothermal operation is conceivable for high moisture tomato peel residues (TPs). Results show that for typical torrefaction conditions where about 20-30% of the dry mass is removed in the form of volatile gases (i.e., 285 °C and 30 min for TPs), the process cannot be autothermal and, consequently, an additional utility fuel is required. Under these conditions, in fact, the total thermal energy potentially available in the torgas was approximately 72% lower than the overall energy required for torrefying raw tomato peels, which have 80.5% initial moisture content. The net thermal efficiency of the whole conversion process was estimated to be approximately 70%, whereas the energy yield of the torrefaction unit was 85%. This suggests that for high moisture content agro-industrial residues the integration of torrefaction unit with another plant providing waste heat may be a better option compared to stand-alone plant with internal heat integration in order to save the overall energy efficiency.

Introduction

In the process industry, torrefaction is a relatively new operation, which, over the past 10 years, has been recognized as a technically feasible method for converting any lignocellulosic material into a high-energy-density, hydrophobic, compactable, easily-grindable and biochemically stable coal-like solid. In turn, the torrefied product is suitable for commercial and residential combustion and gasification applications [1]. Basically, torrefaction is a thermo-chemical process, which is performed in an inert or oxygen-limited environment at atmospheric pressure and at an operating temperature within the 200-300 °C. Under these conditions, properties of biomass are improved through the removal of a fraction of its volatile matter in the form of both light gas (mainly CO, CO_2, CH_4 and traces of H_2) and other organic condensable compounds (including water, organics and lipids), known as “torgas” [2]. The final product is the residual solid, which is often referred to as torrefied biomass. In a properly designed and operated torrefaction system, the gases released during torrefaction may be combusted to generate heat for the drying and torrefaction steps, thus increasing the overall process efficiency. In the recent past, most of the research and development on torrefaction has been largely focused on clean and dry biomass resources such as waste wood. Nevertheless, due to the lower price and the larger availability of waste streams and residual biomass, the interest into these latter as feedstock for torrefaction is increasing. In this paper the potential of torrefaction treatment for upgrading low value industrial tomato peel residues (TPs) from Campania region (Italy) into high quality solid energy carriers [3] was assessed. In more details a simple mathematical model has been developed, based on mass and energy balances, for simulating the basic processing units included in a typical stand-alone torrefaction plant. The aim of the model was to estimate the effect of TPs moisture content on the net thermal efficiency of the torrefaction treatment. Another target of the model was to assess whether autothermal operation is conceivable for high moisture content tomato peel residues. This research is complementary to the experimental study on the torrefaction of TPs carried out in our previous work [3].

Experimental

Tomato peels (TPs) used in this work were collected from a tomato processing factory in Salerno (40°47'24.5"N, 14°46'15.8"E), Campania region (IT), in September 2014. They have a 80.5% moisture content and a low calorific value (LHV) of 24.14 MJ/kg on dry basis [3]. A simultaneous TG-DTG-DSC analysis was carried out in a Netzsch thermogravimetric analyzer STA 409. Nitrogen (N_2) was used as the purge gas at a flow rate of 200 ml/min. Sample and reference holders were open-type alumina pans. Low sample weights (~ 10 mg) and small particle sizes (< 400 μm) were selected in order to reduce the effect of intra-particle mass and heat transport. During the isothermal run, the dried sample was first heated up to a temperature of 110 °C (20 °C/min), which was held for 10 min. Then the temperature was increased to the desired test value (i.e., 285 °C) at a heating rate of 5 °C/min and kept constant for 1 h.

Model concept

A stand-alone torrefaction plant is conceived to consist of a drier, a torrefaction reactor, a burner, a flue gas heat recovery system and a solid product cooler. The dryer ensures a low and constant biomass moisture content to the torrefaction unit.

This latter, in turn, heats the dried feedstock up to the target temperature and converts the biomass into the desired solid product, upon removing a fraction of the volatile matters. The burner releases the chemical energy retained in the torrefaction gases through combustion. The heat exchanger recovers the sensible heat of the hot flue gas leaving the burner. Finally, the torrefied solid product is cooled down to a safe temperature (< 50 °C), at which the product can be handled and stored [4]. It was assumed that the moisture is totally removed in the drying unit where wet tomato peels are heated up to 100 °C. Accordingly, the energy required for drying 1 kg of raw TPs was calculated as the sum of the heat Q_{ph} needed for preheating TPs from room temperature to the drying temperature, i.e. 100 °C, and the heat Q_{dr} required for complete evaporation of moisture in the feedstock, as follows:

$$Q_{dryer} = \frac{Q_{ph} + Q_{dr}}{\eta_{f,D}} = \frac{W_{TPs} \cdot \int_{T_O}^{100} C_{pw} dT + W_{TPs} \cdot M_{TPs} / 100 \cdot \Delta H_{vap}}{\eta_{f,D}} \tag{1}$$

where W_{TPs} is the mass of wet tomato peels entering the drier (kg), C_{pw} is the specific heat of wet tomato peels (MJ kg^{-1} K^{-1}), T_o is the room temperature, taken as 25 °C, M_{TP} (% wt.) is the moisture content of wet tomato peels, ΔH_{vap} is the latent heat of vaporization of water at boiling (2.257 MJ kg^{-1}), and $\eta_{f,D}$ is the efficiency of the drying unit, which was assumed equal to 0.85 [5]. Biomass heat capacity is known to be influenced by both temperature and biomass moisture. In keeping with the treatment of non-woody biomass in the literature [6], the heat capacity of wet tomato peels was estimated using experimental correlations obtained for wet wood, which has a moisture content higher than the fiber saturation point (~ 26%). In more details, correlations proposed by Simpson and Tenwolde [7] and Regland et al. [8] for estimating the heat capacity of woody biomass with varying temperature and moisture content were assessed and average values were used to solve the integral in Eq. 1. The torrefaction unit was modelled on the basis of experimental correlations (Eq. 2-4) providing the dependence on torrefaction operating conditions for the low-heating value (LHV), mass (M_Y) and energy (E_Y) yields. Equations 2-4 were derived from our previous study on fluidized bed torrefaction [3], by means of batch tests performed at 200, 240 and 280 °C for holding times equal to 5, 15 and 30 min.

$$LHV\ (MJ/kg,\ db) = 19.9535+0.0209 \cdot T(°C)+0.0159 \cdot t(min) \qquad R^2=0.96 \tag{2}$$
$$M_Y\ (\%,\ db) = 130.6892-0.1627 \cdot T(°C) -0.2154 \cdot t(min) \qquad R^2=0.97 \tag{3}$$
$$E_Y\ (\%,\ db) = 119.5931-0.1057 \cdot T(°C)-0.1664 \cdot t(min) \qquad R^2=0.91 \tag{4}$$

The total energy, $Q_{torrefier}$ (MJ), for the torrefaction of the dry mass contained in 1 kg of raw tomato peels is represented by the sum of the energy needed for the post-drying heating of TPs to the torrefaction temperature, Q_{pd} (MJ) and the heat load of torrefaction, $Q_{torrefaction}$ (MJ). Although torrefaction of tomato peels starts at its onset temperature, which is about 180 °C [3], for sake of simplicity, the heating of dried TPs from 100 °C to the torrefaction temperature, T_T (K), was included in the post-drying zone, as follows:

$$Q_{torrefier} = \frac{Q_{pd} + Q_{torreafction}}{\eta_{f,T}} = \tag{5}$$

$$\frac{W_{TPs} \cdot (1 - M_{TPs}/100) \cdot C_{pd} \cdot (T_T - 100) + W_{TPs} \cdot (1 - M_{TPs}/100) \cdot (1 - M_Y/100) \cdot \Delta H_{tor}}{\eta_{f,T}}$$

where C_{pd} is the specific heat of dry or torrefied biomass, taken as 0.000269 MJ kg^{-1} K^{-1}, M_Y is calculated from Eq. (3) at selected decomposition temperature (285 °C) and time (30 min), ΔH_{tor} is the specific enthalpy of torrefaction expressed in units of energy per unit of dry mass loss (MJ kg^{-1}), and $\eta_{f,T}$ is the efficiency of the torrefaction reactor, which was assumed equal to 0.85 [5]. Torrefaction is a mildly exothermic or endothermic process depending upon the torrefaction temperature [4]. In this work, a unique value (i.e., ΔH_{tor}=-5.72 MJ kg^{-1}) was assumed for the enthalpy of torrefaction of tomato peels, which was obtained directly from a DSC measurement carried out at the decomposition temperature of 285 °C. In keeping with Michel and McCormick [9] the low heating value of torgas leaving the torrefier was estimated using the energy balance between the raw biomass and the solid product as follows:

$$LHV_{torgas} = \frac{LHV_{TTPs} \cdot (1 - E_Y/100)}{(1 - M_Y/100)} \tag{6}$$

where LHV_{TTPs} (MJ kg^{-1}, db), E_Y (%, db) and M_Y (%, db) are respectively the low heating value, the mass yield and the energy yield of torrefied tomato peels as obtained by Eq. 2-4 for the selected operating conditions. LHV_{torgas} data calculated by energy balance (Eq. 6) are generally within 10% of values obtained using torgas composition [9]. Accordingly, the available energy which is generated by the combustion of torgas can be expressed as follows:

$$Q_{burner} = LHV_{torgas} \cdot W_{TPs} \cdot (1 - M_{TPs}/100) \cdot (1 - M_Y/100) \cdot (1 - H_L) \cdot \eta_{f,C} \tag{7}$$

where $\eta_{f,T}$ is the efficiency of combustor, which was assumed equal to 0.85 [5] and H_L is the heat loss fraction through the heat exchanger, taken as 0.005 [5]. Temperature of torrefied TPs leaving the torrefied was considered to be the same as torrefaction temperature, T_T. The heat available by cooling the torrefied solid product was calculated as follows:

$$Q_{cooler} = W_{TPs} \cdot (1 - M_{TPs}/100) \cdot (M_Y/100) \cdot C_{pd} \cdot (T_T - T_C) \tag{8}$$

In a properly designed and operated torrefaction system the extracted energy, Q_{cooler}, may be partially recovered in the form of hot air, which could be gainfully utilized for providing a part of the energy required for drying or pre-heating the biomass or directly as preheated burner air. Therefore, the net energy required to process 1 kg of wet TPs, ΔQ_{total} (MJ), can represented as follows:

$$\Delta Q_{total} = (Q_{drier} + Q_{torrefier}) - Q_{burner} \tag{9}$$

The investigated system is considered globally autothermal when the energy content of torgas Q_{burner} balances both the heat duty of drying and torrefaction ($Q_{drier} + Q_{torrefier}$) and hence ΔQ_{total}=0. A process thermal efficiency η_P was defined as the ratio between the available energy of the solid product (MJ) and the sum of the energy inputs from the raw feedstock and auxiliary utilities, as follows:

$$\eta_P = \frac{W_{prod} \cdot LHV_{prod}}{W_{feed} \cdot LHV_{feed} + Q_{utility}} \tag{10}$$

In this study, fossil fuels only have been considered for operating the process below the point of autothermal regime ($\Delta Q_{total} < 0$). Model calculations were performed using a Microsoft Excel spreadsheet.

Results

Results of modeling mass and energy balance for a stand-alone torrefaction plant operated at 285 °C and 30 min residence time are shown in the flow-chart of Fig. 1. Data highlight that for typical torrefaction conditions, where about 20-30% of the dry mass is removed in the form of volatile gases (i.e., M_Y=77.86% and E_Y=84.48% on dry basis for TPs torrefied at 285 °C and 30 min), the process cannot be operated autothermally. In fact, the total thermal energy available in the torgas was approximately 72% lower than the overall energy required for torrefying raw tomato peels, which have 80.5% initial moisture content. Model results also show that the drying step requires the largest energy consumption (~ 2.41 MJ) of the total pretreatment system, while TG-DSC measurements showed that torrefaction of dry tomato peels is a mildly exothermic process upon the investigated operating conditions. In the temperature range 180-285 °C an exothermic peak was, in fact, observed in the DSC plot (not shown). The numeric integration of DSC signal (W g^{-1}) across a defined time area (1h) provided a value of the enthalpy of torrefaction (MJ kg^{-1}) equal to 5.73 MJ/kg dry mass loss. The net thermal efficiency of the whole conversion process was estimated to be approximately η_P=70% while the E_Y of the torrefaction unit was 85%.

Conclusions

Findings from this research work suggest that the thermal integration of a torrefaction unit with another plant or industry may be the best option for the treatment of high moisture agro-industrial residues in order to save the overall energy efficiency. In particular, since a potential end-user for torrefied biomass is the gasification process, which has large amounts of waste heat coming from the refinement chain of the syngas, a full integration between the mass and energy flows of torrefaction and gasification processes appears a promising option and hence deserves further critical analysis.

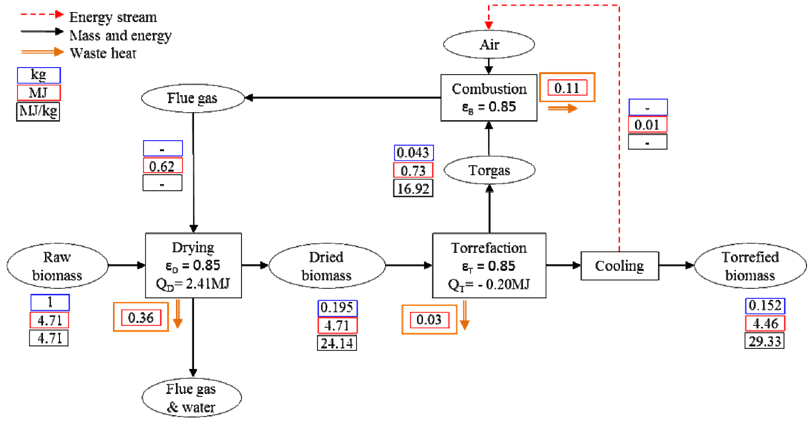

Figure 1. Mass and energy flows for torrefaction of wet tomato peels at 285 °C and 30 min residence time

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