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ORIGINAL ARTICLE

Physical property and resistance to airflow through bulk and thin-layer lemon fruit

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Keywords
lemon fruit; modeling; pressure drop; resistance to airflow; storage.

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Nomenclature
A, B = constants; A_1, A_2, A_3, B_1, B_2, B_3 = product-dependent coefficients; L = length, mm; W = width, mm; H = height, mm; GMD = geometric mean diameter, mm; ε = porosity; R^2 = coefficient of determination; RMSE = root mean square error; P % = mean relative percentage deviation modulus; Q = airflow rate, $m^3 s^{-1} m^{-2}$; ΔP = pressure drop, Pa m^{-1}; ρ = air density, kg m^{-3}; ρ_t = kernel density, kg m^{-3}; ρ_b = bulk density, kg m^{-3}; μ = air viscosity, $m^2 s^{-1}$; ϕ = sphericity(%).

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Abstract

Introduction Physical properties of lemon fruit are important for drying system and Kept in stock. *Objective* The prediction of airflow resistance is fundamental to the design of efficient drying and aeration systems for lemon fruit. *Methods* Using a laboratory unit, two sets of experiments were carried out, namely thick and thin layers. In the thick-layer experiments, four bed depths, 11 flow rates and four temperatures 25, 35, 45 and 55 C. In the thin layer (two kernels depth, 3 cm), the kernels were put together in three arrangements: A, B and random; five moisture contents and 11 flow rates were studied. *Results* Results indicated that resistance to airflow through a column of lemon fruit increased with increasing bed depth and airflow rate. In the latter experiment, pressure drop decreased with a decrease in moisture content. Airflow rate was the most significant factor affecting the pressure drop of lemon fruit in both experiments. *Conclusion* Three applicable models (Shedd, Hukill and Ives, and Ergun) were used to evaluate the pressure drop data. The Ergun model, with higher values for coefficient of determination and lower values for sum of square error and mean relative deviation modulus, is the best model for predicting pressure drop across lemon fruit bed for the conditions studied.

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Introduction

Lemons, *Citrus aurantifolia*, are small citrus fruits whose skin and flesh are green in color and which have an oval or round shape with a diameter between 2.5 cm and 3 cm. Iran is an important lemon producer in the world, and Iranian output exceeds 615 000 tons year^{-1}, making Iran the ninth largest producer in the world (FAO, 2006; http://www.Fao.org/2007/2/20). When air flows through a porous bed of materials like agricultural products, the air pressure will drop. To recover the pressure, dimensioning of the fans is necessary and the energy demand for the fan depends highly on the pressure drop. Inattention to the relationship between air velocity, bed type, moisture content, bed depth, filling method, channel characteristics of the porous bed in any drying process can result in excessive water loss, shrinkage and quality degradation, and also causes large pressure drops that require more powerful fan systems. However, lower airflow rates result in increasing product temperature and risk of insect influx. When storing in bins, it is necessary to maintain previously dried lemons at uniform and sufficiently low temperature to avoid mold growth and other undesirable biochemical reactions. The prediction of airflow resistance in beds of agriculture material has been studied widely for more than 70 years (Kashaninejad & Tabil, 2009). Studies on the effect of different factors such as airflow rate, bed type, moisture content of bulk, bed depth, filling method, amount and type of foreign materials and direction of airflow through the bulk on airflow resistance have been conducted for grains (Shedd, 1951, 1953; Hukill & Ives, 1955; Jayas *et al.*, 1987; Sokhansanj *et al.*, 1990; Dairo & Ajibola, 1994; Li & Sokhansanj, 1994; Giner & Denisienia, 1996; Chung *et al.*, 2001) and other agricultural products such as parchment Arabica coffee (Agullo & Marenya, 2005), chickpea (Masoumi & Tabil, 2003) and pistachio nuts (Kashaninejad & Tabil, 2009). Knowledge about the airflow resistance across a bed of lemon is one of the most crucial data for designing important processes such as drying, cooling and also for control of optimal storage conditions. These data have not been reported in the available literature.

The main objectives of this study were the following:

(1) To measure some important physical properties of lemons.
(2) To identify the effect of airflow rate, bed depth, bed channel characteristics, moisture content and air temperatures on static pressure drop across a bed of lemon.
(3) To determine the appropriate mathematical model for pressure drop predicting across the lemon bed.

Materials and methods

Sample preparation

The lemon fruits used in this study were collected from a garden in Jahrom, Fars Province of Iran, in 2011. The initial moisture content of the product was 84% (wet base). Samples of different moisture content levels were made by adding appropriate amounts of distilled water, and samples were kept in sealed polyethylene bags in refrigerator (+4 °C) for 10 days to assure adequate and uniform moisture distribution. An ample amount of lemons was transferred from the cool place to the laboratory 6 h prior to use to allow them to reach room temperature. The moisture contents of the lemons were determined by air-drying samples in an oven (Heraes T5050, Heraeus Materials Technology, Chandler, AZ, USA) at 100 ± 5 °C until a constant weight was reached (Kashaninejad & Tabil, 2009). The lemon moisture contents used in this study were 84%, 64%, 44%, 24% and 10% (w.b.). Lemon samples were placed into the oven and 10 of them were randomly measured by digital scale and heating continued until the specified moisture content was reached.

Experimental apparatus

To measure airflow resistance across the bed of lemon, a test rig was designed and fabricated in the Department of Agricultural Engineering, Shiraz University, Shiraz, Iran. The main parts of the test rig are illustrated in schematic Figure 1. A centrifugal fan (Parma, 1400 rpm, 50 Hz, Italy) was used as an airflow source. The airflow was measured using a hot wire anemometer (Lutron, Taiwan) located far enough from the fan outlet in a PVC pipe (15 cm inter diameter) and connected to a plenum chamber. The plenum chamber and lemon holding chamber were made of a smooth PVC pipe with 40 cm internal diameter. The lemons in the container were supported by a perforated stainless sheet of metal placed at the bottom of the lemon holding chamber. Inlet air temperature to the lemon bed could be precisely controlled by a thermostat sensor (Atbin, ± 0.1 °C, Tehran, Iran) hanging just before the air stream was introduced into the lemon bed. An electrical heating unit (6 kW) was attached to the fan inlet regulating the air temperature introduced into the lemon bed. The pressure drop was measured by an accurate inclined manometer (TecQuipment, Nottingham, UK, pat: 771 493 ± 1 mm H_2O). To regulate the temperature, the thermocouple sensor was connected to a column of lemon and the thermostat was connected to an electrical unit.

Depth of lemon bed and filling methods

(1) Two sets of experiments were carried out, in the thick-layer experiments, four depths of lemon beds were adopted (25 cm, 50 cm, 75 cm and 100 cm). A discharging tube with zero height of fall was employed for charging the bin at each depth to have a loose bed of lemon samples.
(2) In the thin-layer experiments (two kernels depth, 3 cm), samples were put together in three arrangements, A, B and random, in the holding chamber (Figure 2). Due to the special shape of the lemon kernel, the channel characteristics formed by these arrangements in the porous bed were different.

Determination of some physical properties of lemon

Fifty kernels of lemons were picked up randomly from a bulk of lemons to determine dimensions and sphericity.

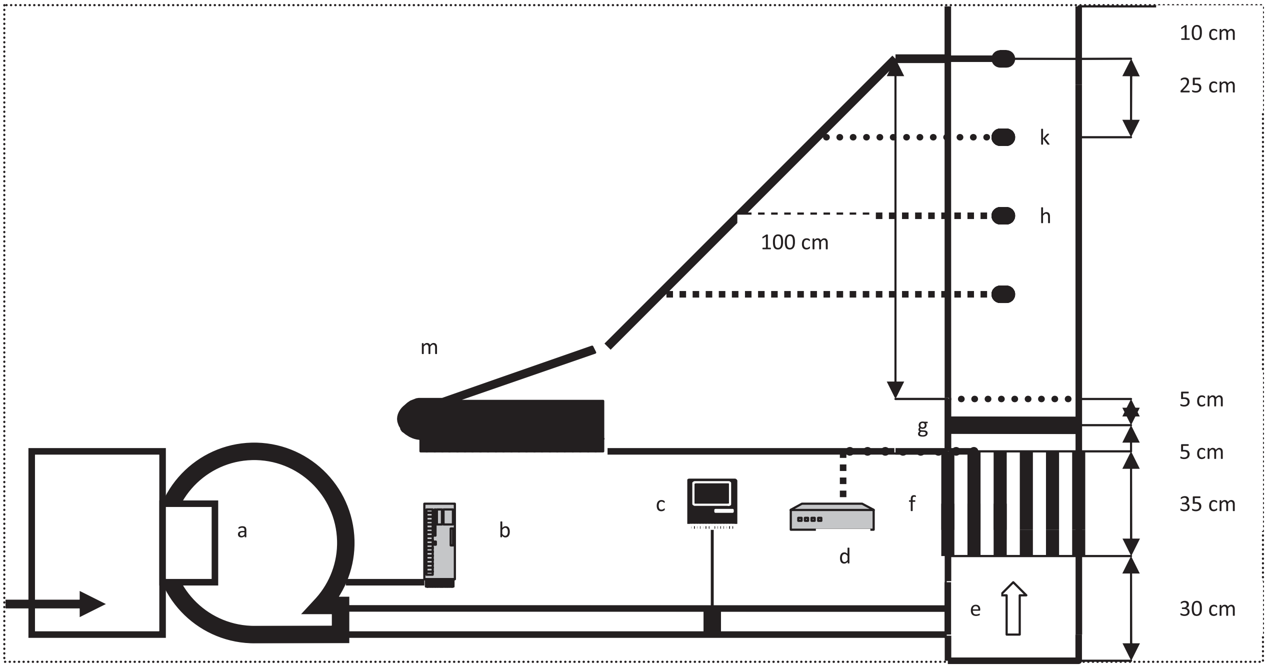

Figure 1 Schematic diagram of the apparatus used for airflow resistance measurement of lemons fruit. (a) electrical heating unit and centrifugal fan, (b) invertor, (c) hot wire anemometer, (d) thermostat (e) plenum chamber, (f) airflow straightener (m) manometer, (g) screen floor, (k, h) pressure taps.

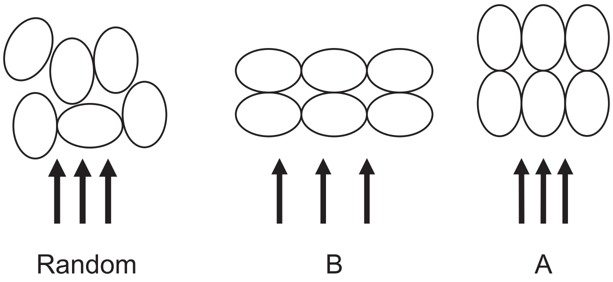

Figure 2 Three arrangements for lemon fruit.

Three principal dimensions, length (*L*), width (*W*) and height (*H*), were measured by a caliper (Mitutoyo, Kanagawa, Japan, ± 0.05 mm). The geometric mean diameter (GMD) and percentage of sphericity (ϕ) of fruits and nuts were calculated by the following equations (Mohsenin, 1996):

$$\mathrm{GMD} = (LWH)^{\frac{1}{3}} \tag{1}$$

$$\phi = \frac{(LWH)^{\frac{1}{3}}}{L} \times 100 \tag{2}$$

The porosity of a given bulk of material has a tangible effect on airflow resistance. To calculate the porosity, lemon particle density (ρ_t) and bulk density (ρ_b) were measured. Kernel density of lemon is the mass per unit volume of a single lemon. Particle density of dry lemon was measured using the liquid displacement method. Toluene (C_7H_8) was used instead of water because it has low surface tension, so that it fills even shallow dips in a dry lemon and its dissolution is negligible (Mohsenin, 1996).

Bulk density of three different arrangements, A, B and random free-fill (loose bed), were calculated from the mass and volume of the circular container of a known volume filled with samples. The porosity (ε) of the bulk lemon was determined using the following equation (Mohsenin, 1996):

$$\varepsilon = \frac{\rho_t - \rho_b}{\rho_t} \times 100 \tag{3}$$

Experimental procedure

During the experiments, room temperature was recorded as 20 ± 2 °C and relative humidity was in the range of 30 ± 5%. In this study, the measurement of the resistance to airflow of the lemon bed was carried out in two steps. First, the pressure drop across a thick layer (25 cm, 50 cm, 75 cm and 100 cm depth) of lemons (84% w.b initial moisture content) loose chamber, was measured. In the next set of experiments, the resistance to airflow of the lemons was measured for thin-layer at three different arrangements, five moisture contents (84%, 64%, 44%, 24% and 10% w.b) and two bed depths (one and two layers). Airflow rates ranging from 0.1 to 1.1 $m^3\ s^{-1}\ m^{-2}$ with four air temperatures (25 °C, 35 °C, 45 °C and 50 °C) were adopted for the thick-layer experiments. All the experiments were performed in three replications.

Mathematical modeling

Several models have been reported in the literature to predict pressure drop across grain and other beds of agricultural materials. The oldest and most famous model used is the Shedd model (Shedd, 1951 and 1953).

$$Q = A_1(\Delta P)^{B_1} \tag{4}$$

One important drawback of the Shedd model is that it can be used to predict the airflow resistance only over a narrow range of airflow rates (0.005–0.3 $m^3\ s^{-1}\ m^{-2}$) due to the nonlinearity of the log–log plot. The reciprocal of A_1 in this equation represents the resistance to airflow through the product. Physically, the reciprocal of A_1 in the equation was used to compare resistance to airflow of different samples (Kashaninejad & Tabil, 2009). All of the Shedd measurements were made in columns of grain in which the air was blown in paths parallel to the chamber axis. The model constants A_1 and B_1 depend upon moisture content and bulk density of the given grains. The study included different grains and the results did not show precisely the effect of the bin wall surface on airflow (Shedd, 1953). The Shedd model was recommended by Kashaninejad & Tabil (2009) for pistachio nuts. It was also suggested by Sokhansanj *et al.* (1990) for lentils and finally Jekayinfa (2006) used this model for locust bean seed.

Hukill & Ives (1955) proposed their equation for improved Shedd measurements. Their equation had a good fit with Shedd's equation but it was not easy to use because the equation could not determine the pressure as a direct function of airflow rates (Pabis *et al.*, 1998). The Hukill and Ives model is used in standard D272.3 of the American Society of Agricultural and Biological Engineers to represent the airflow pressure drop data of selected grains (Kashaninejad & Tabil, 2009). The Hukill and Ives equation is valid over a wide range of airflow rates, 0.01–2 $m^3\ s^{-1}\ m^{-2}$ (Hukill & Ives, 1955). Agullo & Marenya (2005) recommended the Hukill and Ives model for parchment Arabica coffee. Sokhansanj *et al.* (1990) reported good fitting results for the Hukill and Ives model compared with the Shedd model for lentils. The equation is in the form of

$$\Delta P = \frac{A_2 Q^2}{\ln(1 + B_2 Q)} \tag{5}$$

The third and more versatile empirical equation is the Ergun model (Ergun 1952). Ergun made a thorough study of the pressure drop versus airflow rate relationship for particulate materials and developed an equation based on fluid-dynamic principles. Ergun showed that the pressure drop can be calculated simply from the summation of two terms, the first term is a linear function of airflow rate and the second is a function of Q^2. The equation is written as

$$\Delta P = A_3 Q + B_3 Q^2 \tag{6}$$

Kashaninejad & Tabil (2009) reported that the Shedd model yielded higher value for the coefficient of determination and lower values for mean square error and mean relative deviation modulus. Agullo & Marenya (2005) reported the same results for Shedd and Hukill and Ives models. Giner & Denisienia (1996) reported that the Ergun equation showed a better result compared with the Hukill and Ives equation; however, both models presented lower error values compared with the Shedd equation. Madamba *et al.* (1994) reported that the resistance to airflow through garlic slices can be characterized by the Ergun equation. This equation has been used successfully to describe the airflow resistance through granular materials (Patterson *et al.*, 1971; Bern & Charity, 1975). In the present study, the airflow resistance experimental data were applied to fit against three more important models (Shedd, Hukill and Ives, and Ergun), using nonlinear regression analysis [Statistical Package for the Social Sciences (SPSS) 16, 2006, SPSS Inc., Chicago, IL, USA]. Several statistical criteria, such as coefficient of determination (R^2), root mean square error (RMSE) and mean relative percentage deviation modulus (P %), were used to evaluate the goodness of fit. The best model describing the airflow resistance of lemons was chosen as the one with the highest coefficient of determination and the least RMSE and mean relative deviation modulus (Kashaninejad & Tabil, 2009).

Results and discussion

Physical properties of lemons

The principle dimensions (L, H and W), the GMD, kernel density of 50 kernels of the lemon fruit were measured, and the data are presented in Table 1 at five different moisture

Table 1 Physical properties of lemon fruit at different moisture content (kernel)

Moisture content (w.b.%)	Kernel density $\left(\frac{\text{gram}}{\text{cm}^3}\right)$	Sphericity (%)	GMD (mm)	Width (mm)	Height (mm)	Length (mm)
84	1.038	0.886	35.67	33.52	33.642	40.28
64	0.698	0.913	33.26	31.85	31.72	36.42
44	0.486	0.918	31.04	29.29	30.21	33.81
24	0.249	0.934	29.34	27.61	29.42	31.1
10	0.238	0.94	28.29	26.2	28.56	30.26

GMD, geometric mean diameter; w.b., wet base.

Table 2 Physical properties of lemon fruit at different moisture content (bulk)

Moisture content (w.b.%)	Porosity (%)	Bulk density $\left(\frac{\text{gram}}{\text{cm}^3}\right)$	Orientation
84	0.47	0.57	A
	0.45	0.54	B
	0.47	0.54	Random
64	0.4985	0.35	A
	0.4699	0.37	B
	0.5128	0.34	Random
44	0.5061	0.24	A
	0.4855	0.25	B
	0.5267	0.23	Random
24	0.5261	0.118	A
	0.4239	0.126	B
	0.538	0.115	Random
10	0.5239	0.1133	A
	0.4789	0.134	B
	0.542	0.109	Random

w.b., wet base.

contents. It can be seen that the principle dimensions and the GMD of the lemon fruit kernels decreases in moisture content. The decreasing trend of kernel density of lemon fruit may be attributed to a higher volumetric expansion of the lemon as compared with mass of the kernel. The porosity and bulk density in the three arrangements were measured in five moisture content (Table 2). The results show that the bulk densities decreased and the porosity value increased with a decrease in moisture content. These variations can be attributed to the increasing sphericity of the lemon with a decrease in kernel moisture content.

Effect of bed depth on pressure drop of bulk lemon fruit

In order to study the effect of bed depth and airflow on pressure drop, data only on dense fill beds at moisture content of 84% w.b were considered. To identify the effects of airflow rate, bed depth and temperature on pressure drop, 11 levels of airflow rates (0.1–1.1 $m^3 s^{-1} m^{-2}$) and four levels of bed depth (25 cm, 50 cm, 75 cm and 100 cm) were used. Figure 3 illustrates the effects of different airflow rates on the pressure drop of the five bed depths. The increase in the pressure drop across the lemon beds was proportionate to the increase in bed depth. The results indicated the resistance to airflow rate compared with the depth of lemon beds. SPSS (version 16) was used for statistical analysis (Table 3).

Thin-layer experimental results

To identify the effects of airflow rate, moisture content, orientation and one and two layers of lemon on pressure drop, 11 airflow rates (0.1–1.1 $m^3 s^{-1} m^{-2}$), five moisture contents (84%, 64%, 44%, 24% and 10% w.b) and three orientations of lemon were used.

The effects of airflow rates, lemon moisture contents and orientation on airflow resistance for thin layers of lemon are presented in Table 4. This table shows that the airflow rate, lemon moisture content and orientation all had significant effects on airflow resistance. Figure 4 illustrates the effects of the different airflow rates and lemon moisture contents on pressure drop. At a given airflow rate, the pressure drop decreased with a decrease in moisture content. This decrease in pressure drop may be attributed to a decrease in bulk density as well as an increase in the bed porosity caused by decreased moisture. Similar results were reported by other researchers such as Sokhansanj *et al.* (1990), Al-yahya & Moghazi (1998) and Kashaninejad & Tabil (2009). Figure 5 illustrates the effects of different airflow rates and orientation on the pressure drop with lemon fruit arrangement. The results showed that in the *Y* arrangement, the airflow resistance was greater than A and random with minimum amount for A case. These variations can be attributed to the shape of airflow channels made by putting the lemons together in a thin layer with different arrangements and the ease of airflow entrance to the thin-layer bed.

The results from both experiments were analyzed in order to select the best model for predicting the airflow resistance across a deep bed and range of lemon moisture contents. Tables 5 and 6 showed the estimated product dependent coefficients and statistical criteria for the three models (Shedd, Hukill and Ives, and Ergun) fitted to the experimental pressure drop data for bulk and thin layers at different experimental conditions. The curve-fitting results showed

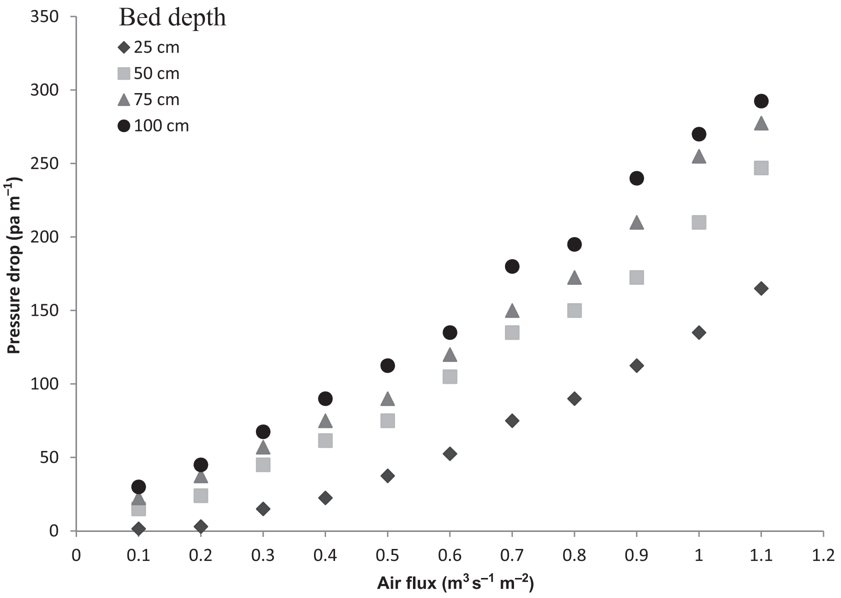

Figure 3 Effect of bed depth on pressure drop of lemon fruit at airflow rate (0.1–1.1 $m^3 s^{-1} m^{-2}$).

Table 3 Effect of airflow rate, bed depth and temperature on pressure drop of lemon fruit

Variable	*F*-value	Sum of squares	Degree of freedom
Airflow rate, *Q*	3 385	1 385 896.359	10
Bed depth, *H*	1 471	180 682.21	3
Temperature, *T*	3.506	430.562	3
$Q \times H$	34.543	42 426.618	30
$Q \times T$	0.174**	213.558	30
$Q \times H \times T$	0.168**	619.253	90

**No significant affected the pressure drop of lemon fruit at $P = 0.01$.

Table 4 Effect of airflow rate, moisture content, orientation and bed depth on pressure drop of lemon fruit

Variable	*F*-value	Sum of squares	Degree of freedom
Airflow rate, *Q*	829.013	652 918.432	10
Moisture content, *M*	32.055	10 098.471	4
Orientation, *O*	105.279	16 583.249	2
Bed depth, *H*	2562	201 787.834	1
$Q \times M$	2.187	6 889.424	40
$Q \times O$	2.305	3 631.451	20
$Q \times H$	78.382	61 732.599	10

that the Ergun model can be used with more confidence (highest R^2 and lowest and RMSE values) for predicting the airflow resistance at five lemon moisture contents as compared with other models (Tables 5 and 6).

Table 5 Estimated parameters and comparison criteria of Ergun equation at various moisture contents and fill methods

Moisture content (w.b.%)	A_3	B_3	*F*	R^2	Residual sum of squares
84	20.524	62.522	4883.69	0.997	26.593
64	63.937	52.98	3294.47	0.995	83.888
44	61.015	60.793	2202.38	0.993	134.702
24	70.424	48.623	3038.14	0.995	95.352
10	27.988	54.437	2074.71	0.994	63.082

w.b., wet base.

Table 6 Estimated parameters and comparison criteria of Ergun equation at various bed depth and fill methods

Bed depth	A_3	B_3	*F*	R^2	Residual sum of squares
25	13.652	78.092	2937.44	0.996	53.019
50	82.143	76.161	2490.35	0.994	202.079
75	70.388	68.271	2311.34	0.993	166.588
100	129.878	47.479	4714.9	0.996	141.334

Conclusions

The following conclusions were drawn from this investigation:

(1) The principle dimensions, the GMD, sphericity and the bulk density of lemon decreased with a decrease in moisture content.

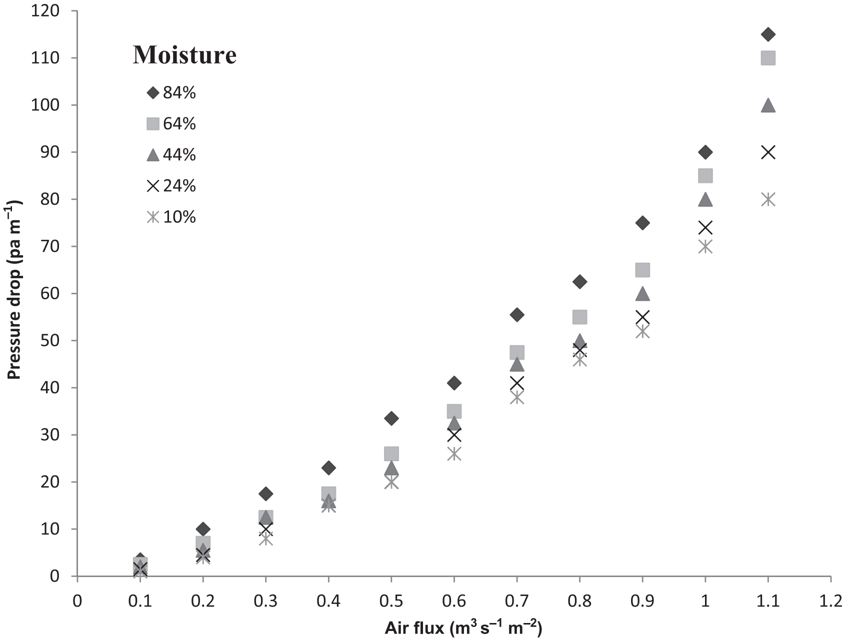

Figure 4 Effect of moisture content on pressure drop of lemon fruit at airflow rate (0.1–1.1 m^3 s^{-1} m^{-2}).

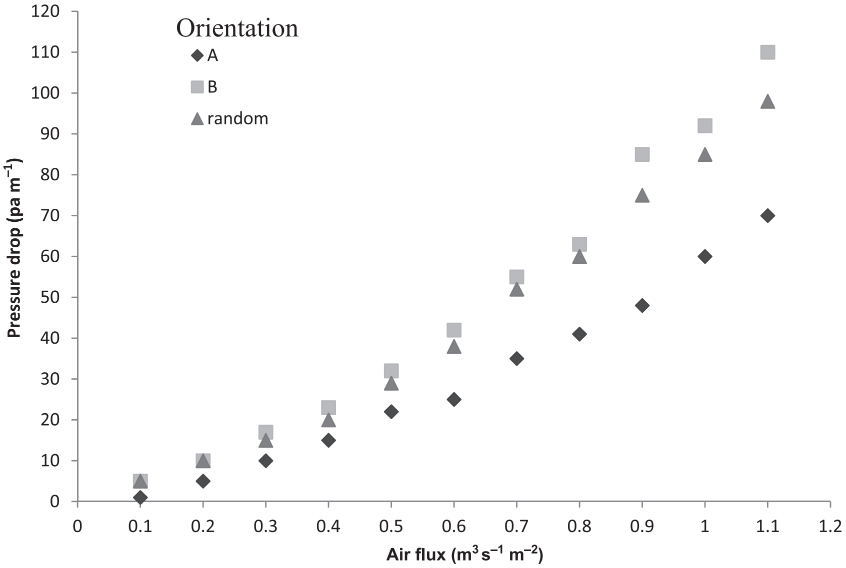

Figure 5 Effect of orintation on pressure drop of lemon fruit at airflow rate (0.1–1.1 m^3 s^{-1} m^{-2}).

(2) The pressure drop increased linearly with an increase in bed depth.

(3) The pressure drop through lemon beds increased more rapidly with increasing airflow rate compared with bed depth.

(4) Airflow rate, moisture content, bed depth and their interactions significantly affected the pressure drop, but airflow rate had the most significant effect on pressure drop of lemon fruit.

(5) An increase in the bed depth range from 25 cm to 100 cm caused about a 55% increase in pressure drop across lemon fruit.

(6) All the three models, Shedd, Hukill and Ives, and Ergun equations, were accurate for predicating the pressure

drop through bulk and thin layers of lemon fruit within the experimental range of study. However, the Ergun equation was considered the best model for predicting pressure drop based on statistical analysis.

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