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Research Paper

Evaluation of thermal drying for the recycling of flexible plastics

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ABSTRACT

The drying of flexible plastic waste is a current industrial problem in the plastic recycling sector. The thermal drying of plastic flakes is considered the most expensive and the most energy-consuming step in the recycling chain, which represents an environmental issue. This process is already present on the industrial scale but not well described in the literature. A better understanding of this process for this material will lead to the design of environmentally efficient dryers with an improved performance.

The objective of this research was to investigate the behavior of flexible plastic in a convective drying process at a laboratory scale. The focus was to study the factors affecting this process such as velocity, moisture, size and thickness of the plastic flakes in both fixed and fluidized bed systems and to develop a mathematical model for predicting the drying rate considering heat and mass transfer of convective drying. Three models were investigated: the first one was based on a kinetic correlation of the drying, and the second and third models were based on heat and mass transfer mechanisms, respectively. It was found that heat transfer was the predominant mechanism of this process, and the prediction of the drying was possible. The mass transfer model, on the other hand, did not give good results. Amongst five semi-empirical drying kinetic equations, three equations (Wang and Singh, logarithmic and 3rd-degree polynomial) provided the best prediction for both fixed and fluidized bed systems.

1. Introduction

Most plastic flexible films such as bags, food and agriculture packaging are considered as disposable plastics or single-use plastics because their recovering rate is very low, considering that the recycling technologies which are currently used have been developed for rigid plastic. Despite their low recycling rate, the consumption of plastic films is increasing sharply. Estimates for total polyethylene (PE) flexible films on the market are between 8.5 and 9 Mt per year, and the total flexible films demand across all polymers is estimated to be 13–15 Mt per year (Plastics recyclers Europe, 2020). The increase in the consumption of this type of plastic is largely due to the many cost and efficiency benefits that can be achieved in the supply chain. Significant environmental benefits can also be achieved by switching from a rigid to a flexible format, with savings of over 50 % in material and energy consumption helping to drive this trend (O'Farrell K. and H. Lewis, 2013; Patel et al., 2000).

Around 25.8 million tonnes of plastic waste are produced in Europe each year, 59 % of which are flexible packaging waste (European Commission, 2018), but only 32.5 % of this waste was recycled in 2018 (Combe, 2020). According to (The recycling magazine, 2018), the European Union (EU) recycling rate for flexible PE was roughly 31 % in 2018. This rate is very low compared to the target adopted by the EU, which sets the objective of recycling 55 % of plastic packaging by 2030. For this reason, a lot of research is devoted to improving the recycling of this type of waste.

Mechanical recycling is the widely adopted technology for large-scale treatment of plastic waste. It has the potential to save the processing energy as well as chemical energy compared to other recovering processes such as chemical recycling. Depending on the type of polymer, the processing energy of polymers ranges from 27 MJ/kg (PE) to 53 MJ/kg (PET) (Kaiser et al., 2018). The environmental benefit of mechanical recycling results from the savings of processing energy minus the energy used to collect, transport, and reprocess the plastic (~9 MJ/kg) (Kaiser et al., 2018). It consists of several operations such as collection, sorting, shredding, washing, drying and regranulation. Critical steps are washing (to remove the organic residues and contaminants) followed by the drying process, and two or more washing-drying processes may apply to remove the maximum of dirtiness and contaminants (Garcia & Robertson, 2017); (Briassoulis et al., 2013).

The disadvantage of mechanical recycling refers to the heterogeneity

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Nomenclature

A	surface of the plastic flake (m^2)
a, b and c	Antoine coefficients
$a = 8.07$, $b = 1730.63$	$c = 233.42$ (T in °C and P in mm Hg)
Cp_a	thermal capacity of air (kJ kg^{-1} K^{-1})
Cp_v	thermal capacity of water vapor (kJ kg^{-1} K^{-1}) Cp_w: thermal capacity of water (kJ kg^{-1} K^{-1})
Cp_s	thermal capacity of plastic (PE) ($kJ^{-1}kg^{-1}$ K)
C_i	the concentration of water vapor at the plastic surface (kg m^{-3})
$C\infty$	the concentration of water vapor in the air (kg m^{-3})
D	diffusion coefficient of water vapor in air (m^2 s^{-1}), $\left(D = 1.87^{-10}\frac{T^{2.072}}{P_{atm}}\right)$
D	Diameter of the tube (m)
d_p	Equivalent diameter of the plastic flakes (m)
ds	Bed diameter (equivalent to dh) (m)
dh	Hydraulic diameter of the tube (m)
ds	bed diameter considered equivalent to d_h (m)
e_p	plastic thickness (μm)
e_w	water layer thickness (μm)
h	Heat transfer coefficient (J S^{-1} K^{-1} m^{-2})
h_{bed}	Heat transfer coefficient of bed of plastic flakes (J S^{-1} K^{-1} m^{-2})
k	Mass transfer coefficient (m s^{-1})
K	Drying rate constant (s^{-1})
L	length of the tube (m)
L	Characteristic length (m)
$\%M$	moisture content in the plastic (kg of water/ kg of wet solid × 100)
M_{H_2O}	Molecular weight of water (kg/mol)
$\dot{m}_v$	vapor mass flow rate (kg/s)
m_w	water mass (kg)
$\dot{m}_a$	air mass flow rate (kg s^{-1})
m_s	plastic mass (kg)
R	Gas constant (8.314 J K^{-1} mol^{-1});
S	Total surface area of the plastic bed (m^2)
P_a	air partial vapor pressure (Pa)
P_s	plastic surface partial vapor pressure (Pa)
Q	Thermal energy needed for evaporation process ($J.S^{-1}$)
Ta	air temperature (K)
T_f	reference temperature, $T_f = 273.15$ (K)
T_s	temperature on the surface of the plastic flakes (K)
T	drying time (s)
v	air velocity (m s^{-1})
Λ	thermal conductivity of air (W $m^{-1}K^{-1}$)
ΔH_{vap}	enthalpy of vaporization (kJ kg^{-1})
μ	air viscosity at $T = 50$ °C (kg $m^{-1}s^{-1}$)
μ_p	air viscosity at temperature T (kg $m^{-1}s^{-1}$) with: $\mu_p = 10^{-5}(0,0046.T_s + 1.7176)$
ρ	air density (kg m^{-3});
ρ_p	plastic density (kg m^{-3});
ρ_w	water density (kg m^{-3});

Dimensionless numbers:

Re	Reynolds number
Re_p	Reynolds number of particles $\left(Re_p = \frac{\rho v dp}{\mu}\right)$
Pr	Prandtl number $\left(Pr = \frac{Cp_{air}\mu}{\lambda}\right)$
Nu	Nusselt number $\left(Nu = \frac{h_{bed} \cdot d_p}{\lambda}\right)$
Sc	Schmidt number $\left(Sc = \frac{\mu}{\rho D}\right)$
Sh	Sherwood number $\left(Sh = \frac{kds}{D}\right)$

of the material and the deterioration of the product's properties in each cycle of the processing chain, especially in the extrusion unit, which is caused by the existence of impurities and the presence of water during extrusion (Grigore, 2017). The problem of moisture is more present in the recycling of flexible plastic packaging. This makes most current material recovery installations have difficulties in manipulating flexible plastic packaging because of the different handling characteristics and the contamination of recycled material contributes to the decrease in quality and increase in variability of the regenerated polymer (Schyns & Shaver, 2021). However, some plastic films are currently recycled like shrink wrap and boxes, so this is feasible under the right conditions (Hopewell et al., 2009). Thus, an effective dewatering process is necessary to avoid the problem of moisture, which decreases the productivity and quality of the extrusion process.

The common drying system used industrially to dry the polymers is a mechanical dewatering system using centrifugal dryers. Specifically, a multistage centrifuge system is recommended for the best dehumidifying of polymers and efficiency (Hasan & Mujumdar, 2006). A centrifugal dryer uses centrifugal or spinning force to remove a portion of water from plastic flakes, and it is the immediate operation to dry different plastic types like PET flakes and PP/PE flakes (ASC, 2020; Hasan and Mujumdar, 2006). Centrifugal machines can lower the moisture content up to 12 % for flexible flakes and to about 5 % for rigid flakes (Horodytska et al., 2018; Larrain et al., 2021; ASC, 2020). However, in order to maintain a stable extrusion, the moisture content of plastic flakes entering the extruder should be below 1 % (Shen and Worrell, 2014; Bustos Seibert et al., 2022), knowing also that an extruder with innovative technology like EREMA type can process up to 12 % of moisture (EREMA, s.f.). These values were estimated for rigid plastic flakes. Nevertheless, not all the plastic flakes sorted from the centrifugal unit have the same moisture content, since this moisture depends on the thickness of the plastic flakes (Horodytska et al., 2018). It is assumed that the moisture content is inversely proportional to the thickness of the plastic, and the thinner the plastic the more water it retains in proportion, and like the flexible plastic is thinner than the rigid, those moisture values required for extruders may be not achieved when the material is a flexible plastic film. Moreover, the behavior of flexible plastic is different from rigid plastic. According to (Horodytska et al., 2018), the retained water in the rigid plastic is present as superficial, whereas as the flexible plastic flakes tend to hold and fold, the water is also retained by capillarity and trapped by tortuosity, unlike rigid flakes that contain only free water after sorting from the washing unit. Therefore, it is supposed that the flexible plastic contains more water than the rigid plastic and since the flexible plastic cake is compressed by the centrifugal force, it is quite hard to remove the water retained by capillarity and tortuosity.

Therefore, a centrifugal dewatering process is not sufficient for efficient dewatering and safety of recycling units, so some studies have recommended adding a thermal drying unit at the final stage of the dewatering process. Thermal drying is an excellent way to remove moisture from flexible plastic through the introduction of hot air. It reduces residual moisture present on the surface of plastic chips (rigid or film) for subsequent process steps, such as extrusion, and can reduce the moisture level below 3 % (ASC, 2020). Partially dried flakes from the mechanical dryer are vacuumed out and sent to the thermal drying system via a transport blower. As the flakes enter the dryer, they are mixed with hot air while traveling through the spiral tubing (thermal drying machinery), with a working temperature usually between 40 and 80 °C (B2B PLAST, s.f.).

These dewatering systems (centrifugal and thermal dewatering)

have been developed for rigid plastic and then extended to flexible plastic film at the industrial scale without optimization, so to increase the recycling rate of this type of plastic, a new high-performance recycling technique with low energy consumption must be designed that targets the quality of the polymer obtained and achieves the goals of a sustainable circular economy. For instance, a hydraulic screw press dewatering equipment is a new technique developed for flexible flakes. This new dewatering system is supposed to reduce the energy consumption of dewatering process and reduce the moisture content of the plastic to 50 % compared to mechanical dewatering (Vasco et al., 2021; RUNI Danish engineering, s.d.).

This study provides some guidelines for a better understanding of a convective plastic dryer and discusses parameters affecting heat and mass transport as well as the efficiency of the dryer. Given the limited information available in the open literature regarding plastics drying, this work can be useful in optimizing the dewatering of flexible plastic as well as increasing the recycling rate of the plastic. Several experiments were carried out to study the influence of different parameters (plastic nature, plastic mass, air temperature, plastic size…). The convective drying was improved by installing an air separator for more efficiency. Heat and mass transfer phenomena were also studied by using different correlations present in the literature and the calculated results for the heat and mass transfer coefficients were compared with the experimental results. The convective dewatering of plastic flakes started to be applied on the industrial scale to remove moisture from flexible plastic but it is not well described in the literature, and the information about how the processing and the parameters affecting the processing of this material are very weak. Therefore, making a further study about optimization of this process is difficult. This research contributes to understand more deeply the thermal drying of the flexible plastic flakes and the parameters affecting this process.

2. Theoretical approach to the drying process

2.1. Drying mechanism

The main mechanisms of drying are surface diffusion on the pore surfaces, liquid or vapor diffusion due to moisture concentration differences, and capillary action in granular and porous materials due to surface forces (Avcı et al., 2001). In the case of non-porous materials such as plastic flakes the drying consists only of the diffusion of liquid or vapor from the plastic surface to the drying air involved by simultaneous mass and heat transfer operation.

Generally, the drying of solid particles involves three drying periods (Inyang et al., 2018; Akbari, 2012): the initial period, the constant rate period, and subsequently the falling rate period. The increasing rate period (initial period) is so important that nearly half of the drying is complete in this period. The constant rate period is controlled by the fluid dynamic state of the drying air (Inyang et al., 2018), the physical form of the product and external conditions such as temperature, and relative humidity. All of them have a great influence on the surface of the product being dried (Avci et al., 2001). Contrarily to the constant rate period, the falling rate period is controlled by liquid diffusion and internal conditions of the solid material such as moisture content, the structure of the solid and its temperature (Avci et al., 2001); (Inyang et al., 2018).

The evaporation proceeds as if it occurred from a free liquid with its surface at the wet-bulb temperature. In this situation, the rate of evaporation of a particular solvent is largely dependent upon the surface heat and mass transfer coefficients (Inyang et al., 2018).

2.2. The moisture content in flexible plastic

The water present on the wet plastic is superficial or external water, which is on the surface of the solid particle, and so this moisture can be removed by evaporation. Assuming that the water is spread over the entire plastic flakes surface with a constant thickness e_w (Fig. 1) after sorting from the washing unit, we can conclude that the moisture content (%*M*, defined as kg of water/ kg of wet solid × 100) varies inversely with the plastic thickness e_p. Thus, the thickness of the water in the plastic given *%M* and e_p can be calculated using the following expression:

$$\%M = \frac{m_w}{m_w + m_p} \times 100$$

$$\%M = \frac{Ae_w\rho_w}{Ae_w\rho_w + Ae_p\rho_p} \times 100 = \frac{e_w\rho_w}{e_w\rho_w + e_p\rho_p} \times 100 \quad (1)$$

Here, ρ_p and ρ_w are plastic and water densities (kg m^{-3}), e_p and e_w are plastic and water layer thicknesses (μm), respectively, and A is the plastic flake surface (cm^2).

As mentioned previously, the moisture content in the plastic material is inversely proportional to the plastic thickness. Thus, a thinner plastic retains more moisture than a thicker one. with the consideration that the water layer thickness on the plastic surface is constant no matter the thickness of the plastic. these results are presented in **Figure S1** (supplementary material).

2.3. Kinetic correlation model for drying

Several research on the study of the kinetics of thin-layer drying was performed with various agriculture products such as corn (Wetchacama et al., 2001), grains and fruit (Avci et al., 2001), and sludge (Danish et al., 2016), Models are needed to enable process design and to minimize energy consumption and total costs subject to quality constraints.

The kinetic model of the moisture transfer during a drying process can be firstly assumed to follow a first-order differential equation of this type:

$$\frac{dX}{dt} = K(X - X_e)$$

Where *X* is the material moisture content (dry basis, kg water/kg dry solid) during drying, X_e is the equilibrium moisture content of dehydrated material, X_i is the initial moisture content, *K* is the kinetic rate constant for the drying (min^{-1}), and MR is the moisture ratio.

The integration of this equation gives:

$$MR = \frac{X - X_e}{X_i - X_e} = e^{-Kt} \quad (2)$$

This equation fits the Lewis model introduced in 1921 (Avci et al., 2001); (Danish et al., 2016); (Haghi & Ghanadzadeh, 2005).

MR can be calculated using the experimental data by calculating the different X at each time. If we assume that the equilibrium moisture content X_e is equal to zero, then:

$$MR = \frac{X}{X_i}$$

Different selected mathematical models predicting the drying

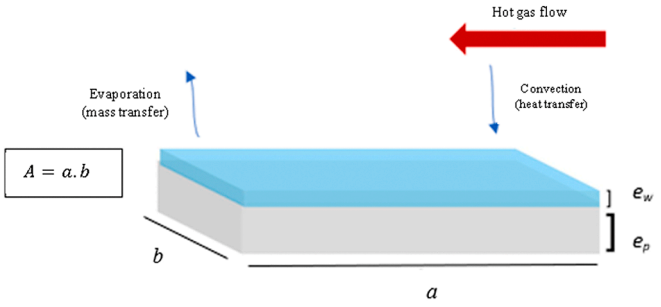

Fig. 1. Illustration of water spreading on the plastic flakes' surface.

kinetics were used to predict the drying of flexible plastic, these models are presented in **Table S1** (supplementary material).

2.4. Transport phenomena model for drying

Another way to interpret the drying mechanism of the flexible plastic flakes is by studying the transport phenomena that this process involves.

Thermal drying consists of passing a hot gas through a bed of solid particles. In this case, two situations could occur: when the drying gas is at a low velocity, a fixed bed exists, whereas at high velocity, the system behaves as a fluidized bed. Thermal drying is the combination of heat and mass transfer operations in which the energy and evaporation of liquid from solid can be easily characterized. On the plastic particles, the liquid is only at the surface of these particles as a free liquid, and this latter will evaporate from the surface at a constant rate. Evaporation proceeds as if it occurred from a free liquid with its surface at the wet-bulb temperature. In this situation, a particular solvent's evaporation rate is largely dependent upon the surface heat and mass transfer coefficients (Inyang et al., 2018).

2.4.1. Heat transfer model

In this section the interpretation of the thermal drying of flexible plastic is based on the heat transfer phenomenon, since the governing transport phenomenon in the drying process can be used to design and analyze the drying system and the drying rate is determined by the set of factors that affect the heat and mass transfer. For this, we supposed in this model that the heat transfer was the governing transport phenomenon, and we studied this transfer independently of the mass transfer. It was considered that the difference between the temperature of the plastic flakes and the drying air was low, so the radiation mechanism was assumed to be negligible. Thus, in this model only the presence of convective heat transfer was taken into account.

The appropriate correlations from the literature for the fixed and fluidized bed systems were used to estimate the heat transfer coefficient theoretically and then compared with the experimental coefficient calculated using the obtained data from experiments. Thus, if the theoretical values of the heat transfer coefficient fit the experimental values, we could assume that the drying process could be studied based only in heat transfer phenomenon.

The studied factor is the heat transfer coefficient, and the corresponding correlations presented in the literature were used to interpret this factor.

The steady state transfer of heat from drying air across the boundary layer, is expressed by the rate equation:

$$Q = hS(T_a - T_s) \tag{3}$$

where h is the average heat transfer coefficient, S is the surface area, T_a is the drying air temperature, T_S is the particle surface temperature and Q is the heat flow of the drying process. The average value of h for any given dryer is a measure of the ability of that dryer to evaporate the liquid.

The most important problem in the drying process is determining the heat transfer coefficient due to the lack of data and information on the drying of plastic particles.

The theoretical prediction of heat transfer coefficient in the case of a fixed bed was correlated by Ranz (Kunii and Levenspiel, 1991):

$$Nu = \frac{h_{bed} d_p}{\lambda} = 2 + 1.8 Re_p^{\frac{1}{2}} Pr^{\frac{1}{3}} \tag{4}$$

where h_{bed} is the heat transfer coefficient, d_p is the equivalent diameter of the plastic flakes, λ is the thermal conductivity of the air, Re_p is the Reynold number of particles and Pr is the Prandtl number.

On the other hand, gas–solid fluidized bed systems are characterized by temperature uniformity and high heat transfer coefficients due to the intense mixture of the solid material by the presence of a large area of solid surface per unit of particle mass exposed to the gas flow. According to Kunii and Levenspiel (1991), when $Re_p \geq 100$ Nu number of a fluidized bed falls between the values for single sphere particles and for fixed bed and it can be calculated using Ranz's correlation.

Correlation for a single sphere was used to predict the heat transfer of the fluidized bed:

$$Nu = \frac{h_{bed} d_p}{\lambda} = 2 + 0.6 \mathrm{Re}_p^{\frac{1}{2}} \mathrm{Pr}^{\frac{1}{3}} \tag{5}$$

With: $Re_p = \frac{\rho v d_p}{\mu}$; $h = \frac{Nu\lambda}{dp}$; In the case of non– spherical particles:

$$d_p = 0.567\sqrt{particlesurface}$$

The estimation of h when very thin plastic flakes are in the dryer can be done without taking into consideration the geometry of the particles. In this case the correlation proposed by Sieder and Tate (Tosun, 2007) for a flow inside tubes can be used:

$$Nu = 1.86(Re\mathrm{Pr})^{1/3} \left(\frac{d}{L}\right)^{\frac{1}{3}} \left(\frac{\mu}{\mu_p}\right)^{0.14} \tag{6}$$

validity:

$$RePr\frac{d}{L} > 10$$

With:

$$Re = \frac{\rho v d_h}{\mu} \; Pr = \frac{Cp_{air}\mu}{\lambda} \; h = \frac{Nu\lambda}{d_h}$$

where μ and μ_p are the air viscosity at 50 °C and at temperature T respectively, d and L are the diameter and the length of the tube, d_h is the hydraulic diameter of the tube, λ is the thermal conductivity of the air, v is the air velocity, ρ is air density and Cp_{air} is the thermal capacity of air.

In order to investigate the validity of the correlation used to interpret the heat transfer for this process, the theoretical results of the heat transfer coefficient were compared to those obtained by experimental estimation using the energy balance of the drying process.

The heat flow of the drying is the thermal energy needed to transfer liquid into vapor and it can be represented by latent heat of evaporation:

$$Q = \dot{m}_v \Delta H_{vap}$$

$$hS(T_a - T_s) = \dot{m}_v \Delta H_{vap}$$

where $\dot{m}_v$ is the vapor flow rate, T_a and T_s are the air temperature and temperature on the surface of the plastic flakes, respectively, and S is the total surface area of the plastic bed.

We used this equation to calculate h using the experimental data:

$$h = \frac{\dot{m}_v \, \Delta H_{vap}}{S(T_a - T_s)} \ldots\ldots\ldots.$$

2.4.2. Mass transfer model

With the same concept used in the previous section (**2.4.1**), the predominant transport phenomenon is supposed to be now the mass transfer, and the mass transfer coefficient is calculated using the corresponding correlations present in the literature.

The moisture transfer during hot air drying occurs in general in two successive steps, firstly from the interior of the wet solid to its surface and secondly from the surface of the solid to the drying gas (superficial transfer). However, for plastic flakes the moisture is present only at the surface, so in this case the moisture transfers into vapor in the boundary layer to the drying air and the mass transfer rate is expressed in terms of the vaporization rate:

$$m_v = kS(C_i - C_\infty) = kS\left(\frac{P_{v-s}}{T_s} - \frac{P_{v-a}}{T_a}\right) \frac{M_{H2O}}{R} \tag{8}$$

where C_i and C_∞ are the concentrations of water vapor at the plastic surface and in the air, respectively, S is the total surface of the plastic bed, M_{H2O} is the molar mass of water, R is the ideal gas constant, T_s and T_a are the temperatures at the surface of the plastic samples and in the air, respectively, and k is the mass transfer coefficient.

The estimation of the mass transfer coefficient can be done using the following correlation valid for both fixed and fluidized bed (Knudsen et al., 1997):

$$\frac{Sh}{Re_p Sc^{\frac{1}{3}}} = \frac{0,765}{Re_p^{0.82}} + \frac{0,365}{Re_p^{0,386}} \tag{9}$$

With: $10 < Re_p < 15000$.

Experimentally, the mass transfer coefficient can be calculated using equation (8). The partial vapor pressure at the liquid–gas interface (P_{v-s}) is equal to the saturation pressure at the particle surface temperature T_s, and can be calculated using Antoine's equation. And the partial vapor pressure of the bulk air (P_{v-a}) at temperature T_a is calculated as shown below:

$P_{v-a} = x\frac{P_{total}}{x+0.622}$ with.$x = \frac{m_v}{m_a}$

The mass transfer coefficient k can be calculated easily from equation (10), where a, b and c are the Antoine coefficients:

$$m_v = kS\left(\frac{10^{a-\frac{b}{c+T_s}}}{T_s} - \frac{P_{v-a}}{T_a}\right)\frac{M_{H2O}}{R} \tag{10}$$

3. Materials and methods

3.1. Materials

The flexible plastic materials used to study the thermal drying were high-density polyethylene (HDPE) and low-density polyethylene (LDPE) films. The plastic films made of HDPE used in the experiments came from shopping bags of the supermarket Lidl. The average thickness of the HDPE films was 25 μm. The LDPE film was a flexible clear PE film designed for packaging, whose average thickness was about 92 μm. The two types of plastic films are considered as flexible plastic, and they were cut by hand into a small piece with almost identical size. For each plastic type, two different samples sizes were prepared as indicated in Table 1.

3.2. Method

The drying of plastic flakes was carried out using two set-ups at laboratory scale. The first set-up (Fig. 2 **a**) was designed for drying the plastic at a fixed bed system. It consisted of a plastic tube of 3.6 cm diameter and 80 cm height. At the bottom of the tube a separation material (similar to a filter) was introduced to prevent the solid from reaching the bottom of the tube to avoid the obstruction of the gas inlet. Thermal anemometers were installed at the bottom and at the top of the column to measure the inlet and the outlet temperatures, and the gas velocity was measured.

Table 1
Parameters affecting the evaporation rate.

Parameters	Fixed bed (set-up 1)		Fluidized bed (set-up 2)
Plastic nature (thickness)	HDPE-bags: thickness = 25 μm LDPE-film: thickness = 94 μm		HDPE-bags: thickness = 25 μm LDPE-film: thickness = 94 μm
Plastic size (S_1: big size and S_2: small size)	LDPE-film: $S_1 = 2.5 \times 2 \times 10^{-4}$ m^2 $S_2 = 1.4 \times 0.6 \times 10^{-4}$ m^2	HDPE-bags: $S_1 = 2.6 \times 2 \times 10^{-4}$ m^2 $S_2 = 0.8 \times 0.3 \times 10^{-4}$ m^2	Only one size for each plastic LDPE-film: S = $0.7 \times 0.6 \times 10^{-4}$ m^2 HDPE-bags: S = $0.8 \times 0.3 \times 10^{-4}$ m^2
Plastic mass	$m_1 = 10$ g and $m_2 = 20$ g		$m_1 = 10$ g and $m_2 = 5$ g
Air velocity (V_1 and V_2)	$V_1 = 1.07/1.18/1.31$ m/s < V_{limit} $V_2 = 1.7/1.74/1.81$ m/s < V_{limit}		One velocity is used $V \approx 4\frac{m}{s} > V_{limit}$
Moisture content	10 %		10 %, 20 % and 70 %

The dry plastic material was introduced inside the column in batch mode, and hot air was circulating from the bottom to the top. The average temperature of the gas was about 60 °C, and after the outlet temperature reached equilibrium, a quantity of water was introduced to wet the plastic. The purpose behind heating the plastic to the equilibrium in the set up before adding the water was to better control the evaporation process. The evaporation started when the outlet temperature decreased from the equilibrium. Then, at the end of evaporation this temperature returned to the equilibrium value, and the evaporation process was supposed to be finished when the outlet temperature was higher than the equilibrium one. The measurement of temperatures and velocity was recorded. The air velocity was set so that it was lower than the minimum fluidization velocity in order to keep the plastic bed fixed.

In order to optimize the drying, for the set-up 2 a cyclone was included to make possible the separation of humid air of drying from the plastic. The outlet of the cyclone was joined to the bottom of the column to make the plastic recirculate in the set-up and increase the drying efficiency (Fig. 2 **b**). Thus, the plastic flakes were in a circulating bed; this circulating bed is considered as a fluidized bed system for the study of this process. The gas velocity was set so that it was higher than the minimum velocity of fluidization to maintain the plastic bed fluidization. From industrial practice only the fluidized bed convective drying systems are relevant.

3.3. Experimental calculation of the evaporation rate

The drying process is a coupled heat and mass transfer between air and a wet solid in order to reduce the moisture content in the solid material by evaporation. The common definition of a drying process was used, as being one where the liquid is removed from a solid specifically by evaporation.

The energy term associated with the different materials into and out of the dryer, as well as the thermal energy $\boldsymbol{Q}$ were considered to establish the energy balance. $\boldsymbol{\dot{m}_a}$ was the air mass flow rate considered as dry air (0 % of moisture). The water vapor mass flow rate $\boldsymbol{\dot{m}_v}$ only appeared at the dryer outlet, whereas the solid mass $\boldsymbol{m_s}$, and the water mass $\boldsymbol{m_w}$ appeared at the inlet and the outlet. In order to achieve drying, the latent heat of evaporation must be supplied to turn liquid water content into vapor. Thus, the minimum amount of heat which must be supplied for a drying process in an increment of time Δt is:

$$Q = \dot{m}_v \Delta H_{vap} \Delta t \tag{11}$$

Using the same temperature reference $T_f = 273.15K$, the expressions depicted in Fig. 3 follow:

The representation of the energy balance (Fig. 3) leads us to deduce the expression of the evaporation rate. The next expressions represent the exchange in heat energy between the outlet and the inlet of the dryer for the air, solid and water content assuming adiabatic conditions.

Energy inlet = Energy outlet

The energy balance equations are explained in section 1 of the supplementary material. According to those equations, we can determine the expression that gives the evaporation mass for an increment of timeΔt (eq. (12):

$$\dot{m}_v = \frac{\dot{m}_a Cp_a(T_{a1} - T_{a2})\Delta t + (m_s Cp_s + m_{w1} Cp_w)(T_{s1} - T_{s2})}{(Cp_v(T_{a2} - T_{s2}) + \Delta H_{vap} - Cp_w(T_{s2} - T_f))\Delta t} \tag{12}$$

The temperature T_s represent the temperature at the solid surface. It is assumed that this temperature is equivalent to the wet bulb temperature. This latter can be calculated by Stull's empirical formula (Stull,

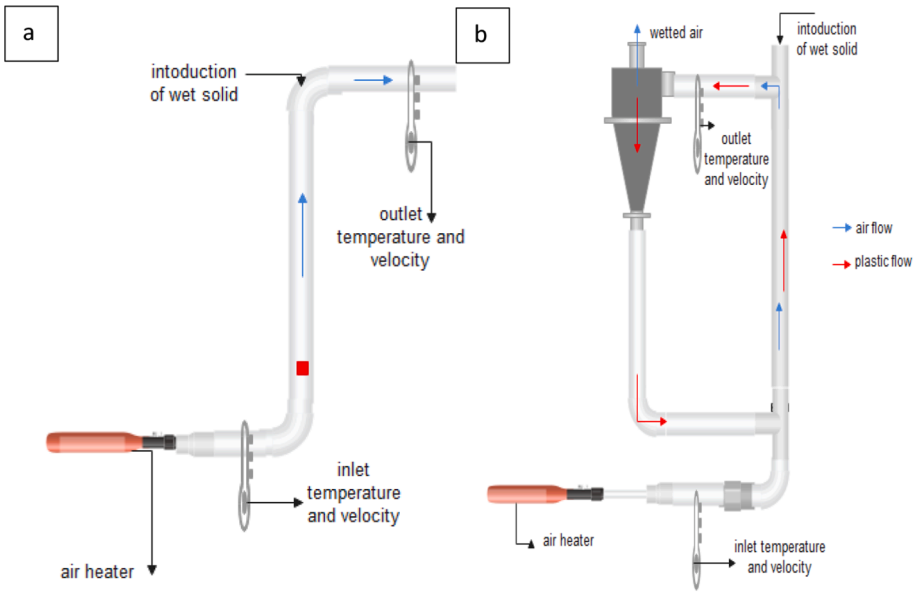

Fig. 2. The thermal drying processing prototype: a) the first set-up (fixed bed) and b) the second set-up (fluidized bed).

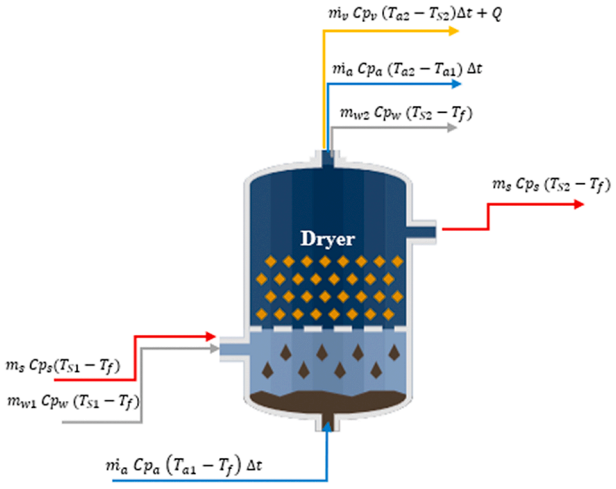

Fig. 3. Energy balance for the dryer.

2011),(Knox et al., 2017), where H% represents the humidity of the air and supposed equal to the initial water content in the dryer (assumed as constant) and T_{ai} the inlet air temperature (eq. (13):

$$T_{si} = T_{ai}\tan^{-1}\left[0.151977(H\% + 8.313659)^{\frac{1}{2}}\right] + \tan^{-1}(T_{ai} + H\%) - \tan^{-1}(H\% - 1.676331) + 0.00391838H\%^{\frac{3}{2}}\tan^{-1}(0.023101H\%) - 4.686035 \quad (13)$$

The evaporation rate calculation was based on the experimental values. This evaporation rate was calculated from the equation of the energy balance (eq. (12) as a function of the initial velocity and the air temperature, which were measured during the experiments.

Assuming that at the variation of time Δt the variation of solid temperature $(T_{si} - T_{si-1})$ is negligible, eq. (12) can be written as:

$$\dot{m}_{vi} = \frac{\dot{m}_a Cp_a(T_{ai-1} - T_{ai})\Delta t}{(Cp_v(T_{ai} - T_{si-1}) + \Delta H_{vap} - Cp_w(T_{si} - T_f))\Delta t} \quad (14)$$

Several experiments were carried out for two different plastics (LDPE and HDPE films) in the two set ups. The experiments consisted of studying various parameters which can affect drying. In order to study the influence of these parameters, the evaporation rate was calculated for each case. These experiments were grouped according to the parameters studied. The inlet temperature for all the experiment was fixed at 60 °C. Table 1 summarizes the parameters studied.

The moisture content in the plastic bed during the drying process was the quantity of moisture still present in the plastic bed after evaporation at time t, and was estimated from the values of the evaporation rate as follows:

$$m_{w(t)} = m_{w(t-1)} - m_{v(t)}$$

4. Results and discussions

4.1. Parameters influencing the evaporation rate

in this section we studied the different parameters that might affect the drying process by comparing the results obtained of the moisture ratio (MR) as shown in Fig. 4, the variation of the flakes mass introduced in the dryer and the moisture content of the plastic were investigated in both set-ups (fixed and fluidized bed) and we obtained the same results, in Fig. 4 **(a) and (d)** we showed the data of fluidized bed. The velocity of the drying air Fig. 4 **(b)** and the flakes size Fig. 4 **(C)** were studied in set-up 1 (fixed bed dryer), the moisture content was investigated in set-up 2 (fluidized bed).

4.1.1. The effect of solid mass

The comparison between the data on the drying of 10 g and 5 g of plastic flakes showed that the increase in solid mass led to an increase in the drying time of the evaporation process. From Fig. 4 **(a)**, we observe that the drying time was 800 s versus 300 s when the mass of LDPE flakes went from 10 to 5 g, respectively. This result may be due to the distribution of water in the bed; the 10 g bed of plastic flakes was higher than the 5 g bed, which was about 11 cm in height versus 5 cm, respectively, so more moisture was trapped inside the topmost bed. the calculation of the porosity of each bed showed that the bed with 10 g of mass had a porosity of 98 % compared to 90 % for the bed with 5 g of plastic flakes, this confirmed that the plastic bed with the greatest height contains more cavities, and more water is trapped inside. Effect of plastic nature (thickness).

The comparison of all the data presented in Fig. 4 for thick and thin plastic (LDPE and HDPE respectively) showed a variation in the drying

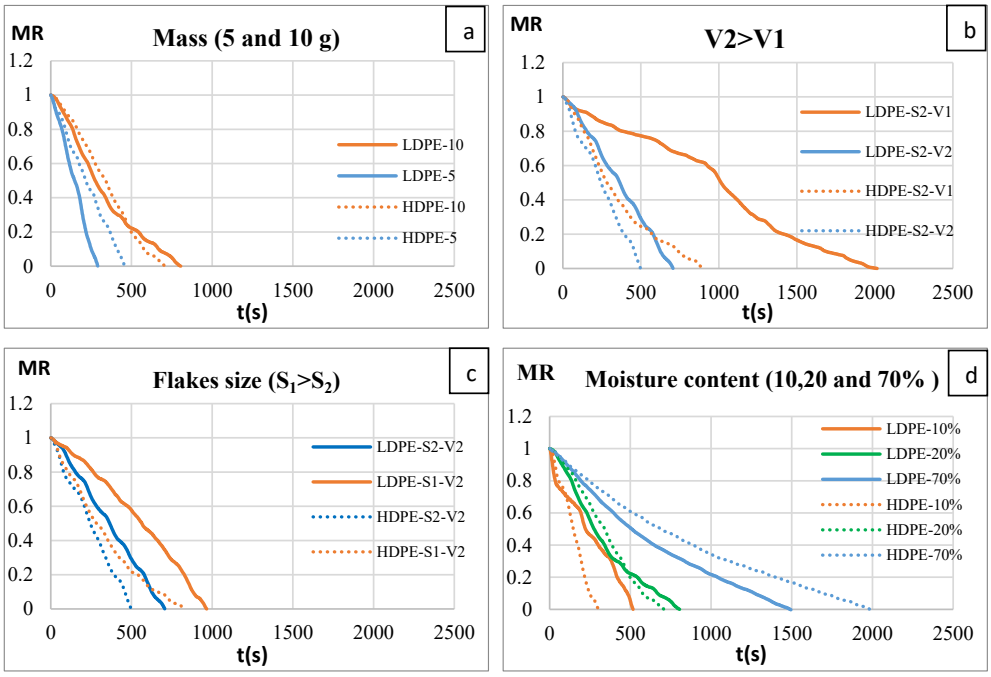

Fig. 4. Parametric study of the drying process by comparison of the result of moisture ratio vs time of different parameters studied, S_1: big size of flakes and S_2: small size of flakes.

time.

In the fixed bed data (Fig. 4 **(b and c)**) the HDPE flakes took less time to be dried compared to LDPE flakes, this could be explained by the fact that the LDPE flakes curl and fold more than the HDPE flakes, so it retained more trapped water than HDPE, this trapped water took more time to be dried than the superficial water.

In the case of the fluidized bed data (Fig. 4 **(a and d)**), we observed variation in drying time, in some cases, HDPE had less drying time and in others LDPE. We were therefore unable to draw any conclusions from these results. Therefore, the thickness of plastic flakes had affected the drying only in the fixed bed drying system.

4.1.2. *Effect of the inlet temperature and velocity*

The drying was done at a constant temperature of 60 °C in order to protect the dryer (PVC tube). It was recommended to use a temperature below 80 °C for this type of tube, since the higher temperature can deteriorate the plastic properties. However, the temperature can decrease the drying time. To confirm this hypothesis, we performed a simple drying of our plastic in a glass column at both 80 °C and 60 °C. In these experiments we could control only the outlet air temperature. The results obtained showed that the time of the drying decreased for a higher temperature (80 °C).

According to the results obtained by the fixed bed set up for both types of plastic, we observed that when the velocity increased from 1.1 m/s (V_1) to 1.75 m/s (V_2) the drying time decreased from 2000 s to 700 s for LDPE and from 900 s to 550 s for HDPE as shown in Fig. 4 **(b)**. Higher air velocity rapidly increased the surface temperature of the plastic flakes, resulting in rapid evaporation of the wet plastic flakes.

Previous research of the drying of food (fruits) confirmed that the increase in the velocity of air leads to an increase in the drying velocity: at constant temperature the velocity of the drying of banana passed from 0.0286 to 0.0321 g/min when the air velocity passed from 0.3 to 0.7 m/s. The same results were observed for the drying of carrot: the drying time of this latter decreased by 25 % when the air velocity increased from 0.5 to 1 m/s (Nguyen, n.d.).

The temperature of the drying air has a major influence on the drying speed. This influence is due to the heat input given to the product which increases with the temperature of the air. This result was confirmed also in previous research (Kunii and Levenspiel, 1991; Wetchacama et al., 2001). On the other hand, there is a limitation of the range of temperature, since a higher temperature can lead to a deterioration in the quality of the dried product, and thermal degradation or oxidation can occur. In this case, it is recommended to work in the temperature range between 50 and 80 °C.

4.1.3. *Effect of plastic size*

The comparison between the drying of the plastic of different sizes (S1 and S2) by comparing the moisture ratio data in Fig. 4 **(c)** led to notice that the flakes (LDPE and HDPE) with higher surface (S1) took more time to be completely dried compared to the flakes with lower surface (S2). The reason for this result might have been the elasticity of the plastic material, and therefore, when these flakes have a larger surface, they fold and roll in on themselves more than when they have a smaller surface, so the bigger flakes contain more trapped moisture that take more time to be evaporated than the free moisture.

In the case of fluidized bed (set-up 2) we noticed that the large size plastic bypassed and prevented the circulation of air and plastic at the pipeline levels. The only plastic which had not bypassed the tube was the smallest one of HDPE-bags with the size of ($0.8 \times 0.3 \times 10^{-4}$ m^2) in a pipeline of 3.25×10^{-2} m in diameter. As result, it was recommended that the plastic flakes length be ¼ the pipeline diameter.

4.1.4. *Effect of water content*

The amount of water vapor in the drying air is clearly related to the water content in the plastic flakes. The water content was higher as the evaporation rate was higher, and this was noticed from the experimental data obtained. As well as this, it is evident that the drying time generally decreases with an increase in the moisture content of the plastic flakes.

The results obtained of evaporation rate showed that when we decreased the water content of the plastic from 70 % to 10 %, the drying time decreased as shown in Fig. 4 **(d)**. As an example, the drying time of LDPE flakes in fluidized bed decreased from 1500 s to 500 s when the moisture content in the LDPE flakes decreased from 70 % to 10 %. Similar results were noticed for the fixed bed dryer. It is obvious that a

large amount of water in the plastic takes longer to evaporate than a small amount. Moreover, a large amount of water in the flexible plastic can increase the amount of trapped water that is difficult to remove. For this reason, a thermal dryer is usually added in series after the mechanical dewatering (centrifugal dewatering) [**17, 9**] in the industry to decrease the moisture up to 2 %, since in the recycling manufacturing plastic flakes come out from the centrifugal dewatering unit with an average water content of 12 to 20 % (Horodytska et al., 2018).

4.2. Drying characteristic

According to the obtained drying characteristic curves, the entire drying rate period could be divided into two phases in the case of the fluidized bed system (Fig. 5 **a**). Initial period A was characterized by a fast-increasing rate due to the heating of the superficial moisture by the hot air. Thus, the heat energy was transferred to the moisture resulting in the evaporation of the moisture content in the plastic flakes. The second phase was a falling rate period B. In this phase the drying rate decreased rapidly. In this period the majority of the moisture was evaporated and then, the drying rate started to be in a steady state and came back more or less to its initial value, sign of the end of the drying process.

The drying rate for a fixed bed system was quite similar to the drying rate curves of agriculture products, characterized by three periods (Fig. 5 **b**). Like for the fluidized bed, we had an initial period A which was faster than in the previous system, a falling period B, and a constant period D. Contrarily to the fluidized bed, after the initial period the drying curve started to be constant, which means that the evaporation process was at a constant rate. Unlike the fluidized bed, the superficial moisture in this case was on the surface of the hole bed not on the surface of each plastic flake, so at the increasing rate period all the superficial moisture was evaporated. At the constant rate period the moisture trapped by capillarity inside the plastic flakes bed diffused to the bed surface and evaporation was achieved at constant rate. These results were compatible with the results obtained by other studies of the drying rate of coal, sludges and agriculture (Akbari, 2012); (Avcı et al., 2001); (Inyang et al., 2018).

4.3. Kinetic correlation model of the drying

The drying rate data obtained for two different flexible plastic flakes (LDPE and HDPE) and for different moisture content were used to well established drying empirical models such as Henerson-Pebis, Lewis, logarithmic, Wang and Singh, and 3rd degree polynomial models that were previously used to study the drying behavior of high moisture containing biomasses, sludge and food. The results of the applied models to LDPE and HDPE flakes for both systems (fixed and fluidized bed) are presented respectively in **Table S2** (supplementary material). All proposed models are compatible with the experimental results as shown in Fig. 6.

In order to estimate the model that best describes the data, the coefficient R^2 was determined for each model as shown in **Figure S2** (supplementary material). According to the comparison of the R^2 for LDPE and HDPE and for different moistures content in the material the logarithmic, Wang and Singh and the 3rd degree models are the models that gave the better prediction results. The logarithmic model was used to predict the drying kinetics of some agriculture product such as canola (Gazor & Mohsenimanesh, 2010), whereas Wang and Singh's model was also used to describe the drying kinetics of bamboo shoot slices in a microwave drying system(Bal et al., 2010).

4.4. Heat and mass transfer models

The investigation of the heat and mass transfer was made separately by supposing the existing of only one transfer phenomenon. Then, the heat and mass transfer coefficients were calculated theoretically and experimentally for the different experiments of the fixed and fluidized bed dryers. For the fixed bed the calculation of heat and mass coefficients was made for different experiments of HDPE-film and PE-film with different air velocities and different flakes size, whereas for the fluidized bed the experiments were carried out for three different moisture content and mass. For each experiment the h and k coefficients values taken were the values of the steady state.

4.4.1. Heat transfer model

Fig. 7 shows the evolution of experimental heat transfer coefficient (h_{exp}) vs the theoretical heat transfer coefficient (h_{th}) comparing with the line $h_{exp} = h_{th}$. We can notice the convergence of h_{exp} to h_{th}. As a result, the prediction of heat transfer coefficient for this process could be done using the correlation existing the literature.

The appropriate correlation to interpret the thermal phenomenon in both fixed and fluidized bed systems of the thin film with 25 μm (HDPE) was the correlation of flow in a tube (*equation (6)*. In this case, the only consideration was the flow of the air inside the tube without considering the geometry or the size of the plastic flakes, since this latter had no influence in the transfer.

In the case of LDPE-film with the thickness of 94 μm, it was important to take the particles geometry into account. For this reason, the appropriate correlation was the fixed bed correlation (*equation (4)* for the first set-up and the fluidized bed correlation (*equation (5)* for the second set-up. These two correlations consider the diameter of the particles inside the dryer and the heat transfer coefficient obtained by these correlations were more or less similar to the results obtained by the experimental expression (*equation 7*).

From Fig. 7, we can observe that the values of the heat transfer coefficient for HDPE were lower than its values for LDPE flakes. This may be explained by the bigger total surface area of the HDPE flakes bed compared to LDPE bed. We could also notice that this coefficient was

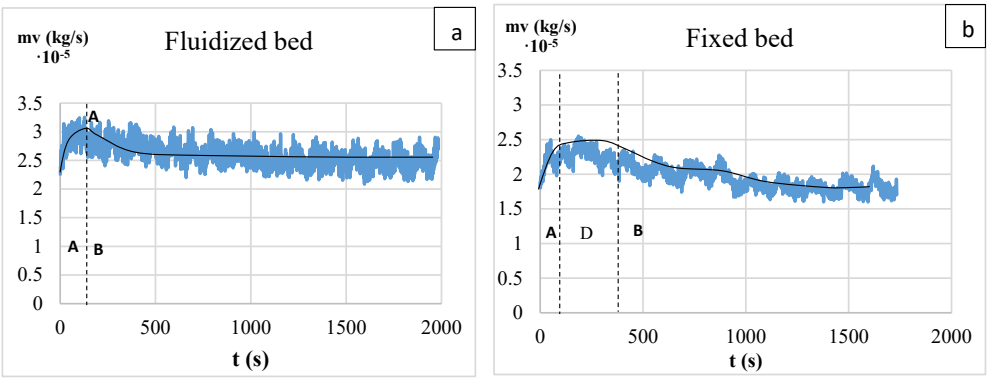

Fig. 5. Drying characteristic curve of fluidized (a) and fixed (b) bed systems.

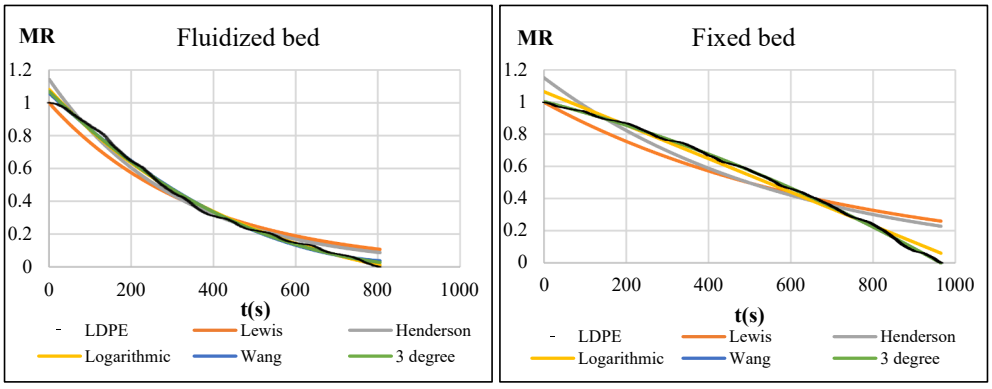

Fig. 6. An example of a comparison of models with predicted and experimental values of PE film flakes.

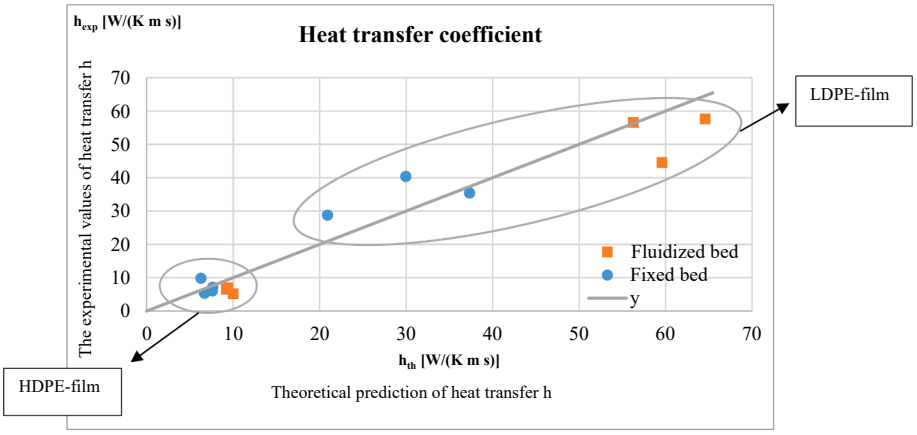

Fig. 7. The evolution of the experimental heat transfer coefficient vs the theoretical one for fluidized and fixed bed.

quite smaller for fixed bed than for fluidized bed. Consequently, the fluidization of the flakes improved heat transfer.

From the parametric study of the heat transfer, the experimental data obtained under the influence of velocity, flakes surface and bed mass did not show any interesting variation in the heat transfer coefficient value.

4.4.2. Mass transfer model

The mass transfer coefficient was calculated for different experiments from the data obtained by the first and the second set-up. In the fixed bed set up we studied the influence of the velocity and the flakes sizes as parameters that can have influence in mass transfer, whereas the moisture content and the plastic mass were studied in the fluidized bed set-up.

The calculation of the experimental mass transfer coefficient and the theoretical coefficient for the two set-ups showed that the mass transfer coefficient values obtained from the drying data were far from the obtained results using the correlation for fixed and fluidized bed (**Table S3**, supplementary material). The experimental values obtained for this coefficient were very high, in the order of 10^2 m/s. However, the theoretical values were in the order of 10^{-2} m/s. Therefore, the prediction of the mass transfer of flexible plastic drying is not feasible using the available correlation in the literature.

From these results and the results obtained from the heat transfer model, we concluded that the experimental mass transfer coefficient was bigger than the heat transfer coefficient and the prediction using a correlation was possible only for the heat transfer model, so we can say that the predominant transport phenomenon for the drying of flexible plastic was heat transfer.

The parametric study of the mass transfer phenomenon using the experimental data showed that the air velocity had an effect in the mass transfer, and these results were obtained for both types of plastic films. The air velocity increased the plastic surface temperature quickly, which accelerated the mass transfer between the moisture and the drying air. However, when the flakes surface was bigger the mass transfer coefficient value decreased. The high quantity of water in the film also decreased the mass transfer of the evaporation process, and this was confirmed in the drying of both types of film. The plastic flakes mass introduced in the dryer also affected the mass transfer. It was noticed from the parametric study as shown in **Figure S3** (supplementary material) that lower mass led to decrease the mass transfer of the process.

5. Conclusion

This work contributed to the improvement of knowledge in the process of thermal drying of flexible plastic flakes, which is an important step in the recycling chain. A better understanding of this process can lead to improved process efficiency.

The experimental results on the thermal drying clearly showed the effect on the drying time of changes in the velocity of the drying air, the moisture content in the flakes, the bed mass, and the size of the plastic flakes.

The results found indicated that the drying kinetics in all cases followed the drying kinetic models used in the study of the drying of sludge and agriculture, and the best predicting model were the polynomial model and logarithmic model.

The investigation of the transfer coefficients showed that the values of the heat transfer coefficients obtained by theoretical correlations fitted the experimental values, but this was not the case for mass

transfer. Therefore, based on these results, we assumed that heat transfer is the determining transport phenomenon in this process.

The results obtained showed that the drying time of the flexible plastic was lower in the fluidized bed system compared to the fixed bed system. This later generated a lot of cavities where the air was not be well distributed and a part of the moisture content in the plastic flakes was trapped. This air took more time to pass through this bed, and it could be difficult to evaporate the trapped moisture in the bed. However, the fluidization of the bed made the moisture in direct contact with hot air which favored the evaporation process. Thus, switching from fixed to fluidized bed enhances the heat and mass transfer.

To summarize, the heat transfer model can be used on the design and the analysis of a thermal dryer system of flexible plastic. The drying rate can be improved by determining all the factors affecting heat and mass transfer.

In conclusion, the thermal drying process is known for its higher energy consumption, which is considered inconvenient for the mechanical recycling facilities and should be optimized. The results obtained in this study can be useful for future research on the examination of the existing drying processes in the industry and for the optimization of this process in the plastic recycling chain considering different variables such as energy consumption, drying kinetics, etc.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2023.05.054.

References

Akbari, H. (2012). Fine Coal Drying and Plant Profitability . *Challenges in Fine Coal - Processing, Dewatering and Disposal , February 2015*. https://www.researchgate.net/publication/272509412.

ASC*: Plastic recycling machines*. (2020). Retrieved: 21/09 /2021, from https://www.plasticrecyclingmachine.net/centrifugal-dryer-dewatering-machine/.

Avci, A., Can, M., Etemoglu, A.B., 2001. Theoretical approach to the drying process of thin film layers. Appl. Therm. Eng. 21 (4), 465–479. https://doi.org/10.1016/S1359-4311(00)00060-0.

ASG*: recycling machinery; thermal drying for PET flakes* . (s.f.). (t. d. flakes, Productor) Retrieved: 30 03 / 2021, from https://www.plasticrecyclingmachine.net/thermal-dryer/.

B2B PLAST. (s.f.). (s. thermique, Productor) Retrieved: 15/ 04/ 2021, from http://www.b2bplast.fr/sechage/.

Bal, L.M., Kar, A., Satya, S., Naik, S.N., 2010. Drying kinetics and effective moisture diffusivity of bamboo shoot slices undergoing microwave drying. Int. J. Food Sci. Technol. 45 (11), 2321–2328. https://doi.org/10.1111/j.1365-2621.2010.02402.x.

Briassoulis, D., Hiskakis, M., Babou, E., 2013. Technical specifications for mechanical recycling of agricultural plastic waste. Waste Manag. 33 (6), 1516–1530. https://doi.org/10.1016/j.wasman.2013.03.004.

Bustos Seibert, M., Mazzei Capote, G.A., Gruber, M., Volk, W., Osswald, T., 2022. Manufacturing of a PET Filament from Recycled Material for Material Extrusion (MEX). Recycling 7 (5). https://doi.org/10.3390/recycling7050069.

Combe. M. (2020). Plastics Europe décortique les déchets plastiques en Europe. *Techniques de l'Ingénieur*. Retrieved 15/ 06/ 2021, from https://www.techniques-ingenieur.fr/actualite/articles/plasticseurope-decortique-les-dechets-plastiques-en-europe-74668/.

European Commission (2018). Communication de la commission au parlement européen, au conseil, au comité économique et social européen et au comité des régions : Une stratégie européenne sur les matières plastiques dans une économie circulaire. Bruxel. Retrieved 15/06/2021, from https://eur-lex.europa.eu/legal-content/FR/TXT/?uri=CELEX%3A52018DC0028.

Danish, M., Jing, H., Pin, Z., Ziyang, L., Pansheng, Q., 2016. A new drying kinetic model for sewage sludge drying in presence of CaO and NaClO. Appl. Therm. Eng. 106 (2016), 141–152. https://doi.org/10.1016/j.applthermaleng.2016.05.191.

EREMA: plastic recycling systems. (s.f.). Retrieved from https://www.erema.com/assets/media_center/folder/app_post_consumer_2022_09_en.pdf.

Garcia, J. M., & Robertson, M. L. (2017). The future of plastics recycling. In *Science* (Vol. 358, Issue 6365, pp. 870–872). American Association for the Advancement of Science. Doi:10.1126/science.aaq0324.

Gazor, H.R., Mohsenimanesh, A., 2010. Modelling the drying kinetics of canola in fluidised bed dryer. Czech J. Food Sci. 28 (6), 531–537. https://doi.org/10.17221/256/2009-CJFS.

Grigore, M. E. (2017). Methods of recycling, properties and applications of recycled thermoplastic polymers. In *Recycling* (Vol. 2, Issue 4). MDPI AG. Doi:10.3390/recycling2040024.

Haghi, A.K., Ghanadzadeh, H., 2005. A study of thermal drying process. In. Indian J. Chem. Technol. 12.

Hasan, M., & Mujumdar, A. (2006). Drying of Polymers. In *Handbook of Industrial Drying, Third Edition*. CRC Press. Doi:10.1201/9781420017618.ch41.

Hopewell, J., Dvorak, R., & Kosior, E. (2009). Plastics recycling: Challenges and opportunities. In *Philosophical Transactions of the Royal Society B: Biological Sciences* (Vol. 364, Issue 1526, pp. 2115–2126). Royal Society. Doi:10.1098/rstb.2008.0311.

Horodytska, O., Valdés, F.J., Fullana, A., 2018. Centrifugal dewatering performance in plastic films recycling. Waste Manag. 80, 211–217. https://doi.org/10.1016/j.wasman.2018.09.015.

Inyang, U.E., Oboh, I.O., Etuk, B.R., 2018. Kinetic Models for Drying Techniques—Food Materials. Adv. Chem. Eng. Sci. 08 (02), 27–48. https://doi.org/10.4236/aces.2018.82003.

Kaiser, K., Schmid, M., & Schlummer, M. (2018). Recycling of polymer-based multilayer packaging: A review. In *Recycling* (Vol. 3, Issue 1). MDPI AG. Doi:10.3390/recycling3010001.

Knox, J.A., Nevius, D.S., Knox, P.N., 2017. Two simple and accurate approximations for wet-bulb temperature in moist conditions, with forecasting applications. Bull. Am. Meteorol. Soc. 98 (9), 1897–1906. https://doi.org/10.1175/BAMS-D-16-0246.1.

Knudsen, J.G., Hottel, H.C, Sarofim, A.F.,Wankat,P.C, Knaebel, K.S. Heat and mass transfer, Perry's Chemical Engineers' Handbook (ed.). *Seventh, International edition*. (1997) section 5-27.

Kunii, D., Levenspiel, O., 1991. Fluidization engineering. In D.Kunii, & O.Levenspiel, *Fluidization engineering* (second edition ed., p. page 269). Butterworth-Heinemann.

Larrain, M., van Passel, S., Thomassen, G., van Gorp, B., Nhu, T.T., Huysveld, S., van Geem, K.M., de Meester, S., 2021. Techno-economic assessment of mechanical recycling of challenging post-consumer plastic packaging waste. Resour. Conserv. Recycl. 170 https://doi.org/10.1016/j.resconrec.2021.105607.

Nguyen, T. H. (n.d.). *Étude expérimentale et modélisation du procédé de séchage des végétaux*. https://tel.archives-ouvertes.fr/tel-01297965.

O'Farrell, K., Lewis, H., 2013. Flexible plastic packaging. Design smart material guides, Australian Packaging Covenant, Sydney. Retrieved from http://www.helenlewisresearch.com.au/wp-content/uploads/2014/03/Flexible_Plastic-DSMG-082013.pdf.

Patel, M., von Thienen, N., Jochem, E., Worrell, E., 2000. Recycling of plastics in Germany. Resour. Conserv. Recycl. 29 (1–2), 65–90. https://doi.org/10.1016/S0921-3449(99)00058-0.

Plastic recyclers Europe. (2020). Flexible films market in Europe : state of play . (Eunomia, Ed.) Retrieved from https://www.plasticsrecyclers.eu/wp-content/uploads/2022/10/flexible-films-market.pdf.

RUNI danish engineering. (s.d.). Récupéré sur SYSTEC, GERMANY - PLASTIC FILM RECYCLING: https://www.compactor-runi.com/cases/industry/systec-germany-plastic-film-recycling.

Schyns, Z. O. G., & Shaver, M. P. (2021). Mechanical Recycling of Packaging Plastics: A Review. In *Macromolecular Rapid Communications* (Vol. 42, Issue 3). Wiley-VCH Verlag. Doi:10.1002/marc.202000415.

Shen,L., Worrell,E.. (2014). Plastic Recycling. *Handbook of Recycling: State-of-the-art for Practitioners, Analysts, and Scientists*, 179-190. Doi:10.1016/B978-0-12-396459-5.00013-1.

Stull, R., 2011. Wet-bulb temperature from relative humidity and air temperature. J. Appl. Meteorol. Climatol. 50 (11), 2267–2269. https://doi.org/10.1175/JAMC-D-11-0143.1.

The recycling magazine, (2018). plastics recycling growth in Europe. *The recycling magazine*. Retrieved 06 15, 2021, from https://www.recycling-magazine.com/2018/02/14/plastics-recycling-grows-europe/.

Tosun, I., 2007. EVALUATION OF TRANSFER COEFFICIENTS: ENGINEERING CORRELATIONS. In: Modeling in Transport Phenomena. Elsevier, pp. 59–115. https://doi.org/10.1016/B978-044453021-9/50005-1.

Vasco, J.C., Silva,N., Fernando Lagoa, Carlos Capela,Lizete Heleno, Marcelo Gaspar,, and Nelson Oliveira. (2021). Energy-Efficient Dewatering Technique for Recycled Films. *Proceedings of the 1st International Conference on Water Energy Food and Sustainability (ICoWEFS 2021)*, 370-381. Doi:10.1007/978-3-030-75315-3_42.

Wetchacama, S., Soponronnarit, S., Prachayawarakorn, S., Pongpullponsak, A., Tuntiwetsa, W., & Kositcharoeankul, S. (2001). Study of Parameters Affecting Drying Kinetics and Quality of Corns. In *Nat. Sci.)* (Vol. 35).