Pressure Drop Through In-Bulk Flax Seeds

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ABSTRACT: The airflow resistance of in-bulk flax seeds *(Linum usitatissimum)* and the effect of airflow rate, bed depth, type of packing, and presence of foreign material ("fines" and "chaff") were studied. A good fit of the experimental data ($R > 0.993$) was obtained through the model $\text{DPL} = cQ + dQ^2$ (where DPL is pressure drop per unit of bed depth, Pa/m; Q is airflow rate, $\text{m}^3/\text{s-m}^2$; c and d are constants; and airflow range is 0.011–0.141 $\text{m}^3/\text{s-m}^2$). The airflow resistance increases when bulk density and bed depth increase. In dense packing the pressure drop is 1.3 to 1.5 times the pressure drop in loose packing. The resistance increases with the increase of fines and decreases with the increase of chaff.

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KEY WORDS: Aeration, airflow resistance, flax seeds, pressure drop.

It has been reported (1) that in 20 yr the utilization of 17 or more important oils and fats (palm, soybean, cotton, peanut, sunflower, canola, coco, flax, corn, fish, pig, tallow, etc.) will have increased about 47%. Then, as happened in the 1992–1993 and 1993–1994 harvests, demand will improve production. In the international field, Argentina occupies second place among the oleaginous flax producers, preceded by Canada (20 and 37% of total production, respectively), and exports almost exclusively oil and expellers.

Until the present time, oleaginous flax *(Linum usitatissimum)* has been used as a source of oil for nonalimentary use, and its worldwide demand had been gradually diminished by its replacement with synthetic products. However, recent genetic engineering and biotechnology research in Australia has led, through application of mutants, to *Linum usitatissimum* seeds ("linola" or "flaxola") practically identical to traditional flax seeds in their proximate components but with oils resistant to oxidation, with no more than 2–4% linolenic acid and no less than 70–75% linoleic acid, maintaining the concentration of oleic acid (2). These studies originate new perspectives for flax production as an alternative oleaginous food, and there are researchers who foresee that these new varieties will be commercially available in the next 5 yr.

With the aim of avoiding possible further in-field loss, many farmers harvest the grains with excessive moisture content to be stored. Fat acidity as well as germination power and mycotoxin contamination are very important indicators of grain quality. During storing, fungus proliferation is the most important cause of germination loss, darkening, toxin production, and increase of fat acidity. In post-harvest processing aeration is the most usual process used to maintain low uniform temperature and prevent moisture buildup.

The fatty acid composition of flax oil is easily affected by temperature. It therefore becomes indispensable to condition the grain at reduced temperatures through the use of aeration in order to preserve its quality during storage. The needed air flow, from which the aeration systems are designed, must be calculated with information on the airflow resistance of the stored material. This resistance, or pressure drop, depends on airflow velocity, bed characteristics, depth of silage, and type of packing.

The essential objectives of this work were to determine the pressure drop through in-bulk Argentine flax, to analyze the effect of the airflow velocity, bed depth, content of foreign material, and filling method on the resistance to airflow, and to study their mathematical modeling.

EXPERIMENTAL PROCEDURES

Apparatus. Figure 1 shows a diagram of the equipment employed to measure the airflow resistance of in-bulk flax seeds. The most important components are a metallic cylindrical bin for storing, an airflow production system, and airflow and pressure drop instruments.

A centrifugal fan (maximum flow 0.1 m^3/s) with variable inlet-air was used. The air was conducted to a conical plenum passing through a tube 2 inches in diameter. A calibrated orifice plate was employed to measure the airflow rate. Inside the chamber an airflow straightener with honeycomb panel structure was placed to create a uniform velocity profile. Between the orifice plate and the fan, two purge taps were installed in order to regulate the airflow in a wide range of air velocities. To support the grain mass, a steel standard mesh (Number 18) was placed at the bottom of the test column (0.36 m internal diameter, 1.60 m height). The column diameter exceeded the minimum value of 20 particle diameters that is necessary for accurate scale-up observations.

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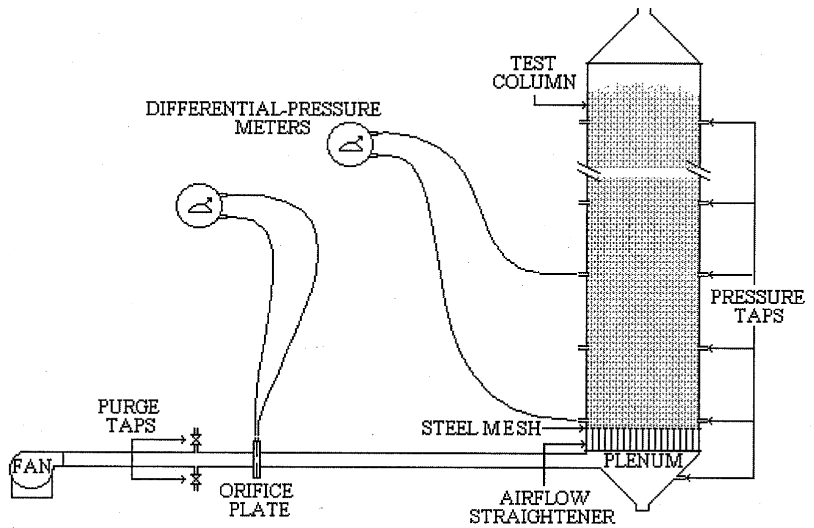

FIG. 1. Schematic of experimental equipment used to study the resistance to airflow of in-bulk oleaginous flax *(Linum usititassimum)* in the range of airflow velocity from 0.011 to 0.141 $m^3/s\text{-}m^2$.

Around the container, piezometric rings, each with four-pressure taps at six different levels, allow measurement of the pressure drop for five bed depths. Eight paired pneumo-magnetic meters of differential pressure with different analog scales (Dwyer-Series 2000 Magnehelic model, exactitude/precision: ±2% of full scale, ranges: 0–6 mmca, 0–25 mmca, 0–80 mmca, 0–25 cmca, minor division: 0.2, 0.5, 2.0, and 0.5, respectively) were used to measure the airflow velocities (0.011–0.141 $m^3/s\text{-}m^2$) and pressure drops.

Materials. A sample (approximately 100 kg) of oleaginous flax *(L. usitatissimum)* "Areco Inta" cultivar, certified pureness-variety, minimum germination 85%, grown during the 1994–1995 season in Argentina, was employed. The grain was harvested after natural field drying. The mean moisture content expressed on a wet basis (w.b.) was 5.81% and the hectoliter weight according to a national classification (3) was 67.16 kg/hL.

Foreign material. To study the effect of foreign material on the pressure drop, samples of "fines" and "chaff" were collected at a local grain-storage plant. The "fines" were defined as the material that will pass through a U.S. Standard Sieve No. 16 (1.18 mm square opening), and were formed by small particles with diameters smaller than flax seeds. Its hectoliter weight was 47.47 kg/hL, its moisture content was 7.94% (w.b.), and its composition was 10.76% inert material (fragments of capsules), 54.80% foreign seeds (*Rapistrum rugosum* 14.06%, broken *Linum* 36.44%, *Ipomoea purpurea* 3.35%, shelled *Avena* sp. 7.19%, *Brassica campestris* 0.73%, *Polygonum convolvulus* 2.87%, *Rumex crispus* trazas, *Triticum aestivum* 7.83%, *Raphanus sativus* 10.54%, *Polygonum aviculare* 0.32%, *Avena fatua* 0.37%).

The "chaff" was the material that remained in a U.S. Standard Sieve Series No. 14 (1.41 mm square opening), and it consisted of capsules and milled flax.

The foreign material was divided into different fractions that were mixed with clean grain using a revolving mixer-machine and manual mixing for 15 to 30 min. The time of mixing was gradually increased with the increase of the added fraction of foreign material. The experiments were designed with the levels (% in weight) 0, 5, 10, and 15% of chaff (with 0% of fines), 0, 5, 10, and 15% of fines (with 0% of chaff), and the combined level of 10% fines and 5% chaff.

Equivalent diameter and grain density. The equivalent diameter of flax grains was determined by measuring the volume of small samples (3–5 g each) in quadruplicate, using a water pycnometer. The mean volume of grain and the equivalent diameter of a sphere with the same volume of grain were calculated. This method cannot be employed to determine the equivalent diameter of foreign material because the small particles cause great difficulties when performing the counting.

Filling method. The filling of the silo was achieved by two different methods. The first consisted of manual charge using a funnel that was slowly moved uphill while the material was coming. This procedure allowed a falling height near zero that produced loose fills. The second was achieved by free falling from a maximum height of 1.60 m, like a real silo, producing dense fills.

Bulk density and bed porosity. The bulk density was determined by measuring the mass of material required to fill the silo in each case and dividing by the volume. The bed porosity was evaluated with Equation 1 (4):

$$\varepsilon = (1 - \rho b/\rho g) \cdot 100 \qquad [1]$$

where ε = bed porosity, %; ρb = bulk density, kg/m^3; ρg = grain density, kg/m^3.

RESULTS AND DISCUSSION

Analysis of the pressure-drop data. The data for resistance to airflow for five different bed heights of oleaginous flax *(L.*

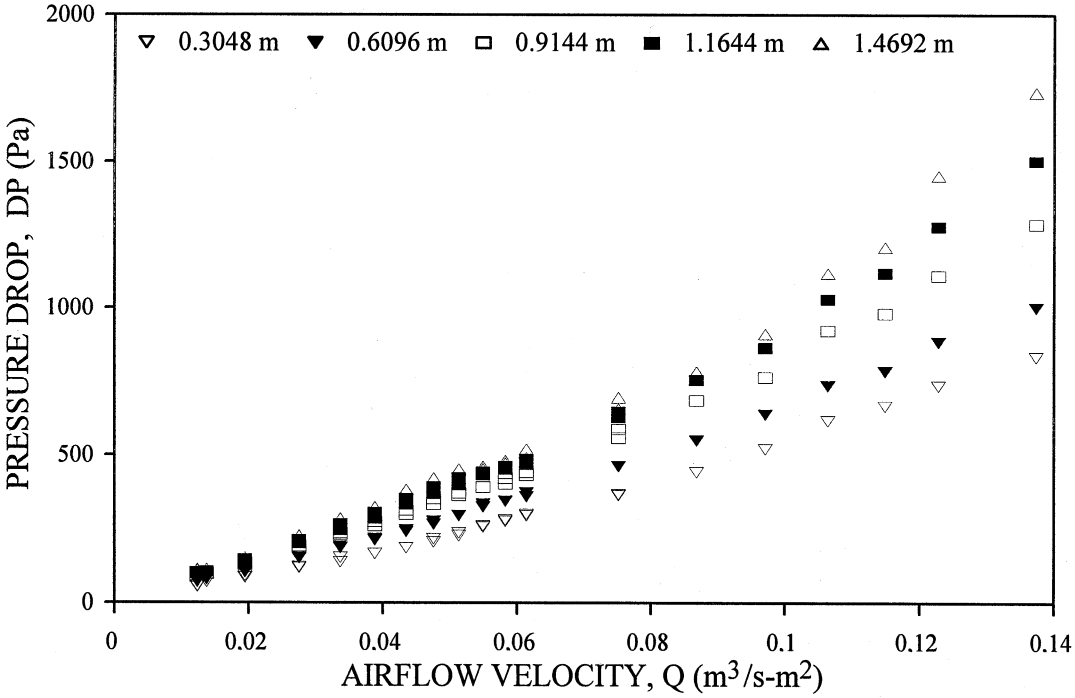

FIG. 2. Resistance to airflow of oleaginous flax *(Linum usitatissimum)* with moisture content of 5.81% at different bed depths in the range of airflow velocity from 0.011 to 0.141 $m^3/s\text{-}m^2$.

usitatissimum) with moisture content of 5.81% in the loose fill are presented in Figure 2. It can be observed that the pressure drop increases with the increase of airflow velocity and bed depth. The increase is more important for the airflow velocity increase than the bed depth increase. Starting from the different models that are reported in the literature, it was decided that the first step would be to analyze the results observed considering three alternative models: Shedd's equation (5,6) frequently mentioned in the literature, Henderson's equation (7) developed for corn, soybeans, and oats, and Mattei's equation (8), a simplification of the known Ergun's equation (9). The Shedd's equation has the form:

$$\mathrm{DPL} = A \cdot Q^B \qquad [2]$$

where DPL = pressure drop per unit of bed depth, Pa/m; Q = airflow velocity, $m^3/s\text{-}m^2$; and A, B = constants for each particular grain.

The Henderson's equation is:

$$\mathrm{DP} = a \cdot Q^b \qquad [3]$$

where DP = pressure drop in the bed, Pa and a, b = constants for each particular grain and bed depth.

The Mattei's equation is the expression:

$$\mathrm{DPL} = c \cdot Q + d \cdot Q^2 \qquad [4]$$

where c and d are constants for each particular grain.

Equations 2, 3, and 4 were fitted for each of the 28 experiments (10 beds of clean grain, fines, chaff, clean grain with fines, clean grain with chaff; two types of packing; different bed depths) in airflow velocity range of 0.011 to 0.141 $m^3/s\text{-}m^2$. The corresponding constants for each model and their correlation coefficients (R) are presented in Table 1. From analysis of the results at each bed depth, it was observed that Mattei's model describes the experimental data of resistance to airflow better than Shedd's or Henderson's for clean flax in loose fill and dense fill, and for mixtures of clean grain with fines and chaff ($R = 1$ for most of the cases, Table 1).

Effect of the filling method. For clean grain, the observed values of resistance to airflow at one determined airflow velocity were significantly different for the two filling methods (Fig. 3). Similar results were obtained (10,11) in previous studies for wheat beds. The higher pressure drops correspond to dense fill, representing a bulk density of 658 kg/m^3. For the range of airflow velocity employed in this study, the resistance to airflow per unit of bed depth in dense fill (for both 0.3048 m and 1.1644 m bed heights) was 1.3 to 1.5 times the resistance to airflow of loose fill.

Effect of bed depth. Table 1 shows that different values of constants for each equation and bed depth were obtained. These results can be caused by variations on the bed porosity produced by the material weight. This indicates that the dependence of the pressure drop on the bed depth is not exactly linear, as is shown in Figure 4 for flax in loose and dense fill, mainly at the highest airflow velocities. In previous studies similar conclusions were obtained (12,13) for corn and oats.

Taking this behavior into account, and with the aim of determining a relation among pressure drop, airflow velocity, and bed depth, the applicability of the simplified Henderson's equation (7) (valid for corn, soybeans and oats) was analyzed. The mathematical expression is:

$$\mathrm{DP} = m \cdot Q^n \cdot H^{-t} \qquad [5]$$

TABLE 1
Physical Properties and Estimated Parameters of Shedd's, Henderson's, and Mattei's Equations for Oleaginous Flax *(Linum usitatissimum)*, Foreign Material, and Mixtures of Flax with Foreign Material (range of airflow velocity: 0.011–0.141 $m^3/s\text{-}m^2$)[a]

Bed composition			Bed depth (m)	Bulk density (kg/m^3)	Type of pack	Shedd's model			Henderson's model			Matteis' model		
Flax (%)	Fines (%)	Chaff (%)				*A*	*B*	*R*	*a*	*b*	*R*	*c*	*d*	*R*
100	0	0	0.3048	649	Loose	21058	1.097	0.99	6414	1.097	0.99	11930	61028	1.00
100	0	0	0.6096	649	Loose	12839	1.089	1.00	7809	1.088	1.00	8031	29050	1.00
100	0	0	0.9144	649	Loose	10400	1.082	1.00	9562	1.084	1.00	6384	27275	1.00
100	0	0	1.1644	649	Loose	9636	1.103	0.99	11187	1.102	0.99	5255	28626	1.00
100	0	0	1.4692	649	Loose	8204	1.104	0.99	12031	1.104	0.99	3988	30803	0.99
100	0	0	0.3048	658	Dense	33744	1.135	1.00	10298	1.135	1.00	17215	76197	1.00
100	0	0	0.6096	658	Dense	21422	1.132	1.00	13039	1.131	1.00	11028	49384	1.00
100	0	0	0.9144	658	Dense	17574	1.125	1.00	16080	1.125	1.00	8789	46089	1.00
100	0	0	1.1644	658	Dense	15107	1.123	0.99	17551	1.122	0.99	7357	42531	1.00
100	0	0	1.4692	658	Dense	12953	1.127	0.99	19030	1.127	0.99	6045	38501	0.99
0	0	100	0.3048	527	Dense	7581	0.910	0.99	3467	1.068	0.99	8546	11557	0.99
0	0	100	0.6096	527	Dense	4378	0.930	0.99	4416	1.126	0.99	4361	10325	0.99
0	0	100	0.9144	527	Dense	3609	0.943	0.99	5734	1.153	0.99	3395	9862	0.99
0	100	0	0.3048	426	Dense	22838	0.878	1.00	7281	0.894	1.00	35420	–51347	1.00
0	100	0	0.6096	426	Dense	22130	0.892	1.00	15006	0.931	1.00	31586	–27281	0.99
0	100	0	0.9144	426	Dense	21724	0.909	1.00	22306	0.951	1.00	29035	–16858	1.00
95	5	0	0.3048	611	Dense	13071	0.954	0.99	6620	1.178	0.99	11845	23528	1.00
95	5	0	0.6096	611	Dense	12762	0.962	0.99	12589	1.178	0.99	11173	23031	1.00
90	10	0	0.3048	638	Dense	17022	0.973	0.98	10499	1.275	0.98	12853	44979	0.99
90	10	0	0.6096	638	Dense	14490	0.927	0.98	16229	1.197	0.98	13501	30451	0.99
85	15	0	0.3048	659	Dense	15079	0.888	0.99	7705	1.107	0.99	16844	25963	0.99
85	15	0	0.6096	659	Dense	15217	0.888	0.98	18126	1.168	0.98	15887	39983	0.99
95	0	5	0.3048	611	Dense	10543	0.987	0.99	5451	1.233	0.99	8311	19916	1.00
95	0	5	0.6096	611	Dense	9790	0.966	0.99	10462	1.229	0.99	8038	19303	1.00
90	0	10	0.3048	629	Dense	10776	1.015	0.99	5066	1.221	0.99	8124	17465	1.00
90	0	10	0.6096	629	Dense	9947	0.991	0.99	9812	1.222	0.99	7800	17220	1.00
85	0	15	0.3048	651	Dense	11309	1.020	0.99	5623	1.242	0.99	8265	21362	1.00
85	0	15	0.6096	651	Dense	10198	0.990	0.99	10642	1.235	0.99	7973	20269	1.00

[a] *A, B*: constants of Shedd's model; *a,b*: constants of Henderson's model; *c,d*: constants of Mattei's model; *R*: coefficient of correlation.

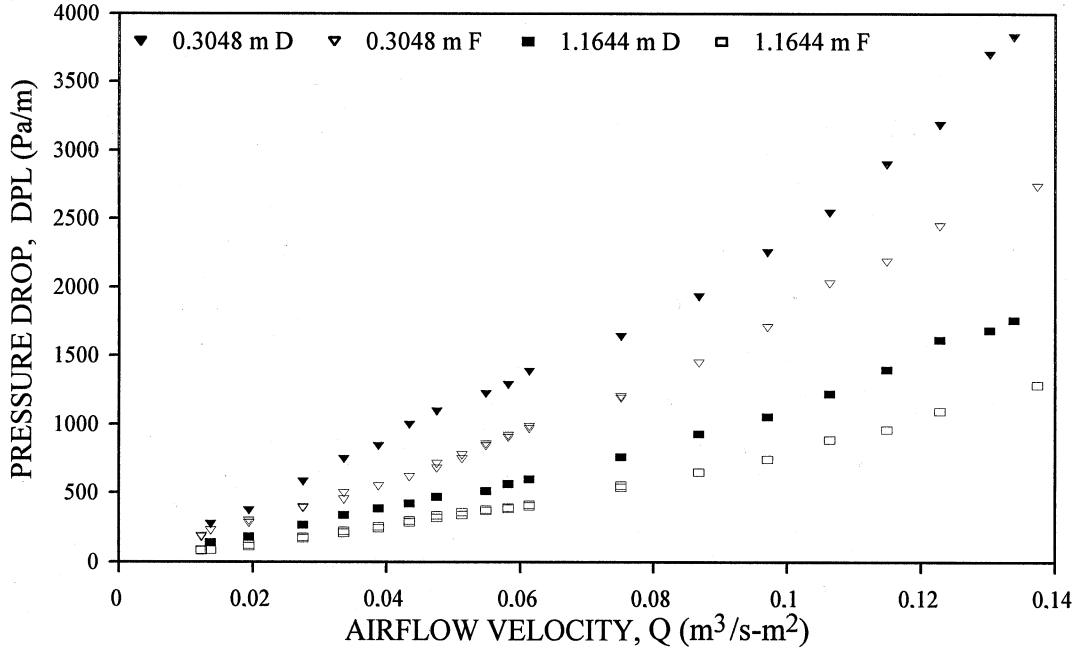

FIG. 3. Effect of filling method on the resistance to airflow of oleaginous flax *(Linum usitatissimum)* for beds of 0.3048 m and 1.1644 m depth (D and F indicate dense and loose fill, respectively).

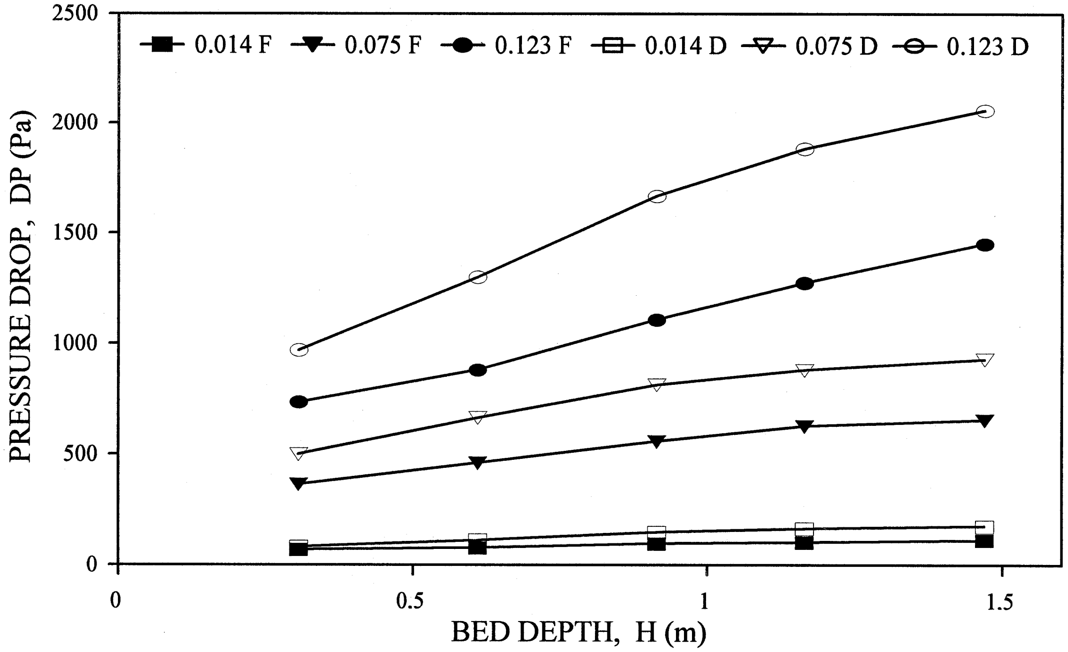

FIG. 4. Effect of bed depth on the resistance to airflow of oleaginous flax *(Linum usitatissimum)* in loose fill (F) and dense fill (D) at three different airflow velocities: 0.014, 0.075, and 0.123 $m^3/s\text{-}m^2$.

where H = bed depth, and m, n, t = constants for each particular grain.

This equation represented an adequate fitting of the experimental data for clean flax in dense fill ($R = 0.991$), clean flax in loose fill ($R = 0.990$), fines in dense fill ($R = 0.998$), and chaff in dense fill ($R = 0.978$) (Table 2).

Effect of foreign material. The fines caused higher values of pressure drop per unit of bed depth than clean grain, while the chaff offered less resistance to airflow than clean flax.

When clean grain was mixed with fines, the increase of fines content in the sample led to large values of resistance to airflow per unit of bed depth (Fig. 5). For samples without chaff, increases in the fines fraction of 5 to 10 and 5 to 15% corresponded to increases of 81 and 116%, respectively, in the pressure drop at 0.011 $m^3/s\text{-}m^2$, and increases of 24 and 56% at 0.141 $m^3/s\text{-}m^2$.

For samples without fines, the increase in the chaff fraction of 5 to 10% produced a decrease of 7% on the resistance to airflow, but subsequently increases of up to 15% in the chaff fraction produced an increase of 3–4% in the pressure drop (Fig. 6). Similar results to this particular behavior were reported by Jayas *et al.* (14) in a study of flax beds with different moisture contents, foreign material, and airflow directions.

Combined effect of fines and chaff. With the aim of determining a relation which may allow us to calculate the resistance to airflow for flax beds accommodating the interactive effect of different fines and/or chaff contents, the next modification of Mattei's equation (8) was made:

$$\mathrm{DPL} = X_1 \cdot Q + X_2 \cdot Q^2 + X_3 \cdot Q \cdot \mathrm{FF} + X_4 \cdot Q \cdot \mathrm{FG} \qquad [6]$$

where FF = fines fraction, FG = chaff fraction, and X_1, X_2, X_3, X_4 = constants.

The constants of Equation 6, calculated from the pressure drop data in beds of clean flax, fines, chaff, and mix (up to 15% in mass) of clean flax with fines and chaff, were $X_1 = 11798$, $X_2 = 11606$, $X_3 = 19686$, and $X_4 = -7484$ ($R = 0.921$). However, it is not frequent in practice to find samples with fines or chaff fractions higher than 15%. Equation 6 was again

TABLE 2
Constants of Shedd's, Mattei's, and Modified Henderson's Models for Beds of Oleaginous Flax *(Linum usitatissimum)* in Loose and Dense Fill, and Fines and Chaff in Dense Fill[a]

Type of bed	Type of pack	Shedd's model			Mattei's model			Simplified Henderson's model			
		A	*B*	*R*	*c*	*d*	*R*	*m*	*n*	*t*	*R*
100% Flax	Loose	9159	1.095	0.948	7118	35356	0.712	17220	1.290	−0.429	0.990
100% Flax	Dense	14846	1.128	0.949	10081	50657	0.709	25418	1.303	−0.436	0.991
Fines	Dense	22226	0.893	0.988	32014	−31808	0.972	23482	0.940	−0.875	0.998
Chaff	Dense	4930	0.931	0.868	5434	10582	0.681	5330	1.123	−0.0277	0.978

[a] See Table 1 for definitions.

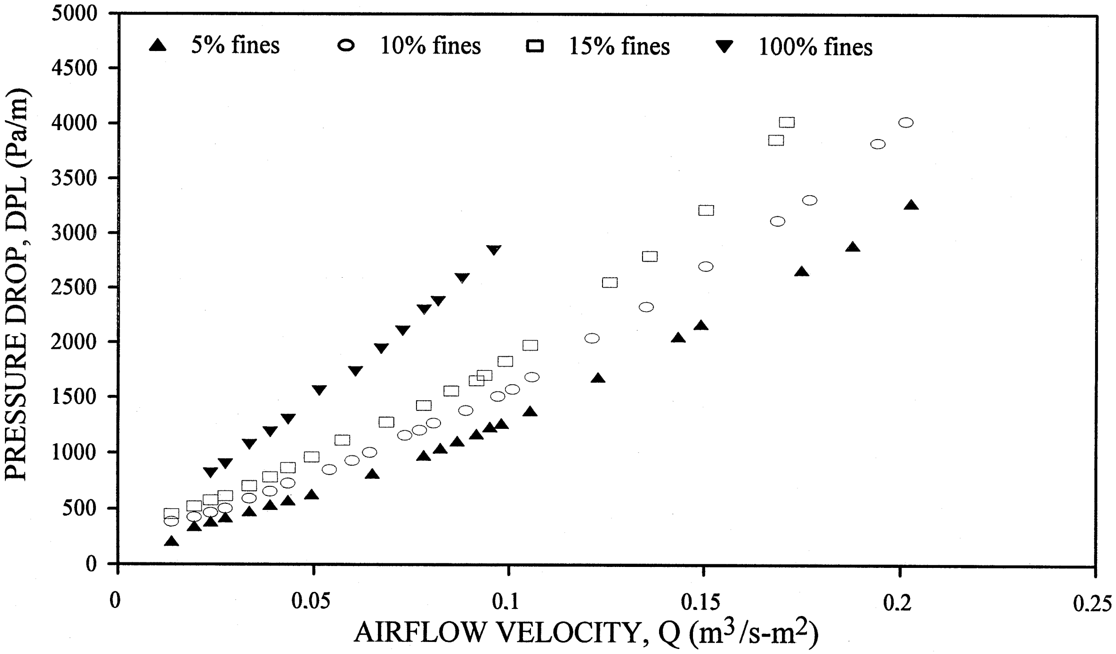

FIG. 5. Effect of fines content on the resistance to airflow of oleaginous flax *(Linum usitatissimum)* at 0.6096 m bed depth.

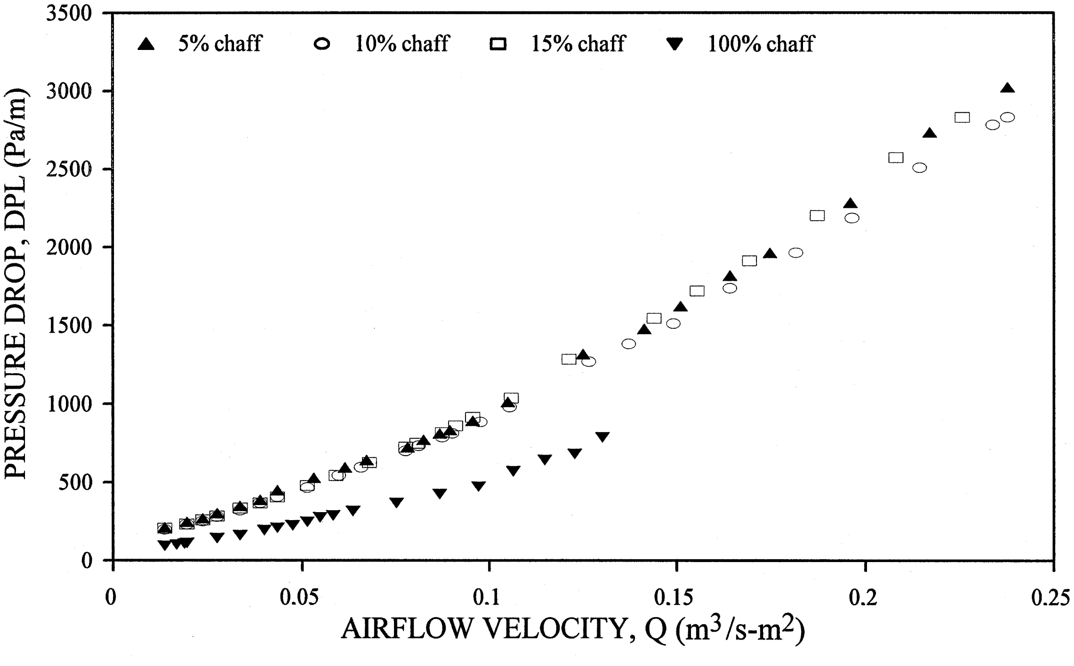

FIG. 6. Effect of chaff content on the resistance to airflow of oleaginous flax *(Linum usitatissimum)* at 0.6096 m bed depth.

tested and a higher correlation coefficient was obtained. The new constants were $X_1 = 7996$, $X_2 = 22402$, $X_3 = 68724$, and $X_4 = -4178$ ($R = 0.988$).

Based on the results of this work, we selected the Mattei equation as meeting our objective for mathematical modeling. It describes accurately the experimental data of resistance to airflow at each bed depth for clean grain in loose and dense fill and for mixtures of flax with fines and chaff.

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