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Simulation and flowsheeting of agro-industrial residues torrefaction: the case of tomato peels waste

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***Abstract*— Torrefaction is a thermal pretreatment for biomass feedstocks of various origin, which is usually carried out in an inert atmosphere, at ambient pressure and in a temperature range of 200-300 °C. It has the ability to reduce the main logistic and application limitations of biomass, arising from its heterogeneity, low bulk density, low energy density, hygroscopic behavior and fibrous nature. During torrefaction a combustible gas ('torgas') consisting of different organic compounds 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.**

This paper focuses on the valorization of biomass made available from low-value, wet agro-industrial residues. The aim of this work is to provide the conceptual design and technical analysis of a torrefaction process for recovery and upgrade of wet tomato peels, which are a typical industrial waste in the Campania region (IT).

The Aspen Plus^{TM} software was used to depict the flowsheeting of the investigated torrefaction process, to develop and solve material and energy balances of the whole process, to carry out the internal heat integration steps. A novel aspect is the modeling of the torrefaction reactor, which was carried out by taking advantage of experimental correlations available in the literature from authors' previous work. Drying of the wet biomass feedstock results a very energy-demanding operation. The main output of this study is the calculation of the process energy demand from external sources. Therefore, the paper discusses how far the torrefaction process of high-moisture tomato peel residues is from autothermal operation, provided the best available process design options and internal heat integration steps.

***Index Terms*—[1] Tomato peels, torrefaction, flowsheeting, simulation, Aspen Plus^{TM}.**

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I. 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, 2]. 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" [1, 3]. The final product is the residual solid, which is often referred to as torrefied biomass. The main biomass components (e.g., hemicellulose, cellulose, lignin and extractives) decompose to a different extent and with a different rate in the torrefaction temperature window [4], thus providing a different contribution to the mass and energy yield of the converted 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. Many other feedstocks, however, arising as waste streams and residual biomass have a lower value and a larger availability, and are gaining an increasing interest in torrefaction. As far as agro-industrial wastes, despite their high potential, the current knowledge about the technical and economic performance of their torrefaction treatment is still poor.

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 [5] is assessed. In more details, a process model has been developed, based on mass and energy balances, and implemented into a flexible Aspen Plus^{TM} flowsheet for simulating the basic processing units included in a typical

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torrefaction plant. Some papers based on modeling and simulation of an integrated torrefaction process by means of the Aspen Plus™ software were published in literature; works by Arteaga-Perez et al. [6] and Haryadi et al. [7] are the closest and the most useful ones with reference to this study.

The main output of this work is the calculation of the process energy demand to be provided from external sources. Therefore, the paper discusses how far the torrefaction process of high-moisture tomato peel residues is from autothermal operation, in spite of the best available process design options and internal heat integration steps.

The present work assumes that a plant eventually implementing the investigated torrefaction process should be located within or close to the site of an industrial tomato-processing factory. This assumption sounds realistic for many reasons, first of all the advantages derived from the logistics of TPs storing, handling and transporting. Moreover, this work complements the experimental study on the torrefaction of TPs carried out in authors' previous works [4, 5].

II. Materials and Methods

A. *Tomato Peels*

In this paper tomato peels are considered as the main residue of tomato industrial processing to be devoted to the torrefaction process. The estimate of the amount of tomato skins to be treated is calculated on the basis of the following case study. 50000 tons of bulk tomatoes, harvested from mechanical harvesting, arrive at the tomato processing factory in a 50-day working campaign [8]. After the washing phase, the so-called MOTs (i.e., Materials Other than Tomato) are removed and the washed tomato is sent to juice extraction. In this plant section, the mechanical separation is carried out for residues (i.e., peels, seeds and minor fruit parts); they are going to constitute MPS (secondary raw materials) together with other minor wastes from other plant sections, amounting to 1850 t [8]. When dividing this amount by the number of production days (i.e., 50), a generation of MPS of 37 t/d (daily) and 1.54 t/h (hourly) is found. For the present work, therefore, a calculation basis of 2 t/h was assumed for wet tomato peels.

TABLE I. Properties of Tomato Peels

Moisture (%wt., a.r.)	80.50
Proximate analysis (% wt., db)	
Volatile Matter	86.52
Fixed Carbon	11.67
Ash	1.81
Ultimate analysis (% wt., db)	
C	58.38
H	7.72
N	1.49
O (by diff.)	30.60
LHV	
as received (MJ/kg)	4.71
dry basis (MJ/kg)	24.14

Tomato peels (TPs) were actually sampled from a tomato processing factory in Salerno (40°47'24.5"N, 14°46'15.8"E), Campania region (IT), in September 2014 and then subject to analysis. The results are in Table I: they have a moisture content as high as 80.5% wt., but a calorific value (LHV) as high as 24.14 MJ/kg on dry basis [5].

B. *Aspen Plus™*

Aspen Plus™ was used to simulate the process. It is a flowsheeting software developed by AspenTech, which allows to simulate a whole industrial process by integrating chemical and physical transformations in a very detailed way, as done by Sofia et al. [9]. The modeling is carried out by using block units, which simulate different unit operations and sub-processes, connected to each other by material streams or energy flows. Aspen Plus has a huge database of chemical compounds with their properties, as well as the ability to define non-conventional components, such as biomass and coal, through their ultimate and proximate analysis, as done by Ferrentino et al. [10]. This latter feature allows to simulate the torrefaction of biomass. Finally, it is possible to include calculator blocks to integrate a Fortran code and fix design specifications. Aspen Plus uses an iterative solution method, calculating streams block after block, up to convergence.

III. Simulation

A. *Process Flowsheeting*

The following general assumptions hold:

- The process is continuous and steady-state
- All the process units work at atmospheric pressure
- Carbon dioxide is used instead of nitrogen wherever an inert gas is required in the investigated process. This assumption is based on the idea that CO_2 will be more and more available at a convenient price from the sequestration stages being implemented in combustion processes. Moreover, torrefaction tests performed in TGA (not shown here) demonstrated that CO_2 acts as an inert gas during the torrefaction treatment of TPs.
- Due to the low pressure and the presence of conventional gaseous compounds (such as H_2O, CO, CO_2), the ideal gas law equation is adopted for calculating thermodynamic properties

The flowsheeting work in Aspen Plus™ was preceded by a rough schematization of the tomato peels torrefaction process in terms of a block diagram, as shown in Figure 1.

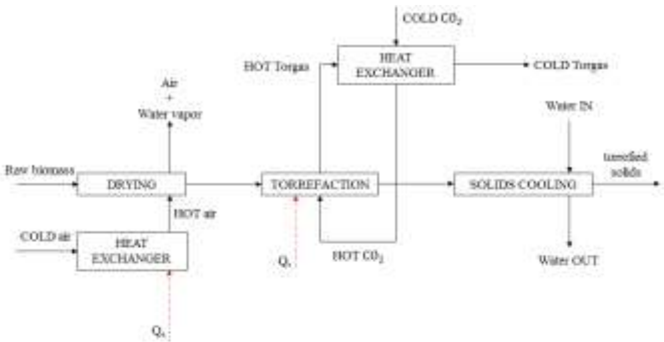

Figure 1. Block diagram of the torrefaction process.

The raw feedstock (i.e., the wet tomato peels) is first dewatered in an air dryer, where most of moisture is removed as water vapor while, obviously, the required heat rate Q_e is to be supplied from an external source of energy.

The dry tomato peels proceed to a reactor where they lose the residual moisture and undergo the torrefaction reactions in a given residence time while being in contact with a continuous hot CO_2 stream. As expected, a heat duty Q_t is required in the torrefaction reactor and is to be supplied from an external source of energy; such a heat duty must provide, at least, the sensible heat necessary to raise the dry tomato peels to the torrefaction temperature. It is in fact well known torrefaction could be a mildly exothermic or endothermic process depending upon the torrefaction temperature [1, 4].

The hypotheses directly related to the torrefaction reactor in the investigated process were the following:

- Tomato peels enter the torrefaction reactor with a residual moisture content (after drying) x_{tw} = 15 % wt.
- Torrefaction is carried out at a temperature T_t = 240 °C
- The average residence time of solids inside the torrefaction reactor is t_t = 5 min
- The yield of torrefied material from tomato peels is calculated on the basis of the experimental results and subsequent correlations of Brachi et al. [5]
- The yield and the chemical composition of the gases formed by torrefaction (torgas) is calculated on the basis of the experimental results and subsequent correlations of Tito Ferro et al. [11]
- Ashes are considered inert and do not participate in chemical reactions

The experimental correlations (Eq. 1-3) providing the dependence on torrefaction operating conditions for the low-heating value (LHV), mass (MY) and energy (EY) yields were derived from our previous study on fluidized bed torrefaction [5], by means of batch tests performed at temperatures equal to 200, 240 and 280 °C, for residence times equal to 5, 15 and 30 min.

$$LHV\ (MJ/kg,\ db) = 19.9535+0.0209 \cdot T_t(°C)+0.0159 \cdot t_t(min) \quad R^2=0.96 \tag{1}$$

$$M_Y\ (\%,\ db) = 130.6892-0.1627 \cdot T_t(°C) -0.2154 \cdot t_t(min) \quad R^2=0.97 \tag{2}$$

$$E_Y\ (\%,\ db) = 119.5931-0.1057 \cdot T_t(°C)-0.1664 \cdot t_t(min) \quad R^2=0.91 \tag{3}$$

The experimental correlations (Eq. 4) providing the torgas composition y as a function of the torrefaction operating conditions were derived from the results published by Tito Ferro et al. [11] in the form of linear regression:

$$y\ (\%\ vol.) = a\ T_t\ (°C) + b \tag{4}$$

where the regression coefficients are in Table II.

The low values of the correlation coefficient R^2 are due to the fact that the experimental studies by Tito Ferro et al. [11] were conducted on a wide range of lignocellulosic biomass.

TABLE II. REGRESSION COEFFICIENTS FROM TITO FERRO ET AL. [11] DATA

Gas	a	b	R^2
CO	0.1312	-12.286	0.3789
CO_2	-0.1359	113.31	0.3913
CH_4	0.0035	-0.08094	0.5212
C_2H_6	0.001	-0.179	0.2767

Two streams leave the torrefaction reactor, i.e., one made by torrefied solids and another by volatiles diluted in the CO_2 stream (torgas). Both streams need cooling before any further step. Torgas, which is mainly composed of CO_2, cannot be burned, but lends itself to recover most of its enthalpy, thus pre-heating the cold CO_2 stream in a heat exchanger. The torrefied solids must be cooled down for their subsequent storage as the desired product, and before coming into contact with external air, which would oxidize them; therefore, a water-refrigerated unit is considered as the final block for cooling solids.

A simple enthalpy balance is carried out at steady state over the whole control volume comprising both the drying and the torrefaction sections, as well as the integrated heat exchanger operations. It is written as:

$$Q_e + Q_t - Q_r = \Delta Q \tag{5}$$

where Q_r is the enthalpy recovered in the various steps of integrated heat exchange and counterbalancing the heat duties required for drying and torrefaction; ΔQ is the enthalpy to be additionally supplied from an external source of energy, if any.

B. Aspen Plus™ flowsheet implementation

The above process was simulated in Aspen Plus™ through the implementation of two sections in series, i.e., "drying" and "torrefaction" (see Figure 2).

The "drying" section simulates the air drying of tomato peels through a stoichiometric reactor (the RStoic1 block in Figure 2). Although drying is not normally a chemical reaction, the following pseudo-chemical reaction has been considered to convert a portion of biomass to water:

$$\text{Biomass (wet)} \rightarrow 0.055084\ H_2O \tag{6}$$

This is due to the fact that Aspen Plus treats all unconventional components as if they had a molecular weight equal to 1. The reaction therefore indicates that 1 mole of biomass reacts to form 0.0555084 moles of water.

The heat duty required for drying is provided by an air stream, which is heated by the conventional "exchanger" blocks EX1 and EX2 in Aspen Plus.

An embedded "Calculator Block" is used to check the actual drying of the processed solids.

The "torrefaction" section implements torrefaction of the dried tomato peels according to the principle of sequential modular simulation with 5 Aspen Plus™ blocks:

1. RStoic2 is a first stage of torrefaction with final drying of TPs to 0 %wt. moisture.

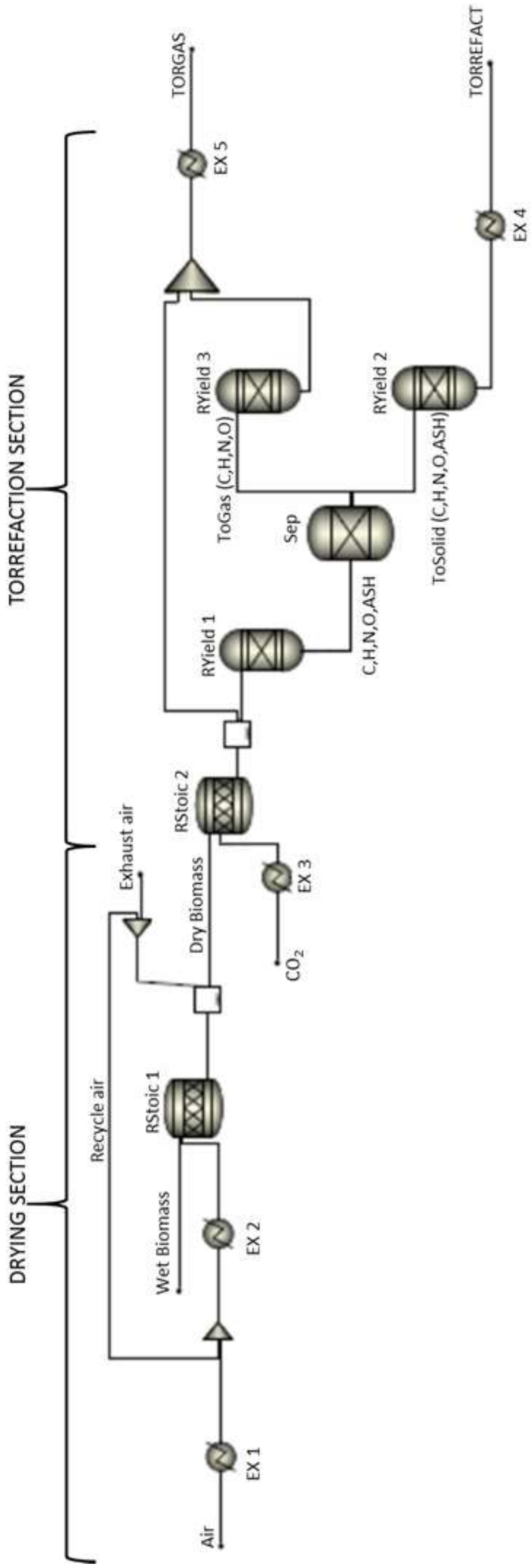

Figure 2. ASPEN flowsheet implementation.

2. RYield1 transforms incoming biomass from a non-conventional component into a conventional component, based on its elemental composition shown in Table I.
3. SEP defines the solid torrefied product and separate it from torgas. The above equations 1-3 was written in a Fortran code and then embedded in this Aspen Plus block.
4. RYield2 defines the solid product formation. This block recomposes the torrefied solid as a non-conventional element from its elemental constituents.
5. RYield3 defines torgas formation. This block recomposes the gaseous product from its elemental constituents. The above set of equations 4 was written in a Fortran code and then embedded in this Aspen Plus block.

After the "torrefaction" section, cooling of both torgas and torrefied solids is implemented in Aspen Plus by means of conventional "heat exchanger" blocks (see Figure 2).

IV. Results and Conclusions

Table III reports for the present case study (e.g., a calculation basis of 2 t/h of wet tomato peels) the heat duties as calculated by Aspen Plus^{TM} block by block. A negative heat duty for a given block indicates that enthalpy is made available by that block as a heat source.

TABLE III. Details of the Heat Duties

Aspen Plus^{TM} block	Heat Duties (W)
EX1	141945
EX2	1048508
EX3	16091
EX4	-42274
EX5	-16091
RStoic1	0
RStoic2	96987
RYield1	637472
RYield2	-542472
RYield3	-87498
ΔQ	1252667

It is noteworthy that the RStoic1 block (i.e., the stoichiometric reactor for drying in Figure 2) exhibits a null heat duty, since it is an adiabatic reactor. This is in agreement with the way drying has been actually implemented in Aspen Plus (see above); however, the enthalpy flow actually required for drying is provided through the heat exchange blocks EX1 and EX2. Moreover, it has to be noted that the heat duty associated to the heating exchanger EX3 has exactly the same absolute value, but the opposite sign of the cooling exchanger EX5, thus indicating a perfect heat integration for the CO_2

process stream, which heats up at the expenses of the hot torgas (see Figure 1).

The negative values of heat duties as calculated for the blocks RYield2 and RYield3 indicate the "pseudo-heat of formation", which is made available upon the "re-composition" of the torrefied solid and the torgas, respectively, from their elemental constituents. Such an enthalpy flow counterbalances the sensible heat required to raise the dry biomass up to the torrefaction temperature.

In the end, the overall heat duty of the process is $\Delta Q = 1.25$ MW. Therefore, the enthalpy balance carried out at steady state over the whole control volume including both the drying and the torrefaction sections, as well as the integrated heat exchanger operations, demonstrates that the torrefaction of high-moisture tomato peel residues is a very energy-demanding operation and that enthalpy is to be additionally supplied from an external source of energy.

Anyway, the thermal integration of a torrefaction unit within another plant remains a valuable option for the treatment of high moisture agro-industrial residues in order to achieve an overall energy saving. In particular, since a potential end-user for torrefied biomass is the biomass gasification technology, 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 investigation.

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