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Fluidized Bed Design and Process Calculations for the Continuous Torrefaction of Tomato Peels with Solid Product Separation

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This work reports the Authors' concept idea and the gross design of a plant system capable of continuously separating the torrefied solids from the inert bed material downstream from a fluidized bed reactor, where biomass torrefaction is performed in a continuous operation mode. It is constituted of three units that process solids: i. a bubbling fluidized bed, equipped with a heat exchanging tube bundle, acting as a torrefaction reactor; ii. an inclined plate sieve separator for collection of the torrefied product as oversize solids; iii. a loop-seal for reinjection of undersize particles, i.e., the inert solids, back into the bed.A simple model of the torrefaction reactor as a well-stirred system has been devised to predict the conversion of feedstock (i.e., tomato peel particles) on the basis of an empirical correlation previously established by the Authors under batch conditions; the variability of biomass particle residence time in the bed as induced by the fluidization of inert solids has been accounted for by introducing a distribution function of the biomass residence time, and this latter has been suitably incorporated within the equations yielding the bed inventory of biomass. The recycling system of undersize inert solids back into the bed through a standpipe and a loop-seal for reinjection has been simply designed according to literature.The resulting set of equations is easily handled and smoothly provides the plant design variables and the relevant process calculations.

1. Introduction

An investigation devoted at screening the agro-industrial residues (Brachi, 2016a) produced in the Campania region (Italy) has assessed that tomato processing residues stand out among those needing a more sustainable and environmentally effective disposal, avoiding fast biologic degradation and emission of odors in the atmosphere. Furthermore, they represent a residual lignocellulosic biomass that, compared to other similar feedstocks, has a great valorization potential in terms of both extraction of bioactive compounds and conversion to biochar, renewable biofuels or chemicals (e.g., torrefaction and gasification).
Torrefaction is nowadays a well-established technology for upgrading biomass to more stable solid fuels. Basically, it is a thermochemical treatment where biomass is heated in an inert environment to a temperature of 200–300 °C. Typically, it is characterized by low particle heating rate (<50 °C/min) and by a relatively long reactor residence time that, depending on feedstock, technology, and temperature, ranges from 30 min to 120 min. It looks at renewable feedstocks and yields renewable biofuels, within the guidelines of the EU Green Deal and toward the targets of EU 2050. It works well on conventional lignocellulosic biomass, but it is also suitable

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for the recovery and the conversion to biofuels of wet and difficult wastes, e.g., agro-industrial residues (Negi et al., 2020). Chen et al. (2021) carried out a comprehensive review and reported the state-of-the-art of biomass torrefaction. They found that the developed reactors in commercial companies or scale-up laboratories consist of (1) fixed bed reactor; (2) rotary drum reactor; (3) screw reactor; (4) microwave reactor; (5) moving-bed reactor; and (6) others such as torbed reactor, belt drier, multiple hearth furnace, vibrating electrical elevator and reactor (REVE), rotating-packed bed reactor, and spouted-bed reactor. However, concluding their discussion, Chen et al. (2021) stated that there is still no obviously preferred one as the reactors simultaneously have pros and cons; in particular, there is no best reactor design suitable for any feedstock, but the proper selection of the reactor is to be referred to the given feedstock (Chen et al., 2021).
The Authors of the present work already focused on the torrefaction of agro-industrial residues, in particular tomato peels (Brachi et al., 2016b) and orange skins (Brachi et al., 2019), by proposing the use of the less investigated fluidized bed technology in the presence of inert solids. While operating in a batch mode with respect to the biomass, they could highlight the inherent advantages of the fluidized bed processing, namely the significant reduction of particle torrefaction time, the homogeneity of process conditions and the uniform characteristics and quality of torrefied products. However, following the above-mentioned research work (Brachi et al., 2016a; Brachi et al., 2019), an important issue remained unsolved: the procedure to separate the torrefied solid product from the inert bed particles while maintaining the fluidized bed operation. This work therefore aims to propose an agreeable technical solution for the above technical issue. The factors driving the conceptual design have been the viability of operation and the process intensification, both relying on the Authors' know-how gained with the bench-scale experimental work.

2. Model equations and sizing calculations

2.1 Model assumptions

The feedstock specifications and the plant capacity have been reasonably fixed taking into consideration the seasonal production of a large tomato processing plant in the Campania region (Italy): this led to a base case (Casa et al., 2021) in which 230 kg/h of dried tomato peels (i.e., starting from 2 t/h of wet tomato peels) are to be processed. Since the torrefaction process involves the partial thermal degradation of biomass under an inert atmosphere, all gaseous streams required for process operation have been considered to consist of CO_2, which acts nearly like an inert gas under the mild torrefaction operating conditions. This choice is intended at "saving" nitrogen, whereas it is sustained by the larger and larger availability of CO_2 made possible by the current carbon sequestration processes in power generation.
The main particle properties of the tomato peels and inert solids co-processed in the continuous fluidized bed are reported in Table 1.

Table 1: Main properties of the bed component materials

Tomato peels	
Moisture mass fraction $\omega_{TP,w}$ [-]	0.15
Particle density ρ_{TP} [kg/m^3]	745
Particle nominal size interval [m]	$(1 – 2)•10^{–3}$
Inert particles	
Type of solids	Fine silica sand
Sauter diameter d(3,2) [m]	$1.5•10^{-4}$
Density ρ_P [kg/m^3]	2813.5
Sphericity [-]	1
Minimum fluidization velocity U_{mf} [m/s] at T=25 °C	0.017

The following assumptions hold:
- torrefaction occurs in fluidized bed reactor of inert sand particles with a continuous feed of both inert gas, i.e., CO_2, and biomass;
- the bed aspect ratio is the same as in the study by of Brachi et al. (2016b): H_{LF}/D_{BED} =1.7;
- the mass fraction of tomato peels in the biomass-sand binary bed is taken as X_{TP} = 9% wt. since, according to Brachi et al. (2017), beyond this value the fluidization pattern deteriorates;
- the mass yield MY is taken as the performance index of the torrefaction treatment;
- a reference condition is taken for torrefaction after the work of Brachi et al. (2016b): a torrefaction temperature T = 240 °C and a torrefaction time τ = 5 min, in an inert atmosphere;
- the torrefaction of tomato peels as a function of temperature and time is accounted for using the experimental correlation by Brachi et al. (2016a):

$$MY\ [\%, db]] = 130.6892 - 0.1627 \cdot T[°C] - 0.2154 \cdot t[min] \quad (1)$$

- the tomato peel particles undergo torrefaction with a variety of residence times t in the reactor, according to the following residence time distribution (RTD) function:

$$E(t) = \begin{cases} 0 & when < \tau_p \\ \frac{e^{-(t-\tau_p)/\tau_s}}{\tau_s} & when \geq \tau_p \end{cases} \quad (2)$$

which is the RTD of two ideal reactors, i.e., PFR and CSTR, in series. Specifically, the PFR residence time is assumed to be $\tau_p = \tau/2\ [min]$ and the CSTR residence time is assumed to be $\tau_s = \tau = 5\ [min]$

According to the above, since the mass yield evolution of an individual feedstock particle is known as a function of T and t, the average mass yield MY* of the biomass torrefied at a prefixed T and for a given time t*, can be calculated by integrating that function, weighted by the expected distribution function of the residence time E(t).

$$MY^*\ [\%, db] = \int_0^{t^*[min]} MY(T, t) \cdot E(t)\, dt \quad (3)$$

As a consequence of above, the mass of biomass (i.e., dry solids) residing inside the fluidized bed with a characteristic time t* is calculated as follows:

$$W_{TP}[kg] = (1 - \omega_{TP,w}) \cdot F_{TP}[\tfrac{kg}{s}] \cdot t^*[s] \quad (4)$$

2.2 Geometric sizing of the fluidized bed reactor

The inventory of inert material W_{SAND} required to promote a good fluidization behavior is calculated by:

$$W_{SAND}[kg] = \frac{1-X_{TP}}{X_{TP}} W_{TP}\ [kg] \quad (5)$$

The volume of the fixed bed is determined taking into account the averaged value of the bed density:

$$\frac{1}{\rho_{BED}\left[\frac{kg}{m^3}\right]} = \frac{X_{TP}}{\rho_{TP}\left[\frac{kg}{m^3}\right]} + \frac{X_{SAND}}{\rho_P\left[\frac{kg}{m^3}\right]} \quad (6)$$

$$V_{LF}[m^3] = \frac{W_{SAND}[kg] + W_{TP}[kg]}{\rho_{BED}\left[\frac{kg}{m^3}\right] \cdot (1-\varepsilon_b)} \quad (7)$$

Consequently, the other bed geometric characteristics can be calculated as follows:

$$H_{LF}[m] = 1.7 \cdot D_{BED}[m] \quad (8)$$

$$D_{BED}[m] = \sqrt[3]{\frac{4\, V_{LF}[m^3]}{\pi \frac{H_{LF}}{D_{BED}}}} \quad (9)$$

$$A_{BED}[m^2] = \pi \frac{D_{BED}^2}{4} \quad (10)$$

However, a geometry with rectangular and not circular cross-section is preferred to handle the issue of continuous discharge and separation of the mixture of solids consisting of inert and torrefied biomass. Hence:

$$L_{BED}[m] = \sqrt[2]{A_{BED}[m^2]} \quad (11)$$

Finally, the mass flow rate of CO_2 necessary for the fluidization of the bed is calculated:

$$F_{CO_2}\left[\frac{kg}{s}\right] = U_{CF,240}\left[\frac{m}{s}\right] \cdot \rho_{CO_2,25°C}\left[\frac{kg}{m^3}\right] \cdot \frac{(25+273.15)\ K}{(240+273.15)K} \cdot A_{BED}[m^2] \quad (12)$$

where $U_{CF,240}$ is the superficial velocity for complete fluidization.
Further details about the fluid dynamics of the bubbling bed and the energy demand of the torrefaction reactor, which is supplied by means of an immersed heat exchanging tube bundle, can be found in Guerriero (2017). For the separation and the subsequent collection of the torrefied peel particles, a weir was considered on the top of the bed followed by a sieve separator arranged as an inclined plane, which in principle allows the inert solids to pass through the mesh of the separation grid, whereas completely conveys the torrefied particles to a gravity collection duct. A Loop-Seal apparatus (Basu, 2006) is then necessary for the recirculation of the inert

solids to the fluidized bed reactor. A schematic of the fluidized bed with the overflow weir, the separation grid for torrefied biomass and the loop-seal for recycling the inert solids is shown in Figure 1

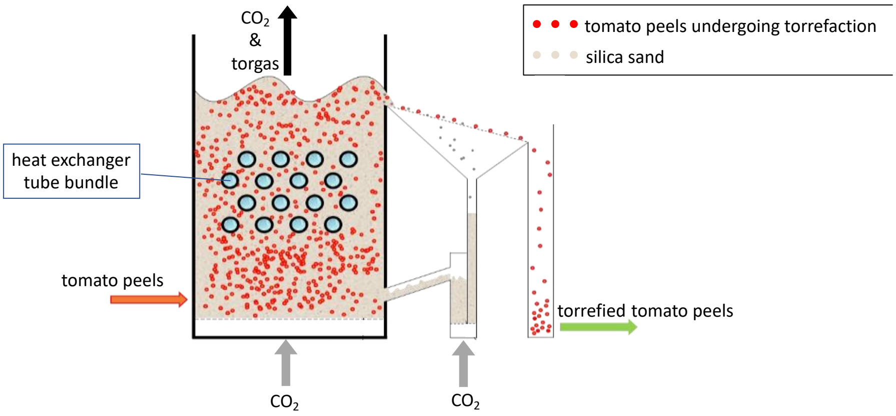

Figure 1: Scheme of the continuous torrefaction process plant with the fluidized bed reactor, the separation system of the torrefied biomass and the loop seal for the recirculation of the inert solids

The loop-seal consists of a downpipe and an adjacent secondary fluidized bed. The solids from the downpipe enter by gravity the loop-seal pot from one side. The aeration of the standpipe is not considered here (Basu, 2006). The principle of balancing the pressure in the system applies (Basu, 2006):

$$P_{pl,s} - \Delta P_{dist,s} - \Delta P_{b,s} > P_{pl,b} - \Delta P_{dist,b} - \Delta P_{b,b} \quad (13)$$

where the subscripts are as follows: pl = plenum; s = loop seal; dist = distributor; b = bed. The pressure drop $\Delta P_{b,s}$ in the recycle chamber of the loop-seal, which hosts the secondary bed with a fluidized height H_S, is:

$$\Delta P_{b,s} = (1 - \varepsilon_s) \cdot \rho_P \cdot H_s \cdot g \quad (14)$$

The pressure drop $\Delta P_{b,b}$ in the main bed below the entry port of the recycled solids at a height H_{RP} is:

$$\Delta P_{b,b} = (1 - \varepsilon_b) \cdot \rho_P \cdot H_{RP} \cdot g \quad (15)$$

Further, according to Basu (2006), it is assumed:

$$\Delta P_{dist,s} = \Delta P_{dist,b} \quad (16)$$

The above Eqs. 13-16 allow calculating the minimum pressure $P_{pl,s}$ in the plenum chamber upstream of the loop-seal that allows its operation. As concerns the geometrical sizing of the loop-seal, the following relationships are used according to Basu (2006). The diameter D_{sp} of the vertical standpipe is calculated by:

$$D_{sp}=(v_s/1.6)^2 \quad [m] \quad (17)$$

where the downward solids velocity in standpipe takes the value v_s = 0.2 m/s according to Basu (2006).

Then, the length L_{LS}, the width W_{LS}, the resulting cross-sectional area A_{LS} of the loop-seal and the cross-sectional area A_{RC} of the recycle chamber are calculated as:

$$L_{LS} = 2.5D_{sp}, \quad W_{LS} = 1.25D_{sp}; \quad A_{LS} = L_{LS} \bullet W_{LS} \quad [m^2], \quad A_{RC} = A_{LS}/2 \quad [m^2] \quad (18)$$

The fluidizing velocity in the recycle chamber is calculated according to the following equation (Basu, 2006):

$$U_{RC} = 8U_{mf} \quad [m/s] \quad (19)$$

Consequently, the mass flow rate of CO_2 necessary for the fluidization of the recycle chamber is:

$$F_{LS,CO_2}\left[\frac{kg}{s}\right] = U_{RC}\left[\frac{m}{s}\right] \cdot \rho_{CO_2,25°C}\left[\frac{kg}{m^3}\right] \cdot \frac{(25+273.15)\,K}{(240+273.15)K} \cdot A_{RC}[m^2] \quad (20)$$

Finally, the cross-section A_{EP} of the inclined exit pipe, which carries solids from the loop-seal back to the bed, is taken equal to that of the standpipe:

$$A_{EP} = (\pi/4)\, D_{sp}^2 \quad [m^2] \quad (21)$$

3. Results

Upon solving the Eq. 3, the residence time is calculated as t* = 30 min. All the geometric characteristics, fluidization features and operating conditions of the fluidized bed torrefaction reactor can be computed in cascade from the Eqs. reported in Section 2.2. They are summarized in Table 2.

Table 2: Main features of the fluidized bed torrefaction reactor

Main fluidized bed data			
F_{TP} [kg/s] as the calculation basis	0.064	A_{BED} [m^2]	0.66
W_{TP} [kg]	115	L_{BED} [m]	0.81
W_{SAND} [kg]	1274	H_{LF} [m]	1.56
D_{BED} [m]	0.92	$U_{CF,240}$ (Brachi, 2016a) [m/s]	0.13
		F_{CO_2} [kg/s]	0.05

Using the equations provided in the previous section, the minimum value of the pressure in the plenum chamber upstream of the loop-seal, which allows this latter to work correctly, is calculated: it is $P_{pl,s}$ = 126000 Pa. Table 3 reports the other consequent results for the geometric sizing of the loop-seal. As the results clearly show, the loop-seal comes out reasonable small compared to the main bed, as well as easy to build and operate.

Table 3: Design and operating data for the loop-seal

Main bed data		**Loop seal data**	
ε_b [-]	0.50	Voidage fraction ε_s [-]	0.5
H_{RP} [m]	0.05	H_S [m]	0.2
$P_{pl,b}$ [Pa]	106000		
Results of sizing calculations			
$\Delta P_{b,s}$ [Pa]	2760	A_{LS} [m^2]	0.0008
$\Delta P_{b,b}$ [Pa]	690	A_{RC} [m^2]	0.0004
$P_{pl,s}$ [Pa]	126000	U_{RC} [m/s]	0.136
D_{sp} [m]	0.0156	F_{LS,CO_2} [kg/h]	0.114
L_{LS} [m]	0.0391	A_{EP} [m^2]	0.00019
W_{LS} [m]	0.0195		

4. Conclusions

A novel concept plant for steady-state fluidized bed torrefaction and continuous separation of the torrefied product has been conceived in a preliminary way. The combination of Authors' experimental results and modeling of the torrefaction reactor in a reasonably simple way (RTD described as a PFR followed by a CSTR) enabled a quick sizing of the fluidized bed.

The gross design provided by this work demonstrates that the proposed concept plant is technically feasible. In a medium-size tomato canning factory, it can continuously process a feed rate of 230 kg/h of dry tomato peels in a small-scale torrefying reactor (a square cross-section of less than 1 m^2) and a small-size loop-seal (rectangular, 4x2 cm) for recycle of inert solids to the bed. In tomato processing industry, the proposed plant design would deliver both an improved sustainability through conversion of residues, i.e., tomato peels, into a renewable solid biofuel, and process intensification through the compact size and the limited allotment of ground space: hence, the proposed concept plant is expected to fit the layout of the tomato processing factory and to be easily allocated within available spare area.

The calculation model for the fluidized bed torrefaction reactor will be improved in future by considering more realistic situations, such as a dependence of the biomass residence time in the bed on particle size, an oversize separation efficiency lower than 100% at the inclined plate sieve, etc.

Nomenclature

A_{BED} – bed cross-sectional area, m^2
A_{EP} - cross-section of the inclined exit pipe, m^2
A_{LS} – cross-sectional area of the loop seal, m^2
A_{RC} - recycle chamber cross-sectional area, m^2
d(3,2) – particle Sauter diameter, m
D_{BED} – bed diameter, m
D_{sp} - vertical standpipe diameter, m
F_{CO_2} - CO_2 flow rate for bed fluidization, kg/h
F_{LS,CO_2} - CO_2 flow rate for fluidization of recycle chamber, kg/h

F_{TP} – mass feed rate of tomato peels, kg/h
g – gravity acceleration, m/s^2
H_{LF} – Height of the fluidized bed, m
H_{RP}- Height of the solids return point to the bed, m
H_s – bed height in loop-seal recycle chamber, m
L_{BED} – side of the square-section bed, m
L_{LS} - loop-seal length, m
MY – mass yield, %db
$P_{pl,b}$ - pressure in the plenum chamber upstream of the bed, Pa
$P_{pl,s}$ – pressure in the plenum chamber upstream of the loop-seal, Pa
t – time, min
T – temperature, °C
$U_{CF,240}$ – superficial velocity for complete fluidization, m/s
U_{mf} – minimum fluidization velocity, m/s
U_{RC} - fluidizing velocity in recycling chamber, m/s
v_s - downward solids velocity in standpipe, m/s
V_{LF} – fluidized bed volume, m^3
X_{SAND}- sand mass fraction in binary bed, [-]
X_{TP} – tomato peels mass fraction in binary bed, [-]
W_{LS} - loop-seal width, m
W_{SAND} – inert material inventory in the bed, kg
W_{TP} - biomass inventory in the bed, kg (db)
ε_b – voidage fraction of the fluidized bed, [-]
ε_s – voidage fraction of the loop seal, [-]
$\Delta P_{b,b}$ - pressure drop in the main bed below the entry port of the recycled solids, Pa
$\Delta P_{b,s}$ - pressure drop in the recycle chamber of the loop-seal, Pa
$\Delta P_{dist,b}$ - pressure drop in main bed distributor, Pa
$\Delta P_{dist,s}$ – pressure drop in loop-seal distributor, Pa
ρ_{BED} – average bed density, kg/m^3
$\rho_{CO_2,25°C}$ – CO_2 density, kg/m^3
ρ_P – inert particle density, kg/m^3
ρ_{TP} – tomato peels particle density, kg/m^3
τ - batch torrefaction residence time, min
τ_p – PFR residence time, min
τ_s – CSTR residence time, min
$\omega_{TP,w}$ – tomato peels moisture mass fraction, [-]

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