Aerodynamic and solid flow properties for flaxseeds for pneumatic separation by using air stream

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Abstract: This study aimed to develop simple empirical equations to predict flaxseeds properties. The first part of the present study deals with the physical, aerodynamic and solid flow properties of flaxseeds which are evaluated as a function of change in moisture content from 8.60% to 23.90% dry basis (d.b.), the dimensions of the length, width and thickness varied from 4.14 to 4.32 mm, 2.03 to 2.13 mm and 0.88 to 0.93 mm, respectively. As the moisture content increased from 8.60% to 23.90% d.b., the bulk density, true density and porosity were found to decrease from 46.65 to 44.89 kg/m^3; 1244 to 1176 kg/m^3 and 46.65 % to 44.89%, whereas angle of repose and terminal velocity were found to increase from 27.60 to 35.80 and 2.46 to 3.56 m/s, respectively. The static coefficient of friction on various surfaces, namely, plywood, stainless steel, galvanized iron, iron and internal also increased linearly with the increase in moisture content. The results of the experimental investigation may help to optimize some engineering parameters of separation equipment. The second part was carried out on a series of experiments to specify the optimum conditions of separating operation which insure the highest grade of separation efficiency with minimum losses. Pneumatic separation equipment was manufactured and tested under different combinations of the following factors: air stream velocity, feed rate and sample moisture content. The performance of the equipment was evaluated by using the indices separation efficiency and percentage of seed losses. The results of the equipment performances showed that the combinations of air stream velocity, feed rate and sample moisture content affected significantly the separation efficiency and grain losses. Air stream velocity of 2–6 m/s combined with 8.5 kg/h. feed rate and 8.6% moisture content can be considered the most favorable combination values of these variables. They gave the highest grades of separation efficiency and the minimum grain losses.

Keywords: flaxseed, physical property, aerodynamics, solid flow properties, pneumatic separation
DOI: 10.3965/j.issn.1934-6344.2009.04.031-045

Citation: Ayman Hafiz Amer Eissa. Aerodynamic and solid flow properties for flaxseeds for pneumatic separation by using air stream. Int J Agric & Biol Eng, 2009; 2(4): 31－45.

1 Introduction

Flax seed (*Linum usitatissimum* L.) is an economic ally important oilseed crop in the world and especially for Egypt, which produces about 30359 tons of seeds from 16438 hectare of land[1]. The plant is not a new crop and native to West Asia and the Mediterranean. As the source of linen fiber, flax has been cultivated since at least 5000 BC; today it is mainly grown for its oil[2,3]. It was used by the Egyptians to make cloth to wrap their mummies, and the Bible contains many references to the plant indicating that flax spinning and weaving were household industries in antiquity[4]. Also, the medicinal properties of the seeds were known to the Greeks and Hippocrates recommended them for inflammations of the

Received date: 2009-03-20 **Accepted date:** 2009-12-25
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mucous membranes. Flaxseed is a rich source of oil (40%) by weight and alpha linolenic acid (also called omega-3 fatty acid) (55%). Generally, oily flaxseeds have greater dimensions than fiber flaxseed[5]. The seeds have a crisp and chewy texture and a pleasant, nutty taste[6]. Traditionally, flaxseed has been grown for its oil, which is used in the manufacture of paints, varnishes and linoleum, because of its drying and hardening properties when exposed to the air and sunlight. Flaxseed oil is used as a purgative for sheep and horses. There is a market for flaxseed meal as both animal feed and human nutrition; also poultry feeding as it increases levels of omega 3 fatty acid in eggs[7]. Whole seed is used in the baking[6,8] of Flaxseed is rich in fat, protein and dietary fiber. Flaxseed is composed of 30%–40% fat, 20%–25% protein, 20%–28% total dietary fiber, 4%–8% moisture and 3%–4% ash, and the oil contains vitamins A, B, D and E, minerals, and amino acids. The composition of flaxseed can vary with genetics, growing environment, seed processing and method of analysis. Generally, the protein content of the seed decrease as the oil content increases[6,9-11]. Flaxseeds also contain substantial amounts (5%–8%) of soluble fiber, mucilaginous material. It has a high water holding capacity and shows similar functional properties to those of gum arabic[12,7]. Quality degradation occurs in particular with excessive moist and excessive hot product, and may be recognized from internal and/or external discoloration of the seed and a musty odor. Flaxseed has a storage life of more than 12 months at 9%–10% water content. To the best of our knowledge, there is no evidence on the physical properties of flaxseed. Thus to design equipment to improve the existing processing method, the physical properties of the seed has to be known. Separating and grading of flax seeds are two most important steps after harvesting to produce high quality product. These steps become costly these days. It is well known that separation of seed can be achieved by utilizing differences in some physical and mechanical properties of separate fractions of mixture (seed, straw, chaff and dust) such as shape, surface, dimensions or masses.

In pneumatic separators, air is used for separation of products according to differences in size, shape, density and characteristics of surface air resistance. Successful operation depends upon proper adjustment of airflow and uniform feeding of the product into the air stream. For the development of equipment such as pneumatic conveyors, pneumatic separators and aspiration systems, it is necessary to study the flow characteristics of seeds in air[13]. Ebaid M.T, et al [14] determined terminal velocity of some grain crops and their impurities (rice, wheat, corn and soybean). Ismail Z.E, et al[15] studied the effect of vertical air stream velocity, total impurities, and specific feed rates on the cleaning efficiency of wheat grain at different moisture contents of mixture. They found that the highest values of cleaning efficiency with minimal losses were in the ranges (93.45%–99.46%) at total impurities of 10%, air velocity of 6-8 m/s and moisture content of 15%.

Dimensions are important to design the cleaning, sizing and grading machines. Bulk density, kernel density and porosity are major considerations in designing the drying, aeration and storage systems, as these properties affect the resistance to air flow through the grain mass. Angle of repose and coefficient of friction are important in designing equipment for solid flow and storage structures. The coefficient of friction between seed and wall is an important parameter in the prediction of seed pressure on walls[16]. Several investigators determined the physical properties of pulses, oilseeds and cereal at various moisture contents such as[17-26]. Although Egypt does not make heavy machines, it makes manual and small power operated machineries for pulses e.g. seeder, thresher, dehuller, splitter etc, this study will provide some of the relevant data to design such machineries for flaxseeds. Moreover, since the moisture dependent physical properties of flax grown under Egyptian conditions are not available in literature, therefore, this study was done to determine some physical properties of flaxseeds at various moisture contents.

The specific objectives of this study were to identify the moisture dependent some of the physical properties such as linear dimensions, sphericity, geometric mean diameter, thousand seed weight, surface area, bulk and true density, and static coefficient of friction against selected surfaces and angle of repose and correlate the terminal velocity relationship with physical properties such as mass, surface area to predict the air velocity required for separation of seed from impurities, and also to the physical-mechanical properties of seed-straw to study the effect of some factors affecting flax seed separation efficiency and seed losses. Pneumatic separation equipment depending on the aerodynamic characteristics was used with a view to their separation in an air stream to enable handling by the above-mentioned technological processes.

2 Materials and methods

2.1 Sample preparation

Dried Sakha-1 flaxseeds were collected from the farm of Gemaza Research Centre, Gharbia as shown in Figure 1. The initial moisture content was (8.60% d.b.) determined by drying flaxseed sample in an air ventilated oven at 103℃ for 72 h[27]. Four levels of moisture contents of flaxseeds were selected 8.60%, 12.78%, 18.60% and 23.90% (on dry basis). The samples at the selected moisture contents were prepared by adding a calculated amount of distilled water and sealing them in separate polyethylene bags and storing them in a refrigerator at 7℃ for 72 h. Before each experiment, the required sample was taken out from the refrigerator and kept sealed in an ambient environment for 24 h to equilibrate the water and temperature throughout the sample. The sample is kept in the ambient environment in sealed conditions so there is no chance for changing moisture.

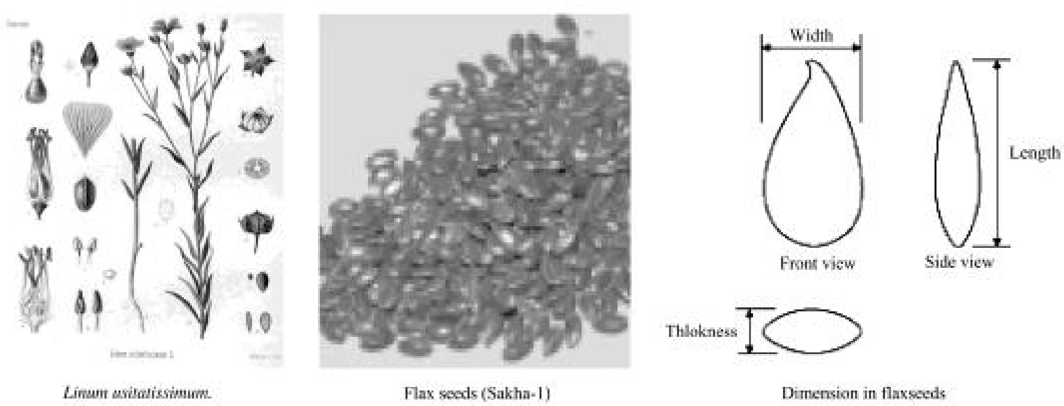

Figure 1 Shape of flaxseed and the geometry of flaxseeds

2.2 Geometric characteristics of flaxseeds

The average diameter of seed was calculated by using the arithmetic mean and geometric mean of the three axial dimensions. The average diameter was also determined similarly to the one calculated by considering it as an effective diameter in terms of the thousand seed mass and the true density as follows[17,28]:

$$d_e = \left(\frac{6000 m_{1000}}{p r_t} \right)^{1/3} \tag{1}$$

Where: d_e is the diameter of a sphere of the same volume as the seed in mm; m_{1000} is the thousand seed mass in g and ρ_t is the true density of the seed in kg/m^3.

The geometric mean diameter D_g in mm and the degree of sphericity in decimal were determined using the equation given by[29].

$$D_g^3 = LWT \tag{2}$$

Where: L is the length in mm; W is the width in mm; T is the thickness in mm. While the sphericity f of seed was determined by

$$f = \frac{(LWT)^{1/3}}{L} \tag{3}$$

The surface area S in mm^2 was determined by the relationship given by[30].

$$S = p D_g^2 \tag{4}$$

2.3 Determination of physical properties

The physical dimensions of flaxseed were determined by taking 100 seeds randomly and measuring the seed length, width and thickness at different moisture contents using a digital caliper to an accuracy of 0.01 mm. The measurements were taken at room temperature of 25℃.

The bulk density (r_b) was determined by filling a 500 mL beaker with seeds by dropping them from a height of 150 mm and weighing the seeds as performed by Kaleemullah S [21]. Dropping the seeds from a height of 150 mm produces a tapping effect in the container to reproduce the settling effect during storage. The true or kernel density (r_k) was determined by the water displacement method. Five hundred milliliter of water was placed in a 1000 mL graduated cylinder in which 20 g seeds were immersed. The immersion time was about 10 second that was too small to absorb water. The amount of displaced water was recorded from the graduated scale of the cylinder. The ratio of weight of seeds to the volume of displaced water gave the kernel density. The displaced water which is collected and weighed is used to calculate equivalent volume of water and hence volume of seed. Due to the short duration of experiment, moisture adsorption was found to be negligible and therefore seeds were not coated for moisture adsorption prevention. Porosity (*P*) was determined in terms of bulk density (ρ_b) and true or kernel density (ρ_t) by using the following formula[29].

$$P = \left(1 - \frac{r_b}{r_t}\right)100 \tag{5}$$

Mass of 1000 seeds of flax was determined by counting 100 seeds randomly and measuring its mass at different moisture contents using an electrical balance having an accuracy of 0.001 g and then it's multiplied by 10 to give the mass of 1000 kernels. The measurements were taken at room temperature of 25℃.

After making the required modifications, the hardness measurement apparatus[31] with the accuracy of 1N, shown in Figure 2 have been used for measuring the hardness of the flaxseeds. The peak deformation force required to compress the sample to a displacement of 2 mm on a non-lubricated flat platform using a flat probe was recorded by the breakage analyzer and used as a measure of product hardness, meanwhile the analog reading was increased with the increasing of the pressure on the seed until the seed has been cracked. At this point, the analog reading means seeds hardness. Only one reading was recorded for each seed of 100 seeds sample at a cross-head speed of 1 mm/s.

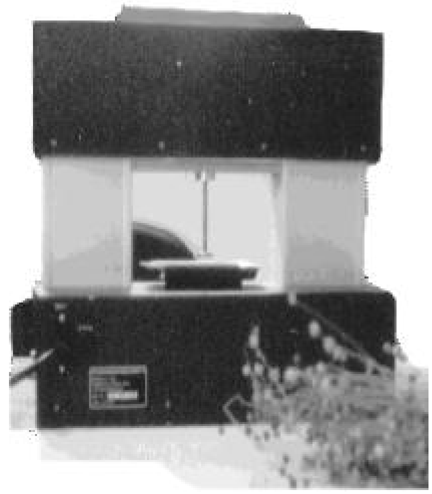

Figure 2 Instrument for measuring hardness of the flaxseeds

2.4 Solid flow properties

The angle of repose (θ) was determined by using a hollow cylindrical mould of 100 mm diameter and 150 mm height. The cylinder was placed on a wooden table, filled with lentil seeds and raised slowly until it forms a cone of seeds. The diameter (*D*) and height (*H*) of the cone were recorded. The angle of repose (θ) was calculated by using the following formula according to[21].

$$q = \tan^{-1}\left(\frac{2H}{D}\right) \tag{6}$$

The static coefficients of friction for flaxseeds were determined on five surfaces (stainless steel, galvanized steel, iron, plywood, and a surface of the same variety of seeds) at four different moisture contents. Seed samples were placed in the tray over the tested surface. The tray, which has the seed sample, was tilted up around its side pivot, the angle of friction was measured when 75% of the seeds reached the bottom and the tray was stopped. The calculated friction angle for the seed sample with each surface was the average of five replications.

According to[32], static coefficient of friction (μ) was calculated as the following formula:

$$\mu = \tan \varphi \tag{7}$$

Where: φ = the angle of tilt.

The angle of the surface was read from a scale and the static coefficient of friction was taken as the tangent of this angle. Other researchers have used this method for other grains and seeds[18, 33].

2.5 Aerodynamic properties.

The terminal velocities of seeds at different moisture content were measured while the particles are placed at the front of the blower at the net inlet side of the transparent tube. After operating the blower and increasing its speed by opening the gate slowly until the flowing air suspend the particles in the vertical active part of the transparent tube, the measured air velocity represents the terminal velocity of the particles. Thermal anemometer 470 was used to measure the air stream velocity (ft/min) then the readings were converted into m/s.

When a particle is suspended in a vertical airflow then the speed of the airflow holding this position is called the terminal velocity (V_t) of the particle and the drag force is balance by the particle weight (*Mg*), such that as follows

$$Mg = \frac{1}{2} C_d r_a A V_t^2 \tag{8}$$

$$V_t = \left(\frac{2Mg}{C_d r_a A} \right)^{1/2} \tag{9}$$

$$C_d = \frac{2Mg}{V_t^2 r_a A} \tag{10}$$

Where: M= mass of the particle, kg; g= acceleration due to gravity, (9.81 m/s^2; V_T = air terminal velocity, m/s; C_d = the coefficient of drag; r_a = air density; 1.25 kg/m^3; A = particle area projected to air, m^2.

The term of ($V^2/2g$) is known as the dynamic pressure.

The terminal velocity (V_T) thus depends on the mass of particle (M), its projected area (A) and the coefficient of drag (C_d) among other constant factors (g and ρ). The coefficient of drag (C_d) varies according to other factors including geometry and surface of particle, and state of airflow around it[13,34].

Observation through a transparent screen shows that flaxseed in a wind tunnel may be located in different orientations. The seed is in the position of a streamlined body, when the longest axis of the seed is parallel to the vector of airflow velocity. The aerodynamic drag here is basically a frictional air drag.

2.6 Separation procedure

The main equipment used in the present study was pneumatic separation equipment Figure 3. It was manufactured at the Agricultural Engineering Workshop, Faculty of Agriculture, Minoufiya University. The airflow was produced by a centrifugal blower fixed on the frame. It has circular inlet hole of (40 mm Dia.) with a gate for controlling the air flow rate, and a circular outlet hole (40 mm Dia.). An electric motor of 600 W with 8000 r/min was used as a source of power. The speed of the blower was changed by a simple mechanism. The smooth iron hopper was fixed to easily feed the mixture of the seeds and the impurities. The hopper had four adjustable walls to obtain the proper slope for the mixture to slide smoothly inside the equipment. Under the hopper there was an inclined smooth channel for receiving the mixture from the hopper tank. The experimental equipment was equipped with three screens as shown in Figure 3 the first and second screens were to retain the seeds and impurities from the blower, while the third screen is used to retain the light materials in sediment chamber. To observe the movement of mixture inside the separating duct, the front face of the equipment was made from plexi-glass. The seeds samples and impurities were mixed to obtain the different levels of the tested samples.

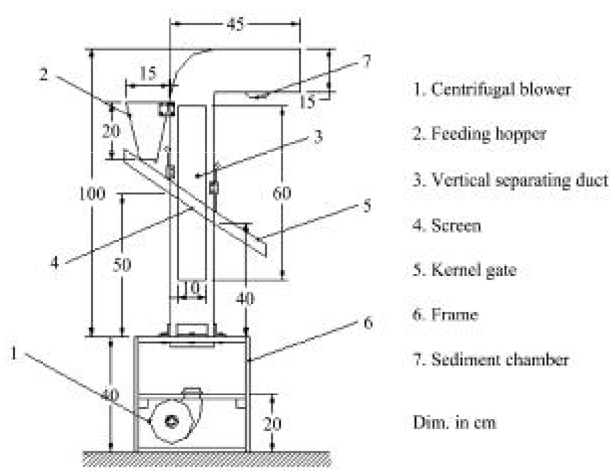

Figure 3 Sketch of the separating equipment

The samples were conditioned to the required moisture content level by adding the required amount of water, stirring occasionally and allowing it to achieve equilibrium, then the moisture content was checked again.

The pneumatic separator was fed by a mixture of seed and foreign materials stored in the metallic hopper.

The specific feed rate was controlled by the gate opening at the hopper bottom. The mixture moved into the separation duct (15 cm × 15 cm cross section). While the air moved vertically, the cleaned material was collected in a bag. The foreign materials carried by the air stream were lifted to a sediment chamber. It was collected and massed. The seed which was separated with the light particles was then separated manually and weighed to calculate the separation efficiency and grain losses percentage.

Three different air stream velocities (2, 4 and 6 m/s) were used. Components of product were separated manually into seeds and impurities. The quantities in each sample of the mixture were 25% straw and 75% seeds. Three feeding rates (8.5, 12 and 16 kg/h) and four levels of sample moisture content of (8.6%, 12.8%, 18.6% and 23.90%) were used during this experiment.

The effect of the above factors on the indices of separation efficiency (S.E. %) and percentage of seed losses (S.L. %) were studied. Three replicates were used. Separation efficiency and seed losses were calculated according to following equation[15].

$$S.E = \frac{M_2 - M_1}{M_2} \times 100\,\%$$

$$S.L = \frac{M_4 - M_3}{M_4} \times 100\%$$

Where: M_1 = the mass of impurities, separated with seeds in the out seeds tank, g; M_2 = the mass of impurities in feeding hopper, g; M_3 = the mass of seeds in the out seeds tank, g; M_4 = the mass of seeds in feeding hopper, g.

2.7 Statistical analysis.

The Data analysis of this experiment was carried out by using the Statistical Analysis System GLM procedures[35]. This system was a two-way analysis of variance with the following model:

$$y_{ik} = \mu + B_i + e_{ik}$$

Where: y_{ik} = an individual observation; μ = Overall mean; B_i = Effect due to moisture content ith = 8.60%, 12.78%, 18.60%, and 23.90% (d.b); e_{ik} = Random effect.

Furthermore, the simple correlation coefficients were calculated. The differences between the mean values of physical and mechanical flaxseeds characteristics were tested for significance using Duncan test[36].

3 Results and discussion

3.1 Influence of moisture content on physical, aerodynamic and solid flow properties for flaxseeds.

Mean values for both measured and calculated variables are presented in Tables (1) at different levels of moisture content. For all traits, there were highly significant differences among these variables for individual and bulk flaxseeds. There were highly significant differences among variables for true density, angle of repose, porosity and weight of thousand seed at ($P \leqslant 0.01$), but for bulk density, there were significant differences at ($P \leqslant 0.05$). The mean values and standard error for these variables. The means values, for seed true density were (1243.83 ± 0.912 and 1176.32 ± 0.91 kg/m^3), for angle of repose (27.60 ± 0.50 and 35.80 ± 0.50, deg), for thousand seed weight (4.64 ± 0.03 and 4.79 ± 0.03, g) and for porosity (46.65 ± 0.26 and 44.89 ± 0.26, %) for seed moisture content levels 8.60 and 23.90%, respectively.

3.2 Physical properties of flaxseeds

3.2.1 Linear dimensions

The variations of length (L), width (D), thickness (T) and the geometric mean diameter (D_g) of the seeds with moisture content are plotted in Figure 4. All the dimensions were increased with seed moisture content up to 23.9%. The frequency distribution curves and the dimension ratio (Figure 5 and 6) for the mean values of the dimensions show a trend towards a normal distribution.

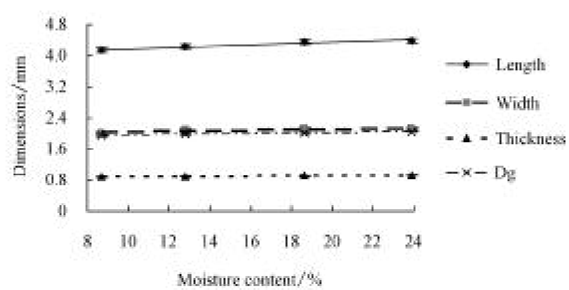

Figure 4 Effect of moisture content on dimensions of flaxseeds

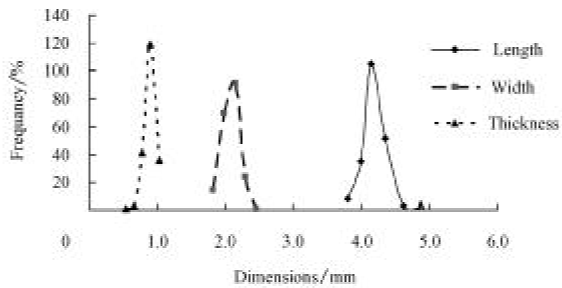

Figure 5 Frequency of dimensions for flaxseeds

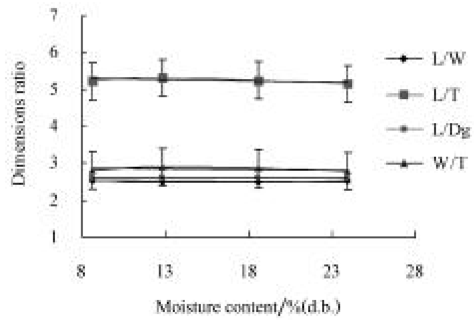

Figure 6 Effect of moisture content on dimensions ratio of flaxseeds

Very high positive correlation was observed between these dimensions and the seed moisture content. This indicates that, on moisture absorption, the seeds expand in length, width and thickness within the moisture range of 8.6 to 23.9% (d.b.).[37] It also found the linear dimensions of lentil seeds to increase with moisture content from 6.5 to 32.6%, d.b. The total average expanded was more along its minor axis in comparison with its other two principal axes. This behavior was also observed by Dehspande S D, et al. [38] for soya bean. Such dimensional changes are important in designing of equipment for cleaning, grading and conveying. The relationships between principal dimensions (L, W, T and D_g) and seed moisture content represented as follows:

$$L= 4.009 + 0.016\, M.C. \qquad (R^2 = 0.951) \qquad (11)$$

$$W = 2.996 + 0.006\, M.C. \qquad (R^2 = 0.745) \qquad (12)$$

$$T= 0.852 + 0.003\, M.C. \qquad (R^2 = 0.980) \qquad (13)$$

$$D_g= 1.894 + 0.007\, M.C. \qquad (R^2 = 0.970) \qquad (14)$$

The average diameter calculated by the arithmetic mean, geometric mean and equivalent sphere method were 2.35, 1.945 and 1.925 mm at a moisture content of 8.60% d.b., respectively. The analysis of variance indicated that the difference among the average diameters of flaxseeds calculated by three methods were significant. In other words, the average diameter of flaxseeds calculated by the geometric mean and equivalent sphere methods in the moisture range of 8.60%-23.90% d.b. are almost the same, compared to the arithmetic mean method (Table 1). Therefore, both the geometric mean and equivalent sphere method can be used to determine the average diameter of flaxseeds. A similar result was found by Kaleemullah S, et al. [28] for areca nut kernels and for flaxseed[39].

Table 1 Means and standard errors of physical, aerodynamic and solid flow properties of flaxseeds

Property	Mean moisture content ± S.E.			
	8.60%	12.78%	18.60%	23.90%
Physical properties				
Length (L, mm)	4.138 ± 0.025^{C}	4.226 ± 0.025^{CB}	4.290 ± 0.025^{BA}	4.322 ± 0.025^{A}
Width (W, mm)	2.026 ± 0.016^{B}	2.098 ± 0.016^{A}	2.102 ± 0.016^{A}	2.130 ± 0.016^{A}
Thickness (T, mm)	0.881 ± 0.011^{B}	0.887 ± 0.011^{B}	0.903 ± 0.011^{BA}	0.932 ± 0.011^{A}
Arithmetic mean ($(L+W+T)/3$, mm	$2..35\pm0.014^{C}$	2.41 ± 0.015^{BC}	2.43 ± 0.014^{BA}	2.46 ± 0.013^{A}
Geometric mean diameter (D_g, mm)	1.945 ± 0.013^{C}	1.987 ± 0.013^{CB}	2.009 ± 0.013^{BA}	2.047 ± 0.013^{A}
Equivalent sphere diameter (d_e, mm)	1.925 ± 0.0026^{C}	1.940 ± 0.0031^{BC}	1.961 ± 0.0026^{B}	1.981 ± 0.0053^{A}
Sphericity (f , %)	47.021 ± 0.220	47.047 ± 0.220	46.844 ± 0.220	47.339 ± 0.220
Surface area (S, mm^2)	6.108 ± 0.040^{C}	6.239 ± 0.040^{CB}	6.308 ± 0.040^{BA}	6.423 ± 0.040^{A}
Roundness (R, %)	37.422 ± 0.275	37.683 ± 0.275	38.082 ± 0.275	38.188 ± 0.275
Projected surface area (A, mm^2)	5.036 ± 0.060^{C}	5.283 ± 0.060^{B}	5.500 ± 0.060^{BA}	5.60 ± 0.060^{A}
Hardness (H, N)	27.76 ± 0.053^{A}	22.23 ± 0.053^{B}	19.77 ± 0.053^{C}	16.28 ± 0.053^{D}
Bulk density (ρ_b, kg/m^3)	663.544 ± 3.199^{a}	657.90 ± 3.199^{ab}	654.356 ± 3.19^{ab}	648.26 ± 3.199^{b}
True density (ρ_t, kg/m^3)	1243.83 ± 0.912^{A}	1224.098 ± 0.91^{B}	1196.41 ± 0.91^{C}	1176.32 ± 0.91^{D}
Porosity (P, %)	46.653 ± 0.257^{A}	46.254 ± 0.257^{AB}	45.307 ± 0.26^{BC}	44.891 ± 0.257^{C}
Thousand seed weight (M_{1000}, g)	4.644 ± 0.027^{B}	4.678 ± 0.027^{BA}	4.720 ± 0.027^{BA}	4.786 ± 0.027^{A}
Aerodynamic properties				
Drag coefficient (length*width)	0.568 ± 0.008^{A}	0.540 ± 0.007^{B}	0.529 ± 0.006^{C}	0.532 ± 0.001^{C}
Drag coefficient (length*thickness)	0.830 ± 0.017^{A}	0.787 ± 0.019^{B}	0.749 ± 0.014^{C}	0.734 ± 0.013^{D}
Terminal velocity (V_t, m/s)	2.460 ± 0.134^{C}	2.816 ± 0.134^{CB}	3.222 ± 0.134^{BA}	3.558 ± 0.134^{A}

Property	Mean moisture content ± S.E.			
	8.60%	12.78%	18.60%	23.90%
Solid flow properties				
Angle of repose (θ, deg.)	27.600±0.500^{C}	28.600±0.500^{C}	33.200±0.500^{B}	35.80±0.500^{A}
Static coefficient of friction (m)				
Wood m_w, tanθ	0.522±0.009^{C}	0.678±0.009^{B}	0.742±0.009^{A}	0.752±0.009^{A}
Stainless steel m_s, tanθ	0.442±0.011^{D}	0.576±0.011^{C}	0.648±0.011^{A}	0.780±0.011^{B}
Galvanized iron m_{gi}, tanθ	0.424±0.010^{C}	0.614±0.010^{B}	0.652±0.010^{B}	0.706±0.010^{A}
Iron m_{ir}, tanθ	0.474±0.009^{C}	0.614±0.009^{B}	0.636±0.009^{B}	0.694±0.009^{A}
Internal m_{in}, tanθ	0.652±0.013^{C}	0.720±0.013^{B}	0.770±0.013^{B}	0.834±0.013^{A}

Means within the same row carry different small superscripts are significant at level $P \leqslant 0.05$,
Means within the same row carry different capital superscripts are significant at level $P \leqslant 0.01$

Table 2 Destructive test of physical, aerodynamic and solid flow properties of flaxseeds

Property	Mean	Range		Var.	S.E.	C.V.%
		Min.	Max.			
Physical properties						
Length (L, mm)	4.24	3.67	4.96	3.57E-02	0.013	1.34
Width (W, mm)	2.089	1.74	2.53	1.44E-02	0.008	0.85
Thickness (T, mm)	0.901	0.48	1.08	6.29E-03	0.005	0.56
Geometric mean diameter (Dg, mm)	1.997	1.64	2.28	9.53E-03	0.006	0.69
Surface area (S, mm^2)	6.27	5.14	7.15	9.33E-02	0.020	2.16
Sphericity (f , %)	47.06	40.31	51.18	2.4058	0.110	10.97
Roundness (R, %)	37.84	33.33	46.76	3.8098	0.137	13.80
Projected surface area(A, mm^2)	5.35	4.09	6.92	0.2261	0.030	3.36
Hardness (H, N)	21.5	10.7	35.5	30.79	0.393	3.88
Bulk density (ρ_b, kg/m^3)	656.15	640.20	672.50	75.48	1.599	388.5
True density (ρ_t, kg/m^3)	1210.16	1173.6	1244.9	704.15	0.456	1186.7
Porosity (P, %)	45.77	44.09	47.51	0.804	0.128	40.09
Thousand seed weight (M_{1000}, g)	4.71	4.58	4.88	5.93E-03	0.013	3.57
Aerodynamic properties						
Drag coefficient (length*width)	0.543	0.434	0.693	0.002	0.003	8.83
Drag coefficient (length*thickness)	0.775	0.526	1.386	0.014	0.008	15.22
Terminal velocity (V_t , m/s)	3.014	2.13	3.81	0.2559	0.067	22.62
Solid flow properties						
Angle of repose (θ, deg.)	31.30	26.00	37.00	1.250	0.250	160.33
Static coefficient of friction (m)						
Wood m_w, tanθ	0.67	0.51	0.78	9.26E-03	0.005	4.3
Stainless steel m_s, tanθ	0.61	0.42	0.81	1.62E-02	0.005	5.69
Galvanized iron m_{gi}, tanθ	0.59	0.42	0.73	1.23E-02	0.005	4.95
Iron m_{ir}, tanθ	0.60	0.47	0.70	7.18E-03	0.004	3.79
Internal m_{in}, tanθ	0.74	0.62	0.87	5.36E-03	0.006	3.27

3.2.2 Sphericity

The values of sphericity were calculated individually from Eqn (3) by using the data on geometric mean diameter and major axis of the flaxseed and the results obtained are presented in Figure 7. The sphericity of the flaxseed increased from 47.02 to 47.34 when the moisture content increased from 8.60 to 23.90% d.b. Similar trends have been reported by Gezer I, et al.[40] for apricot kernels and by Ozarslan C[41] for cotton seed. The relationship existing between moisture content and sphericity is linear and can be represented by the following regression equation:

$$f = 46.81 + 0.021M.C. \qquad (R^2 = 0.921) \qquad (15)$$

3.2.3 Surface area

Variation of the seed surface area with seed moisture content is shown in Figure 8. The surface area was increased with seed moisture content up to 23.90%. The surface area of seeds ranges from 6.108 mm^2 at 8.60% (d.b.) to 6.42 mm^2 at 23.90% (d.b.). The following equations represent the relationships between surface area of seed and seed moisture content:

$$S = 5.951+0.021\ M.C. \qquad (R^2 = 0.947) \qquad (16)$$

Linear increase in surface area with increase in seed moisture content has been observed by Aviara N A, et al.[42] for guna seed and by Sacilik K, et al.[43] for hemp seed.

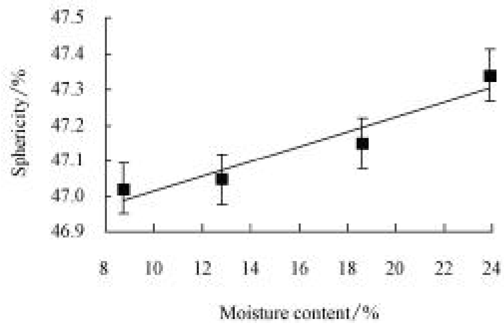

Figure 7 Effect of moisture content on sphericity of flaxseeds

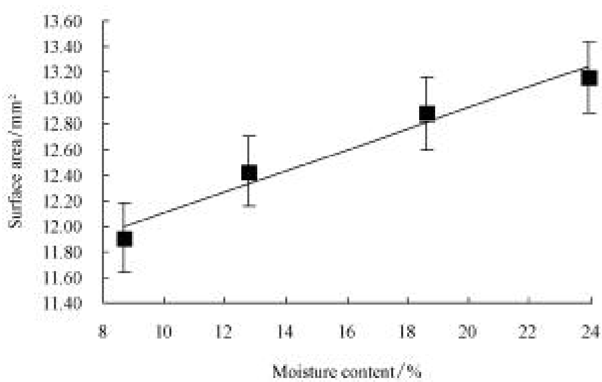

Figure 8 Effect of moisture content on surface area for flaxseeds

3.2.4 Bulk and true densities

The experimental results of the bulk and true densities for flaxseeds at different moisture levels are presented in Figure 9. As the moisture content increased from 8.60% to 23.90% (d.b.), the bulk and true densities decreased from 663.54 to 648.26 kg/m^3 and from 1243.83 to 11764.32 kg/m^3, respectively.

The variation of bulk and true densities were found to be linear with the moisture content and can be expressed as follows:

$$r_b = 668.4 - 4.94\ M.C. \qquad (R^2 = 0.991) \qquad (17)$$

$$r_t = 1267.7 - 23.02\ M.C. \qquad (R^2 = 0.995) \qquad (18)$$

The decrease in bulk density of flaxseeds may have resulted from increase in size with moisture content which gives rise to decrease in quantity of seeds occupying the same bulk volume.

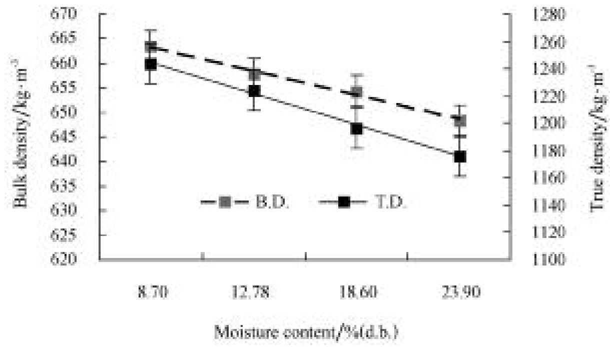

Figure 9 Effect of moisture content on bulk and true densities for flaxseeds

3.2.5 Porosity

The variation of porosity of the seeds with seed moisture content is displayed in Figure 10. The porosity calculated from the relevant data was decreased from 46.65% to 44.89% as the seed moisture content increased from 8.60% to 23.90% (d.b.). The following regression equation represented the linear relationship between porosity and seed moisture content:

$$P = 47.33 - 0.623M.C. \qquad (R^2 = 0.971) \qquad (19)$$

Ozarslan C[41] has reported a similar decrease in porosity from 41.1% to 39.0% for cotton seed.

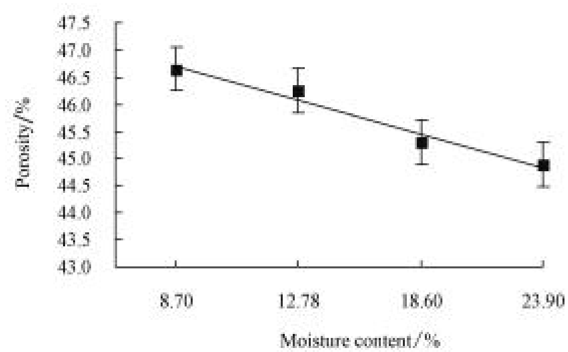

Figure 10 Effect of moisture content on porosity for flaxseeds

3.2.6 Thousand Seed mass

The variation thousand seed mass with seed moisture content is displayed in Figure 11. Mass of thousand seed increases linearly with increasing seed moisture content from 4.64 g at 8.60% to 4.78g at 23.90% (d.b.). The following equation represented the relationship between thousand seed mass and seed moisture content:

$$M_{1000} = 4.59+0.047M.C. \qquad (R^2 = 0.976) \qquad (20)$$

A linear increase in the thousand seed mass with increase in seed moisture content has been noted by Baryeh E A, et al.[44] for pigeon pea and by Wang Bo, et al and Coskuner Y, et al.[26,39] for flaxseeds.

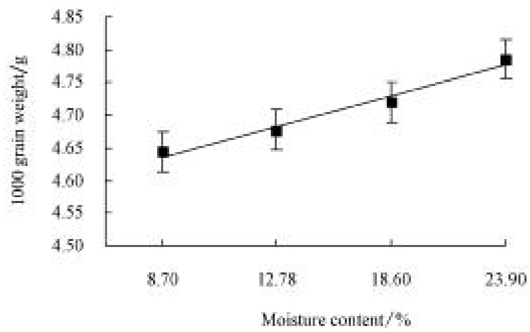

Figure 11 Effect of moisture content on thousand grain weight for flaxseeds

3.2.7 Rupture strength

The results of rupture strength of the seeds with seed moisture content are displayed in Figure 12. The results show that the rupture strength is highly dependent on moisture content for the investigated range of moisture content (8.60%-23.90%, d.b.), greater forces were necessary to rupture the seeds at low moisture content. The small rupture forces at higher moisture content might have resulted from the fact that kernel tended to be very soft at high moisture content. The relationship between the hardness and moisture content is represented by the following equation:

$$H = 3.34 - 0.072\ M.C. \quad (R^2 = 0.947) \qquad (21)$$

The results are similar to those reported by Konak M, et al. [45] for chickpea.

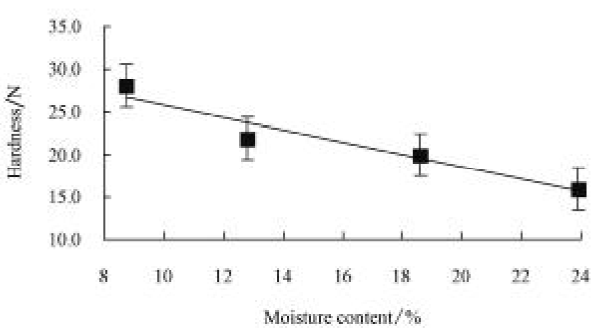

Figure 12 Effect of moisture content on rupture strength for flaxseeds

3.3. Aerodynamic properties of flaxseeds

3.3.1 Drag coefficient

The variation of drag coefficient of the seeds with seed moisture content is shown in Table (1 and 2) and Figure 13. Drag coefficient decreased with the increase of seed moisture content. The relationship existing between drag coefficient and seed moisture content can be represented by the following equation:

$$\text{(Length * thickness)} \quad C_d = 0.856 - 0.033\ M.C. \quad (R^2 = 0.964) \qquad (22)$$

$$\text{(Length * width)} \quad C_d = 0.572 - 0.012\ M.C. \quad (R^2 = 0.742) \qquad (23)$$

The variation of drag coefficient of any particle depends on its density, suspension velocity and projected area. Since agricultural grains cover a wide range of sizes, suspension velocities, densities and shapes, an array of drag coefficient values in the range of spheres and cylinders (0.44-1.0) was expected[34]. In general, it can be concluded that the drag coefficient of seeds depend mainly on shape.

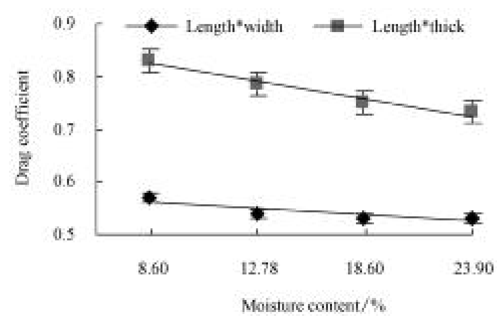

Figure 13 Effect of moisture content on terminal velocity for flaxseeds

3.3.2 Terminal velocity

The variation of terminal velocity of the seeds with seed moisture content is plotted in Figure 14. Terminal velocity shows a linearly increase from 2.46 to 3.56 m/s with the increase of seed moisture content from 8.60 to 23.90%, (d.b.). The relationship between terminal velocity and seed moisture content can be represented with the following equation:

$$V_t = 2.088 + 0.369\ M.C. \quad (R^2 = 0.998) \qquad (24)$$

Research papers [32, 46, 44, 40] have reported a linear increase in terminal velocity with the increase in the moisture content for cumin seed, terebinth, QP-38 pigeon pea and apricot kernel, respectively. The increase in terminal velocity with increase in moisture content within the study range can be attributed to the increase in mass of an individual seed per unit frontal area presented to the airflow.

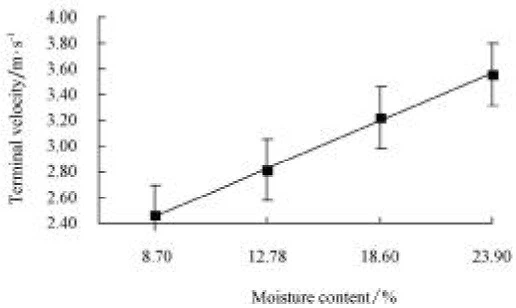

Figure 14 Effect of moisture content on terminal velocity for flaxseeds

3.4 Solid flow properties of flaxseeds

3.4.1 Angle of repose.

The experimental results for the angle of repose of the seeds at various moisture levels are shown in Figure 15. The angle of repose increases from 27.60^o to 35.80^o when the moisture content increased from 8.60% to 23.90%, d.b. The relationship between angles of repose and seed moisture content could be represented by the following equation:

$$\theta = 24+2.92M.C. \quad (R^2 = 0.951) \qquad (25)$$

A linear increase in angle of repose when the seed moisture content increases has also been noted for pumpkin seeds[33], for karingda seeds[47], for cumin seeds[32], for sunflower seeds[48], for quinoa seeds[49], for lentil seeds[50], and for edible squash seeds[51].

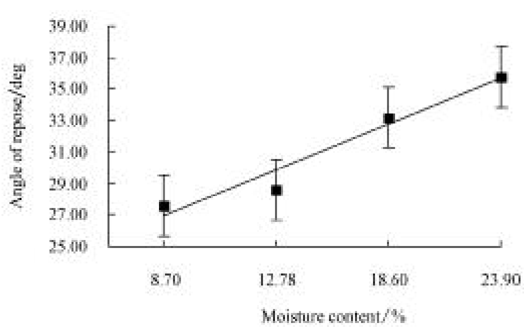

Figure 15 Effect of moisture content on angle of repose for flaxseeds

3.4.2 Static coefficient of friction

The effect of moisture content of flaxseed on the static coefficient of friction against the various test materials surfaces is plotted in Figure 16. From these, the highest coefficient of static friction at all moisture contents considered was for the surface of the same seeds (In.) followed by plywood (W), iron (Ir.), stainless steel (S.S.) and then galvanized steel (G.S.). The static coefficients of friction increased also linearly with respect to moisture content for all five surfaces. Coefficient of static friction was increased with increasing the seeds moisture content up to 23.9%. It was observed that the moisture content had a more significant effect on the coefficient of static friction than the material surface owing to the increase in adhesion between the seed and the surface at higher moisture values. The relationships between coefficients of static friction for wood (m_W), stainless steel (m_{SS}), galvanized steel (m_{GS}), iron (m_{Ir}), and internal friction (a surface of same seeds variety at same moisture content) (m_{In}) and seed moisture content may be represented by the following equations:

$$m_W = 0.486 + 0.076\, M.C. \quad (R^2 = 0.840) \qquad (26)$$

$$m_{SS} = 0.343 + 0.108\, M.C. \quad (R^2 = 0.987) \qquad (27)$$

$$m_{GS} = 0.383 + 0.087\, M.C. \quad (R^2 = 0.865) \qquad (28)$$

$$m_{Ir} = 0.431 + 0.069\, M.C. \quad (R^2 = 0.885) \qquad (29)$$

$$m_{In} = 0.598 + 0.059\, M.C. \quad (R^2 = 0.997) \qquad (30)$$

At all moisture contents, the static coefficients of friction were greatest against internal, plywood, iron, followed by stainless steel, and the least for galvanized metal. This may be due to the smoother and more polished surface of galvanized metal than the other tested surfaces. When compared with other seeds, the static coefficients of friction for hemp seed were lower than those for chick pea[45]. Also, similar results have been reported[26, 39].

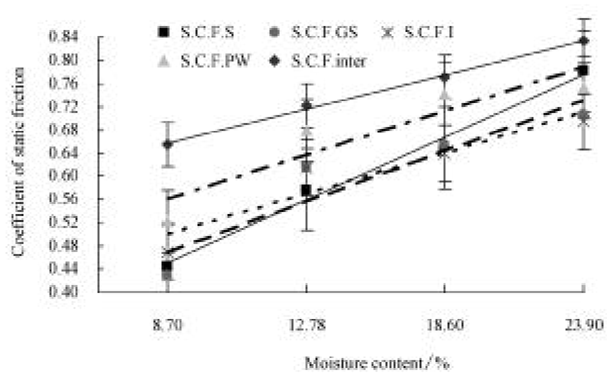

Figure 16 Effect of moisture content on static coefficient of friction for flaxseeds

3.5 Evaluation of laboratory experiments

The experiments were confined to different air steam velocities, feeding rates and moisture contents of mixture. The performance of the equipment was defined by the separation efficiency % and seed losses %. The author aimed to determine the most favorable combination of all these variables to be fulfilled in the adopted agricultural mechanization procedure, so as to ensure the high grade of separation efficiency coupled with minimal seed losses.

3.5.1 Air stream velocity

Figure 17 shows the relationship between the air stream velocity and separation efficiency at different values of moisture content (8.60%, 12.80%, 18.60% and 23.90%) and feeding rates (8.5, 12 and 16 kg/h).

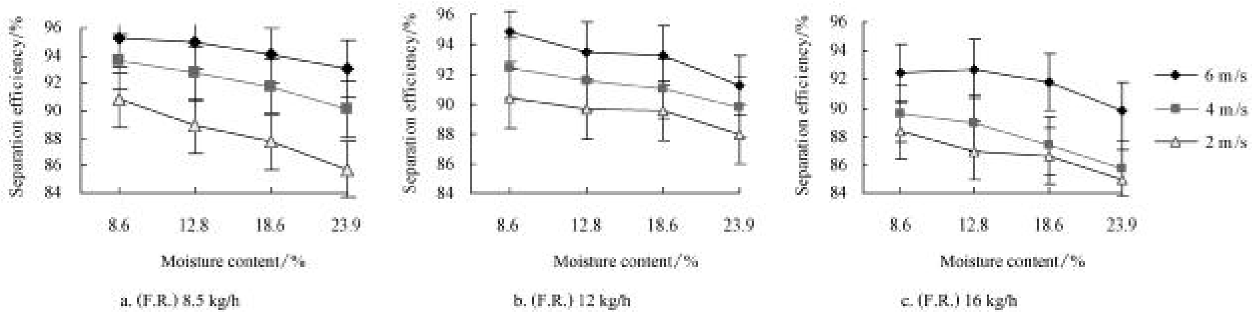

Figure 17 Effect of moisture content on separation efficiency at different levels of air stream velocity and feed rate

Generally, the results show that the separation efficiency increases with the increase of air stream velocity. The minimum separation efficiency obtained was 85% when the air stream velocity, feeding rate, and sample moisture content were 2 m/s, 16 kg/h, and 23.9% respectively. The maximum value was 95.22% was obtained when air stream velocity, feeding rate, sample moisture content were 6 m/s, 8.5 kg/h, and 8.6% respectively. While the lowest value of separation efficiency at lower air stream velocity was due to the presence of some impurities with the seeds recovered.

It could be explained that increasing air velocity leads to an increase of airflow force which causes increasing in the seed losses with the rejected impurities.

Figure 18 shows the relationship between air stream velocity and the percentage of seed losses at different values of feeding rate and moisture content. On the other hand, the highest percentage of seed losses was achieved when increasing the air stream velocity from 2 to 6 m/s. The increment of seed losses by changing the air stream velocity from 4 to 6 m/s at the feeding rate 8.5 kg/h was more than the increment by changing the air stream velocity from 4 to 6 m/s at the feeding rate 12 and 16 kg/h. Generally the smaller amount of seed losses could be achieved more at air stream velocity ranged between 2 to 4 m/s than at 6 m/s.

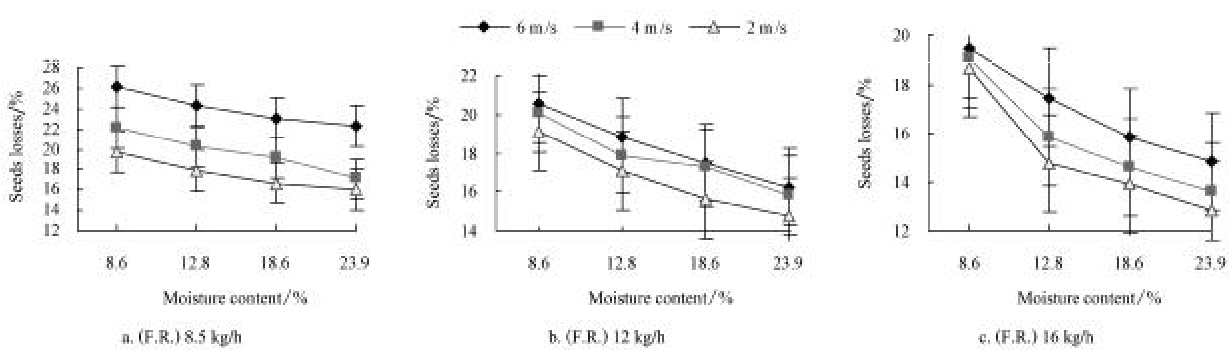

Figure 18 Effect of moisture content on seed losses percentage at different levels of air stream velocity and feed rate

3.5.2 Feeding rate

The separation efficiency as shown in Figure 17 and 18 decreased as the feeding rate increased from 8.5 to 16 kg/h. The highest value of separation efficiency was found at 8.5 kg/h. and 10% total impurities at different sample moisture content. However, the lowest efficiency value was found at 16 kg/h. The effect of the feeding rate is related to the increase of the thickness of mixture layer through the separation duct. Consequently, the separation condition got worse because that affects the air resistance per unit length.

The data of seed losses percentage reveal that, increasing feeding rate decreased the seed losses at 4 to 6 m/s while the effect of feeding rate was not affected on seed losses at 2 to 4 m/s of air stream velocity for experiments under different variables.

The best degree of seed losses obtained with the best separation efficiency were at 2 m/s air stream velocity, 16 kg/h feeding rate and 23.9 % moisture content.

4 Conclusions

The conclusions of the present study can be summarized as follows:

1) The average length, width, thickness, arithmetic mean diameter, geometric mean diameter, surface area, mass of 1000 seeds, angle of repose and terminal velocity linearly increased with the increase in moisture content. Bulk density, kernel density, hardness and porosity decreased linearly with the increase in moisture content. The static coefficients of friction of flaxseeds increased with the increase in moisture content and the highest static coefficients of friction were found on plywood surface and the lowest on a stainless steel surface.

2) The physical properties of flaxseeds were expressed by the linear regression equations as a function of moisture content.

3) Coefficients of drag were 0.543 and 0.775 for flaxseeds. And the mean values of terminal velocity were found to be 3.014 m/s.

4) The air stream velocity was a major controlling factor that affects the separation efficiency and seed losses. The air stream velocity which fulfilled the best result was around 2 to 4 m/s

5) The minimum percentage of seed losses obtained with, the best separation efficiency (95.22%) was at 6 m/s air stream velocity and 8.5 kg/h. feeding rate and 8.6 % moisture content. Using the air as the method of separating of flaxseed is considered efficient to obtain satisfactory values of separation efficiency with minimum losses at suitable levels of feeding rate, and moisture content of mixture. But at high levels of feeding rate and moisture content of mixture using the air alone is considered inefficient to obtain high values of separation efficiency with minimum losses.

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