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A novel alternative method for pistachio nuts splitting using conical spouted beds

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ABSTRACT

Closed shell pistachio nuts must be split for their commercialisation, which is conducted in processing plants designed on purpose. Given that current industrial processes have limitations, and pistachio is a booming product, new opening mechanisms alternative to the traditional ones are being developed. Thus, thermal processing has recently gained attention, but the high energy consumption required in these processes has boosted the search of new alternatives. To our knowledge, there is no information about the treatment of pistachio nuts in conical spouted beds. Accordingly, we propose a novel alternative method for pistachio nuts splitting by involving the mentioned technology. Hydrodynamic runs have been conducted to ascertain the configurations that lead to stable operation, and therefore are suitable for low temperature batch drying and splitting of pistachio nuts. The results show that a single cycle of wetting, drying and cooling of pistachio nuts allows attaining splitting percentages of up to 35%.

1. Introduction

The pistachio tree (*Pistachia vera*) is a drought resistant species native to Western Asia. The pistachio nuts are made up of an outer shell and an edible kernel inside. Given its excellent nutritional properties, the consumption of pistachio nuts has spread throughout the world, and therefore the industry sector related to this fruit has increased over the last decades. In fact, the high market value of pistachio nuts (8 – 9 \$/kg) has boosted their production becoming an investing opportunity in suitable areas. Thus, there are more than one million hectares dedicated to the cultivation of this fruit in the world, and the trend is still increasing. The United States of America is the world leader in the production of pistachio nuts with 48.3% of the global production, followed by Turkey, Iran and Syria (Chen and Pan, 2022). The production of pistachio nuts is also increasing in the Mediterranean countries, such as Spain, where 29000 hectares are being used for pistachio nut crops (4.5% of the total surface in Spain). Furthermore, it seems that climate change contributes to the adaptation of these crops (Couceiro et al., 2008).

Pistachio bloom occurs in spring and the kernel increases throughout summer. The fertilisation and irrigation of the crops throughout the life of the pistachio tree are essential for obtaining high yields with nuts of good quality and flavour (Şahan and Bozkurt, 2020; Hosseini et al., 2022). Pistachio nuts are harvested in late summer or early autumn. The

moisture of freshly harvested pistachio nuts is rather high (40 - 50 wt% w.b.). Accordingly, pistachio nuts are dried to 5 - 6% moisture content before their commercialisation, as mould, yeast and bacterial activity lead to quality deterioration (Khair et al., 2014). After the drying process, separation of closed shell pistachios from split ones is conducted by means of rotative sieves. The split pistachio nuts are commercialised as culinary nuts, whereas the closed ones are commonly used for food-stuff in farms and energy source. Furthermore, the shell of the pistachio nut has been used as a gasification source (Karatas and Akgun, 2018), for obtaining active carbon by pyrolysis or gasification (Nikšiar and Nasernejad, 2017, 2018) and incorporated as fibre in the cement mortar (Karawi et al., 2021). Nevertheless, the economic value of closed shell pistachios is much lower than of the split ones. Therefore, pistachio nut splitting must be maximised in order to increase their added value.

The amount of split pistachios increases during the harvest weeks, as the outer shell is forced to split due to the enlargement of the inner kernel. This phenomenon is also known as longitudinal dehiscence. Nevertheless, other factors, such as the irrigation schedule (Mohammadi Mohammadabadi et al., 2020), balanced nutrition (Khadivi-Khub, 2015), use of fertilisers or parental genotypes (Rabadán et al., 2018) and temperature over the blooming stage (Couceiro et al., 2017; Zhang and Ranford, 2021), have an incidence in the dehiscence of pistachio

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Nomenclature

d_p	Particle diameter, L	H_F	Distance between the bed surface and the fountain confiner, L
ρ_s	Particle density, ML^{-3}	D_F	Diameter of the fountain confiner, L
ρ_b	Bed density, ML^{-3}	L_F	Length of the fountain confiner, L
ϕ	Shape factor, dimensionless	Q_i	Inlet air flow rate, L^3t^{-1}
ϵ	Porosity, dimensionless	Q_{ms}	Minimum spouting flow rate, L^3t^{-1}
D_C	Diameter of the cylindrical section, L	ΔP_m	Maximum pressure drop, $ML^{-1}t^{-2}$
D_i	Cone base diameter, L	ΔP_s	Operating pressure drop, $ML^{-1}t^{-2}$
γ	Cone angle, dimensionless	ΔP	Pressure drop, $ML^{-1}t^{-2}$
D_0	Air inlet diameter, L	u	Inlet air velocity, Lt^{-1}
H_0	Static bed height, L	u_{ms}	Minimum spouting velocity, Lt^{-1}
L_H	Solid entrainment height at the lower section of the draft-tube, L	u_{mb}	Minimum bubbling velocity, Lt^{-1}
L_T	Length of the draft-tube, L	T_i	Inlet air temperature, T
D_T	Internal diameter of the draft-tube, L	y_g	Air absolute humidity, dimensionless
AR	Aperture ratio of the draft tubes, dimensionless	x_s	Solid moisture content, dimensionless

nuts. Thus, even though the volume of the inner kernel is similar to the volume of the shell, a considerable amount of closed shell pistachio nuts still remain after harvesting (Zhang and Weir, 2006). Therefore, an additional post-harvesting step is required to increase the amount of split pistachio nuts.

Several methods have been proposed to artificially increase the amount of split pistachios, whose aim is to promote longitudinal dehiscence. Mechanical methods consist in exerting a longitudinal force on the shell suture by means of apparatuses equipped with pressing devices (Paul, 1936; Ribera, 2003) or endless screws (Esmek, 2016a, 2016b). However, these pieces of equipment are expensive and require a lot of space due to their size. Furthermore, although most of them exert a controlled longitudinal force, breakage of a percentage of fruits is inevitable, which involves a lower price in the culinary market. Accordingly, Burlock et al. (1990, 1991) and Lemos (1996) proposed a previous moistening of the closed shell pistachio nuts before exerting the longitudinal force on the shell. Thus, the pistachio shell is more flexible, and therefore bends rather than break, which avoids nut breakage. The split pistachio nuts are then dried to 5 - 6 wt% w.b. for their commercialisation.

In addition to the previously described mechanical methods, thermal ones have also been proposed to reproduce the longitudinal dehiscence of pistachio nuts. The thermal methods are based on a previous moistening of the pistachio nuts and a subsequent drying at low and mild temperatures (Foroutanaliabad and Foroutanaliabad, 2006). Thus, the longitudinal dehiscence of the shell is attained by the expansion force caused by the evaporation of the moisture in the shell. Drying of previously moistened pistachio nuts can be addressed by different methods. The simplest and most economic one is sun drying (Mokhtarian et al., 2017). However, sun drying requires long drying times, as the thick shell restricts heat and mass transfer rates (Chen and Pan, 2022). Furthermore, these long times involve lipid oxidation, which greatly reduces their quality (Kermani et al., 2017). Bin, vertical and funnel dryers have also been proposed in the literature (Nejad et al., 2003). Nevertheless, the energy efficiency of these technologies is poor. Fluidised beds are a promising alternative for the industrial drying of granular materials. Thus, Özahi and Demir (2015) estimated the energy and exergy efficiencies in the drying of pistachio nuts in a fluidised bed and Amiri Chayjan et al. (2014) modelled the infrared-convective drying of pistachio nuts in fluidised beds. However, certain limitations, such as high energy consumption and poor fluidisation performance of coarse solids in fluidised beds restrict the application of this technology. Spouted beds are well-known for their capacity for the treatment of coarse particles, and they have been applied for drying these types of granular materials since 1954, especially those that are temperature sensitive. In fact, the countercurrent gas-solid flow allows oper-

ating with relatively high gas inlet temperatures without damaging the solid (Spreutels et al., 2014; Freire et al., 2017; Sukunza et al., 2021). Spouted beds have been applied for drying foods, such as peanuts (Zhu et al., 2021), flaxseed (Dehghan-Manshadi et al., 2020), milk (Braga et al., 2021), fruit pulps (Araujo Rodrigues et al., 2022; de Medeiros et al., 2021), sorghum (de Brito et al., 2017), barley (de Brito et al., 2021b) and soybeans (Brito et al., 2021).

A novel alternative method is proposed in this paper for pistachio nut splitting based on a conical spouted bed. Thus, closed shell pistachio nuts are soaked with water and then dried in a conical spouted bed equipped with internal devices. To our knowledge, spouted beds have not been applied for the drying of pistachio nuts, and therefore the main aim of this study is to explore the technical feasibility of the thermal opening of closed shell pistachio nuts using a conical spouted bed and determine the optimal configuration. Thus, a study has been conducted of the hydrodynamics of pistachio nuts in different spouted bed configurations, in which the time required to dry the pistachio nuts and the amount of split pistachio nuts have been evaluated.

2. Experimental

2.1. Materials

The material used in this paper is the closed shell pistachio nut of the Kerman variety, supplied by NUEVOS CULTIVOS AGRARIOS, Ltd. A sample of 500 g of pistachios was taken by the quartering method (ISO 14488:2007 standard). Table 1 shows the physical properties of the closed shell pistachio nuts, which were determined by conducting the corresponding procedures in triplicate. Thus, the moisture content (x_s) was obtained by drying the nuts in an oven for 24 h at 105 °C (ISO 589 standard), which was also confirmed in a Mettler Toledo HE73 halogen moisture analyser. Particle size and shape were determined by approximating pistachio nuts to spheroids. Thus, major and minor axes were measured in 100 pistachios and the average equivalent spherical diameter was calculated. Particle density (ρ_s) and porosity (ϵ) were measured in a Micrometrics Autopore 9220 following the method proposed by Saldarriaga et al. (2014). Shape factor (ϕ) was determined according to the procedure by Zenz and Othmer (1960) (the surface of a sphere with the same volume of the particle over the surface of the particle), and bed density (ρ_b) was measured following the procedure by Brown and Richards (1970). Thus, closed shell pistachios fall within Geldart group D (Geldart, 1973).

2.2. Equipment

The hydrodynamic study of the closed shell pistachios has been conducted in a cold pilot plant unit equipped with a fountain confined

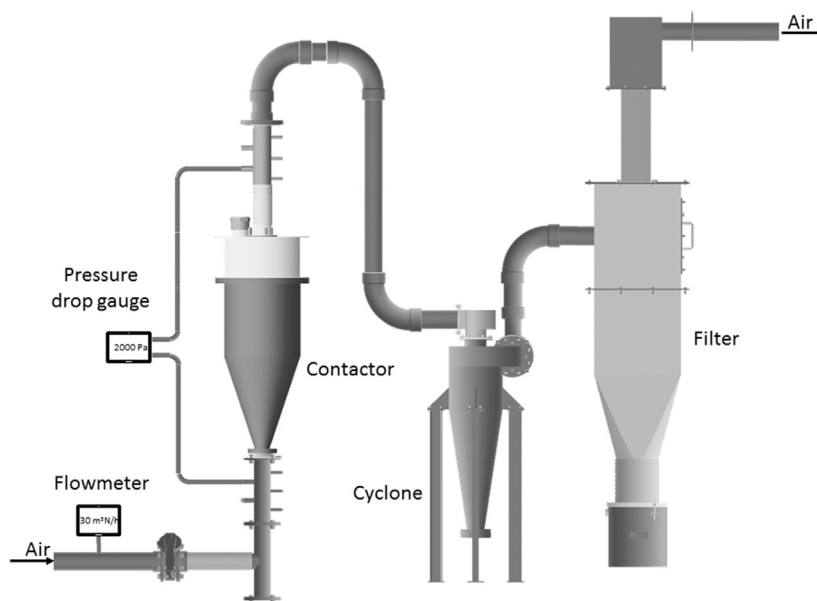


Fig. 1. Schematic representation of the fountain confined conical spouted pilot plant used for the hydrodynamic study.

Table 1
Properties of the closed shell pistachios
(95% confidence interval).

Parameter	Value
x_s (wt% w.b.)	6.45 ± 0.15
d_p^w (cm)	2.15 ± 0.25
ρ_s (kg m^{-3})	785 ± 14
ρ_b (kg m^{-3})	484 ± 9
ϵ	0.38 ± 0.03
ϕ	0.91
Geldart type	D

conical spouted bed, Fig. 1. Apart from the main element (the conical bed), it consists of a blower, flow meter, pressure drop gauge, and a cyclone and bag filter to collect entrained particles. A detailed description of the pilot plant can be found in a previous paper (Tellabide et al., 2020a).

As mentioned, the main component of the pilot plant is the contactor, which is made of transparent and resistant material (polyethylene terephthalate, PET), thus allowing visual observation of the bed behaviour. Given the versatile design of the pilot plant, it allows using contactors of different geometries and internal devices (mainly fountain confiners and draft tubes). Fig. 2a shows the geometric features of the conical spouted bed, whose dimensions are as follows: cone angle (γ), 32, 36, 45 and 60°; column diameter (D_C), 0.36 m; cone base diameter (D_I), 0.06 m; and air inlet diameter (D_0), 0.03, 0.04 and 0.05 m. The static bed height (H_0) used in the runs is 0.27 m. In order to ensure stable operation, two internal devices have been used, namely, draft tube and fountain confiner. The main features of the draft tubes are as follows: tube height (L_T), 0.27 m; tube diameter (D_T), 0.03, 0.04 and 0.05 m; and height of the entrainment zone (L_H), 0.07 m. Open-sided and nonporous draft tubes were tested, whose main difference lies in their aperture ratio (AR), i.e., the open lateral surface area of the draft tube over its total lateral surface area, Fig. 3. Thus, runs were conducted with nonporous draft tubes ($AR = 0\%$), open-sided draft tubes differing in aperture ratio ($AR = 42, 57$ and 78%) and without draft tube ($AR = 100\%$). The diameter (D_F) and length (L_F) of the fountain confiner are 0.2 and 0.5 m, respectively, and the distance between the lower end of the fountain confiner and the bed surface (H_F), 0.07 m. These values were chosen as optimum based on previous studies (Estiati et al., 2019a,b).

Fig. 4 shows a schematic representation of the hot unit for the drying of closed shell pistachio nuts. The dimensions of the contactor (fountain confined conical spouted bed) and internal devices are the same as those in the cold unit. The contactor and internal devices are made of stainless steel, which allows operating at temperatures above the ambient one. Moreover, the contactor is heat-insulated in order to minimise heat losses in the drying chamber. Air is supplied by a 11 kW blower (CL-72-1) and heated by electric resistances, which supply a maximum power of 89 kW. Thus, an air flow rate of $300 \text{ N m}^3 \text{ h}^{-1}$ can be heated to 500 °C. The air flow rate is measured by a thermal mass flow meter (ST50-1F11AA000) and the pressure drop between the inlet and outlet of the drying chamber by a pressure gauge (Yokowaga EJA110E). The temperature of the air at the blower outlet, within the bed, and at the inlet and outlet of the dryer are monitored by means of thermocouples. The inlet and outlet relative humidity of the air is also monitored in order to ascertain the performance of the dryer.

2.3. Experimental procedure

The performance of pistachio nut beds in conical contactors was ascertained based on the evolution of pressure drop with air velocity, which are called characteristic curves in spouted beds. These runs were conducted in the cold unit (allows internal visualisation) for different geometries of the contactor, draft tube and fountain confiner. The closed shell pistachio nuts used in the hydrodynamic runs were dried at ambient temperature for at least one week, which is sufficient time to reach equilibrium moisture content. The contactor was fed with 2.3 kg of these pistachio nuts, which correspond to a static bed height of $H_0 = 0.27$ m. Air velocity was then linearly increased and pressure drop registered, at the same time as the bed behaviour (fluidisation, spout opening, slugging, elutriation, etc.) was visually observed. Subsequently, air velocity was linearly decreased and the minimum spouting velocity accurately determined. This procedure was followed in all the configurations studied.

Pistachio nut splitting in conical spouted beds was carried out following three steps in series, as are: wetting, drying and cooling. Firstly, the closed shell pistachio nuts were saturated with water by soaking for 24 hours. The wet pistachio nuts were then discharged into the spouted bed through the solid feeding point located on top of the contactor. It should be noted that the spouted bed was already running empty with an air flow rate of $Q_i = 1.2Q_{ms}$ at 40 °C. Furthermore, temperature and

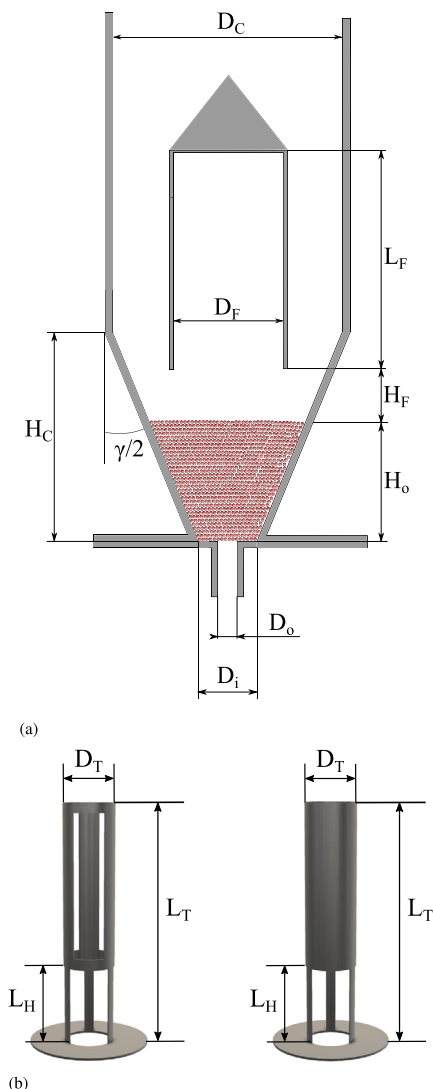


Fig. 2. Geometric factors of a) the fountain confined conical spouted bed and b) open-sided and nonporous draft tubes.

humidity of the air at the inlet and outlet, as well as bed temperature, reached steady state prior to feeding the pistachio nuts. Once the nuts were loaded into the contactor, the absolute humidity of the air at its outlet was monitored throughout the drying stage. This stage was concluded once the outlet air absolute humidity was close to the inlet one (5% difference at most). The moisture content of the pistachio nuts was then reduced to 4 - 6 wt% w.b.

The dried pistachio nuts are then left to cool at room temperature for 24 hours. It should be noted that their moisture content does not significantly change during this stage. Finally, split and closed shell pistachios are manually separated. Thus, pistachio nuts with a longitudinal gap in their shell are categorised as split ones (Nazari et al., 2017). However, closed shell pistachios do not contain any gap in the shell or the gap is only on one side of the shell, Fig. 5. The weight fraction of split pistachio nuts is given as:

$$\text{Split pistachios (\%)} = \frac{\text{Split pistachios (g)}}{\text{Split pistachios (g)} + \text{Closed shell pistachios (g)}} \quad (1)$$

3. Results and discussion

In order to ascertain the configurations leading to stable operation, their characteristic curves (pressure drop vs. air inlet velocity) have been determined. These curves allowed calculating the main hydrodynamic parameters in these beds, i.e., minimum spouting velocity and operating pressure drop. Subsequently, the drying of previously moistened pistachio nuts was carried out, and the simultaneous process of pistachio shell splitting was monitored in detail.

3.1. Characteristic curves for spouted beds with pistachio nuts

Although these curves have been determined for all the configurations, only a few will be described in this section. Thus, contactors of small angle are those involving stability problems and therefore the curves corresponding to the contactor of smallest angle will be discussed. Fig. 6 shows the characteristic curves for a cone angle of 32° and a static bed height of 0.27 m when no draft tube and two draft tubes differing in aperture ratio were used. Thus, Fig. 6a shows the characteristic curve with an inlet diameter of $D_o = 0.03$ m and without draft tube ($AR = 100\%$). Operation with larger air inlet diameters ($D_o = 0.04$ and 0.05 m) without tube leads to instabilities (flat slugging) due to the high air diversion into the annulus. This behaviour is consistent with that reported by Olazar et al. (1992). They reported that the air inlet diameter must be 0.03 m at most in order to attain stable operation with coarse particle ($d_p > 8$ mm) beds of similar size in narrow angle contactors. As observed in Fig. 6a, pressure drop linearly increases as the inlet air velocity is increased, until a peak value (ΔP_m) is attained. A slight increase in air velocity leads to a sharp decrease in pressure drop, with levitation of the particles in the core on the upper surface of the bed. A further increase in air velocity does not open the spout, but a random movement (fluidisation) of pistachio nuts is observed through the transparent wall of the contactor. Thus, an internal jet is observed at the lower section closed to the inlet, but no spout is observed on the upper surface of the bed. This may be explained by the high air percolation into the annulus due to the large particle size ($d_p = 21.5$ mm), which is even enhanced by the non-spherical shape of these particles (Gao et al., 2017). A further increase in the air inlet velocity leads to a slight decrease in pressure drop at the same time as the spout is opened (spouting regime). A highly vigorous bed is observed when the spout has been opened, which is due to the high inlet air velocity ($u > 85$ m s $^{-1}$). Thus, particle-particle and particle-contactor wall (mainly in the fountain) collisions cause undesired pistachio shell breakage (5 - 6%).

When the inlet air velocity is decreased below the range corresponding to the spouting regime, there is a sudden increase in pressure drop at the same time as the spout is collapsed. This velocity is precisely that corresponding to the minimum spouting velocity (u_{ms}), Fig. 6a. It is noteworthy that the minimum spouting velocity detected by decreasing air velocity (the standard procedure in spouted beds) is the same as the one detected by increasing velocity. This is not the case when fine particle beds are used, as spout opening occurs at velocities well above the minimum one when the increasing air velocity trend is monitored. Furthermore, a rather vigorous bubbling bed is still observed below the minimum spouting velocity, which is due to the high air percolation into the annulus. The bubbling bed ends at the minimum fluidisation velocity, which in this case is 45 m s $^{-1}$. It should be noted that the minimum fluidisation velocity for coarse particles is approximately the same as the minimum bubbling velocity (u_{mb}). Furthermore, Fig. 6a shows that the pressure drop in the bubbling bed is slightly higher when the bed is opened by increasing air velocity than that observed when air velocity is decreased from the spouting regime. This is a fact we have observed with large non-spherical particles. Visual observation infers that certain cyclic movement remains in the bubbling bed (up through the core of the bed and down through the wall), which causes a slightly lower pressure drop than that corresponding to the bubbling bed.

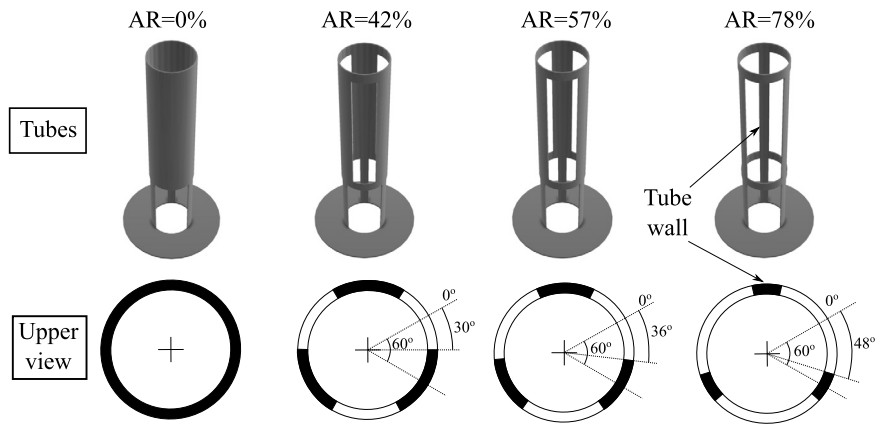


Fig. 3. Schematic representation of the aperture ratio (AR) of the draft tubes.

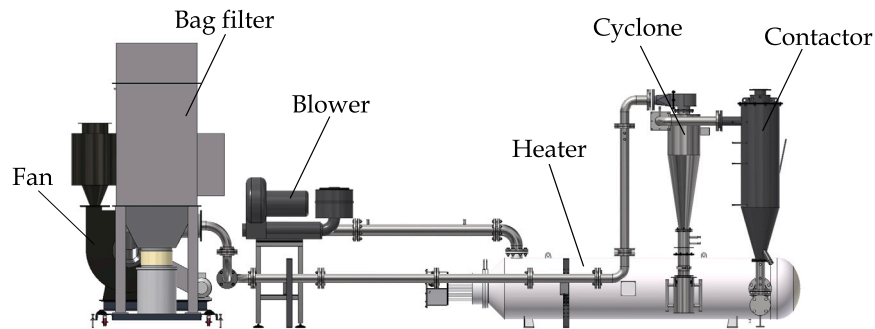


Fig. 4. Schematic representation of the fountain confined conical spouted bed dryer.

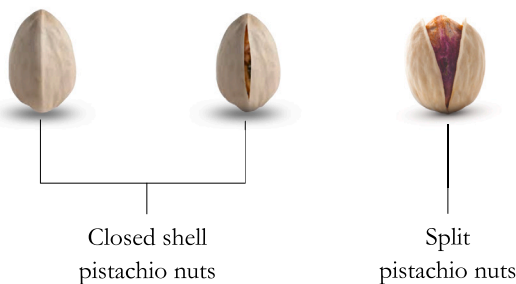


Fig. 5. Different categories used for characterising the dried pistachios.

According to de Brito et al. (2020), air percolation from the spout into the annulus, and therefore bed turbulence and solid circulation, are reduced by employing either open-sided or nonporous draft tubes. Accordingly, draft tubes differing in diameter (D_T) and aperture ratio (AR) have been tested in order to ascertain their influence on the spouted bed hydrodynamics. Preliminary runs conducted using draft tubes with 0.03, 0.04 and 0.05 m in diameter showed that no spout was formed when their diameter is 0.03 and 0.04 m, i.e., the diameter of the tubes is of the same order or slightly greater than the particle size of pistachio nuts ($d_p = 21.5$ mm). This leads to the blockage of both the draft tube entrainment zone and the open lateral slots of the draft tubes by pistachio nuts. Consequently, stable operation was only attained with the 0.05 m draft tube. Regarding the aperture ratio of the 0.05 m draft tubes (AR), stable operation was only observed with 57 and 78% aperture ratios. That is, the draft tube with 42% aperture ratio and the nonporous one do not lead to stable operation, which is because they do not allow solid cross-flow from the annulus into the spout except at the lower entrainment zone (L_H). In fact, aperture ratios below approximately 50% in a 0.05 m diameter draft tube leave slots of sim-

ilar or smaller size than pistachio nuts. Therefore, solid incorporation through only the lower entrainment zone is not enough for stable operation with these tube sizes, as tube clogging occurs close to the inlet. Figs. 6b and 6c show the characteristic curves of spouted beds when 0.05 m draft tubes provided with 78% and 57% aperture ratios, respectively, were used.

The characteristic curve of the spouted beds with 78% aperture ratio draft tube is similar to that without draft tube, Figs. 6a and 6b. Thus, fixed bed, bubbling bed and spouting regimes are observed in both configurations. However, some differences are worth mentioning. The peak pressure drop is slightly higher with a 78% aperture ratio draft tube than without draft tube, which is mainly due to the greater inlet diameter in the former configuration. Nevertheless, a significant reduction in the minimum spouting velocity is observed when operation is carried out with the open-sided draft tube, which is explained by the greater diameter in the configuration with the open-sided draft tube. It should be noted that the minimum flow rate is similar in both cases (219 $\text{m}^3 \text{h}^{-1}$ for the configuration without tube and 213 $\text{m}^3 \text{h}^{-1}$ for the one with open-sided tube). Moreover, in the configuration with 78% aperture ratio draft tube, the pressure drop in the bubbling regime decreases following approximately a linear trend until the spouting regime is reached (minimum spouting velocity), Fig. 6b. This is explained by the greater inlet diameter, and therefore greater spout diameter (Tellabide et al., 2022). Similar results were reported by de Brito et al. (2020) with soybean beds ($d_p = 6$ mm).

However, the air diversion into the annulus is significantly reduced when operating with a 57% aperture ratio draft tube ($D_0 = 0.05$ m), i.e., a lower turbulence due to lower particle-particle and air-particle interactions, Fig. 6c. Thus, two regions are only detected when using these draft tubes, as are: fixed bed and spouting regime. As the inlet air velocity is increased in the fixed bed, a linear increase in pressure drop is observed up to a peak pressure drop, which is significantly higher than in the other configurations. This effect has already been observed

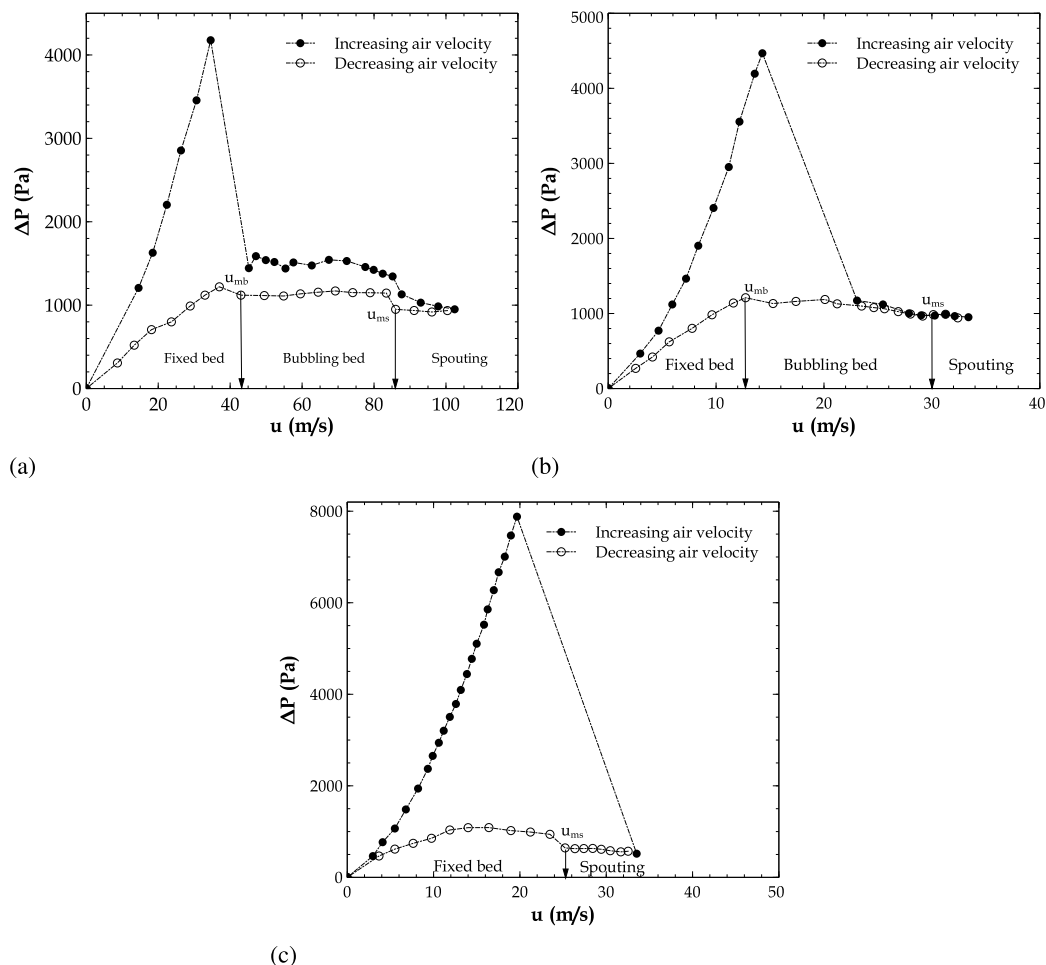


Fig. 6. Characteristic curves of the fountain confined conical spouted beds made up of closed pistachio nuts. System: $\gamma = 32^\circ$, $H_0 = 0.27$ m, a) $D_0 = 0.03$ m, without draft tube ($AR = 100\%$), b) $D_0 = 0.05$ m, with open-sided draft tube ($AR = 78\%$) and c) $D_0 = 0.05$ m, with open-sided draft tube ($AR = 57\%$).

when dealing with fine (Tellabide et al., 2020a) and coarse particles (de Brito et al., 2021a) in beds provided with draft tubes and seems to be due to the hindrance of bed expansion by the presence of the tube. When the air inlet velocity is further increased, the spout is opened and stable spouting is attained. Nevertheless, this velocity is well above the minimum one. Thus, when the air velocity is decreased, spouting regime is registered for a range of velocities, until a slight increase in pressure drop is observed, which corresponds to the minimum spouting velocity, Fig. 6c. It should be noted that air percolation from the spout into the annulus is rather low in this configuration with 57% aperture ratio draft tube, which leads to lower solid circulation flow rate, and therefore lower annulus turbulence. These results are consistent with those reported by de Brito et al. (2020) and Sari et al. (2012).

Table 2 shows the hydrodynamic parameters for the configurations in which stable operation was attained. Note that even though instabilities were observed due to flat slugging with air inlet diameters of 0.04 and 0.05 m in a cone angle of 32° , stable operation was attained in wider cone angles (36° , 45° and 60°). The uneven distribution of the air in these great angle contactors, as well of the support of the wall, allowed the opening of a preferential channel or spout.

Overall, the minimum spouting velocity (u_{ms}) and the operating pressure drop (ΔP_s) decrease as the cone angle is increased. Thus, the support of the bed by the contactor wall is more significant when great cone angles are used, thereby reducing the required kinetic energy required for the spout opening. Other authors operating with powders (Tellabide et al., 2020b), as well as with fine (San José et al., 1996) and high density (Golshan et al., 2018) particles, reported similar re-

sults. The fluidising range is also narrower as the angle of the cone is increased. Thus, the ratio between the minimum spouting velocity (u_{ms}) and the minimum bubbling velocity (u_{mb}) was determined in each configuration, and this ratio, u_{ms}/u_{mb} , decreases as the cone angle is increased, Table 2. Therefore, an increase in the angle enhances the cycling movement of the particles (upward in the spout and downward in the annulus), and therefore stable operation regime. Nevertheless, solid circulation rate is negatively affected when increasing contactor angle.

The air inlet diameter is also a parameter of significant influence on the hydrodynamics of spouted beds. Three air inlet diameters (0.03, 0.04 and 0.05 m) were tested in the spouted beds without draft tube ($AR = 100\%$). Thus, the minimum spouting velocity, operating pressure drop and bubbling range (u_{ms}/u_{mb}) decrease as the air inlet diameter is increased. Although the air percolation into the annulus increases when the air inlet diameter is increased (Tellabide et al., 2022), the velocity of the air at the inlet is significantly higher with small air inlet diameters (higher minimum spouting velocity and operating pressure drop). Furthermore, high air inlet velocities enhance the internal jet, and therefore the agitation of pistachio nuts. Concerning the trend with draft tubes of different aperture ratio, the minimum spouting velocity, operating pressure drop and u_{ms}/u_{mb} ratio decrease as the aperture ratio of the draft tubes is decreased. This is mainly explained by the lower air percolation of the air from the spout into the annulus and of the solid in the reverse way, which lead to a smaller expansion of the spout and a lower solid circulation flow rate. Furthermore, as mentioned above when describing the characteristic curves, aperture ratios of 57% do not lead to bubbling regime.

Table 2
Hydrodynamic characteristics of the configurations tested.

Draft tube	D_0 (m)	γ (°)	u_{ms} (m s ⁻¹)	u_{ms}/u_{mb}	ΔP_z (Pa)
$AR = 100\%$	0.03	32	87.8	1.9	1008.9
		36	84.6	1.9	918.2
		45	79.8	1.8	894.8
		60	76.3	1.6	700.3
$AR = 100\%$	0.04	36	49.5	1.8	785.9
		45	48.0	1.8	743.4
		60	47.3	1.7	730.7
$AR = 100\%$	0.05	36	33.8	1.6	685.2
		45	31.4	1.5	658.8
		60	30.8	1.4	541.0
$AR = 78\%$	0.05	32	31.4	1.4	971.3
		36	30.1	1.3	657.4
		45	29.6	1.2	593.1
		60	28.1	1.2	392.8
$AR = 57\%$	0.05	32	28.0	-	496.8
		36	25.5	-	429.7
		45	24.7	-	441.8
		60	23.6	-	289.9

One of the main findings of this study is the fact that the fountain confiner allows increasing the range of stable operation, even with very coarse particles as those used here. Thus, Olazar et al. (1992) reported that stable operation using coarse particles ($d_p > 8$ mm) should be carried out with an angle between 39 and 45°. However, stable operation in conical spouted beds was also attained with cone angles of 32 and 36° when the fountain confiner was employed.

3.2. Pistachio nuts splitting in conical spouted beds

Pistachio nuts splitting in conical spouted beds involves the drying of previously moistened pistachio nuts. The correct choice of the geometric factors of both the conical beds and internal devices greatly improves the drying kinetics (Rajashekhara and Murthy, 2017; Zhang et al., 2018). Accordingly, a cone angle of 32° was selected for the drying stage, as it allows attaining high solid circulation flow rates (short particle cycle times) of pistachio nuts, as well as high heat and mass transfer rates and drying efficiencies (of up to 95% Sukunza et al., 2021). Thus, three configurations were tested, whose difference lies in the air inlet diameter and aperture ratio of the draft tube. They are as follows: a configuration with an inlet diameter of $D_0 = 0.03$ m without draft tube (named D03AR100) and those with an inlet diameter of $D_0 = 0.05$ m and aperture ratios of $AR = 78$ and 57% (D05AR78 and D05AR57, respectively).

The moisture content of the pistachio nuts after the wetting stage was 35.3 ± 0.96 wt% w.b., which are similar results as those reported by Nejad et al. (2003). It is well known that bed hydrodynamics changes depending on the moisture content, especially at the beginning of the operation when the moisture content is high. Thus, particle density and, therefore bed mass for a given height, increases due to the wetting stage. Furthermore, instabilities may also appear due to interparticle forces between wet particles (Bacelos et al., 2007). In fact, the minimum spouting velocity determined for the pistachio nuts with equilibrium moisture content was not enough for stable operation with wet pistachio nuts. Accordingly, runs were conducted with the three configurations mentioned above (32° contactors equipped with fountain confiner) and the minimum spouting velocities determined are 111.2 m s⁻¹ (D03AR100), 39.3 m s⁻¹ (D05AR78) and 32.8 m s⁻¹ (D05AR57). These values are 15 - 35% higher than those corresponding to the dry nuts (equilibrium moisture content). Nevertheless, it should be noted that the increase in the minimum velocity is significantly lower when a draft tube is used. In order to ensure a stable fountain, the drying of previously moistened pistachio nuts was carried out with an air inlet velocity 1.2 times the minimum one. Higher air inlet velocities have not

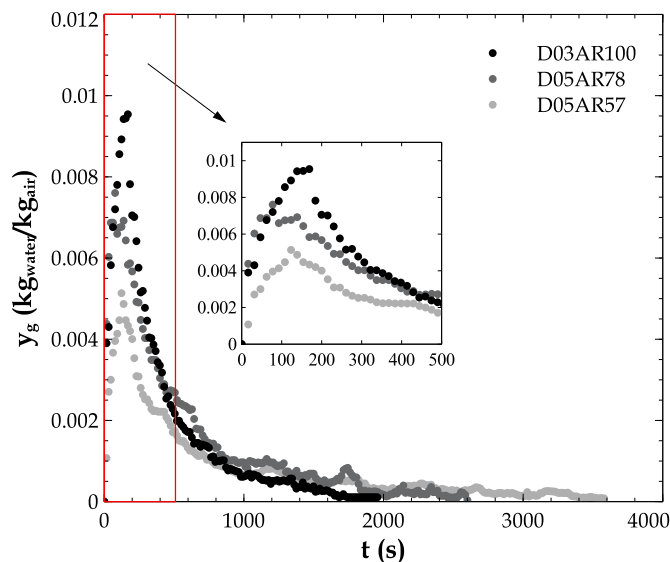


Fig. 7. Evolution of the air absolute humidity with time in the drying of pistachio nuts with different configurations, $\gamma = 32^\circ$, $H_0 = 0.27$ m, $u/u_{ms} = 1.2$, $T_i = 40^\circ\text{C}$.

been tested because they neither improve pistachio nuts splitting nor quality (Gazor and Minaei, 2005). Therefore, the inlet flow rate used was 283 N m³ h⁻¹ in the D03AR100 configuration, 278 N m³ h⁻¹ in the D05AR78 configuration and 232 N m³ h⁻¹ in the D05AR57 one.

Fig. 7 shows the evolution of the air absolute humidity at the outlet with time in the drying of pistachio nuts using the aforementioned configurations. As observed, the highest moisture content peak is attained with an air inlet diameter of 0.03 m and without draft tube. This may be explained by the high turbulence in the bed due to the high air diversion from the spout into the annulus. The drying rate is reduced by employing open-sided draft tubes, as the value of the peak moisture content is lower and the remaining drying period is longer in these configurations. Although the air inlet diameter is larger in the configurations with draft tube ($D_0 = 0.05$ m) than in the one without draft tube ($D_0 = 0.03$ m), the air percolation from the spout into the annulus is significantly reduced when draft tubes are used. Therefore, the beds without draft tube dry faster than those with open-sided ones. Accordingly, the time required to reduce the moisture of pistachio nuts from 35% to 4% increases from 1900 to 2625 s when beds without draft tube ($D_0 = 0.03$ m, $AR = 100\%$) are used rather than those equipped with 78% aperture ratio draft tube. This increase is more significant when a 57% aperture ratio draft tube is used, as 3560 s are required for drying pistachio nuts. An explanation lies in the better gas-solid contact due to the higher air diversion when operating without draft tube (Estiati et al., 2019a; Sukunza et al., 2022).

As mentioned above, the weight percentage of split pistachio nuts was estimated by Eq. (1). Fig. 8 shows the weight percentage of split pistachios and the time required to dry the pistachio nuts from 35 to 4% in the three configurations tested. The maximum fraction of split pistachio nuts was 23.3%, which was attained when operating without draft tube. However, the amount of split pistachio decreased when open-sided draft tubes were employed. Thus, the minimum fraction of split pistachios (15.2%) was achieved when operating with the 57% open-sided draft tube. Alternatively, the shortest time required for drying pistachio nuts (32.6 min) corresponded to the operation without draft tube ($D_0 = 0.03$ m, $AR = 100\%$), whereas the longest (59.7 min) is required when operating with a 57% aperture ratio draft tube ($D_0 = 0.05$ m). Therefore, there is a close relationship between the time required for drying and the fraction of split pistachio nuts, with the latter being higher as the drying time is shorter. As stated above, the more vigorous the circulation and the wider the fountains, the better the gas-solid contact. Since the

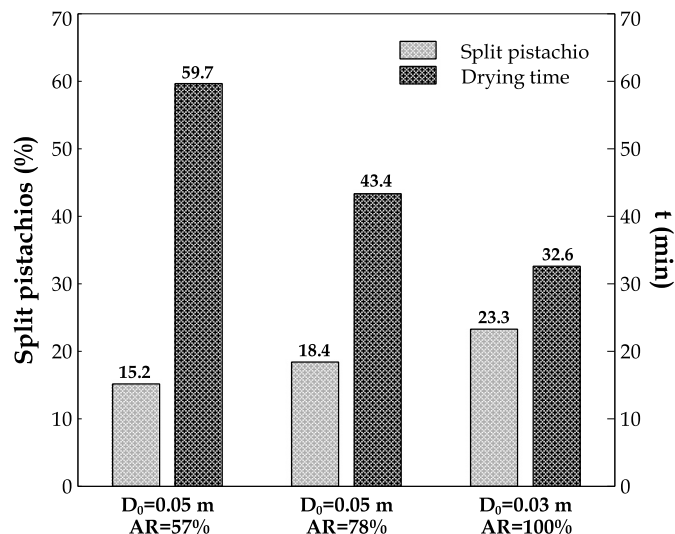


Fig. 8. Time required for drying and percentage of split pistachio nuts under different spouted bed geometries, $\gamma = 32^\circ$, $H_0 = 0.27$ m, $u/u_{ms} = 1.2$, $T_i = 40^\circ\text{C}$.

aim of the thermal splitting of pistachio nuts is to cause a longitudinal expansion force in the shell, fast drying of pistachio nuts is required, as it promotes evaporation of moisture within the shell. Accordingly, the expansion force caused by the vapour is enhanced, and therefore the splitting of pistachio nuts is increased. Furthermore, the collision of pistachio nuts against the wall of the contactor (especially in the downwards fountain periphery) also enhances the splitting of pistachio nuts (Bilim and Polat, 2008). However, excessive solid turbulence may cause shell breakage rather than splitting, which accounted for 5 - 6% when the configuration without draft tube was used ($D_0 = 0.03$, $AR = 100\%$). This situation is avoided when the other configurations are used.

4. Conclusions

The potential of spouted beds for pistachio nuts splitting has been analysed. Thus, a hydrodynamic study, as well the joint process of drying and splitting, have been approached by using a range of configurations with and without draft tube. Narrow angle contactors (32°) are preferred for attaining high turbulence, with the inlet diameter being slightly greater than particle size (0.03 m) when no draft tube is used, as this allows attaining highly stable beds. Nevertheless, inlet diameters of at least twice the particle size (0.05 m) are preferred when draft tubes are used. Furthermore, the width of the draft tube slots must be of at least the particle size, which corresponds to the aperture ratios of $AR = 57$ and 78% in the draft tube used (0.05 m in diameter).

The moisture content of the pistachio nuts has a great influence on the hydrodynamics. Thus, the minimum spouting velocity for wet pistachios is considerably higher than for dry ones (15 -35% higher) when no draft tube is used. Nevertheless, this velocity is only slightly higher when a draft tube is used. Moreover, the fountain confiner allows increasing the operational range of conical spouted beds.

Low temperature drying and splitting of closed shell pistachio has been carried out in different spouted bed configurations. The results show higher drying rates and higher splitting efficiencies in the configurations of high turbulence. An inlet diameter of $D_0 = 0.03$ m without draft tube leads to the highest solid circulation flow rate, followed by the configurations with open-sided draft tubes of $AR = 78\%$ and 57% . Problems associated with shell breakage (5 - 6%) of particles have been observed when the inlet diameter of $D_0 = 0.03$ m is used without draft tube, which is not the case in the other configurations. Therefore, the configuration that best preserves the quality of the product, concerning both inner fruit and hull quality, is the one provided with an inlet diameter of 0.05 m and a draft tube with 78% aperture ratio, as it avoids

shell breakage and allows sufficient air percolation from the spout into the annulus, improving the gas-solid contact and therefore pistachio nuts splitting. Future actions for the improvement of the spouted bed technology for this application are those related to increasing splitting efficiency and reducing the energy requirements in the process.

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

Data will be made available on request.

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