



Aerodynamic properties of Faba bean (*Vicia faba* L.) Seeds

Mesut Dilmac, Sefa Tarhan*¹ and Hakan Polatci

Gaziosmanpasa University, Faculty of Agriculture,
Department of Biosystems Engineering, Tokat, Turkey.

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ABSTRACT

Aerodynamic properties of agricultural materials are the physical properties considering the reaction of agricultural material piles or seeds against airflow. The airflow resistance of faba bean (*Vicia faba* L.) seed piles was experimentally determined and mathematically modeled for two different moisture contents (11.4 % and 25.8% w.b.) for the superficial air velocities ranging from 0.0225 to 1.395 m³·m⁻²·s⁻¹. Modified Shedd's equation and Hukill-Ives equation can be interchangeably used to design aeration systems for the storage and drying bins of faba bean seeds. The terminal velocity values are 11.68 and 12.87 m·s⁻¹ for the moisture contents of 11.4% and 25.8% (w.b.), respectively. The drag coefficient values are 1.02 and 0.88 for the moisture contents of 11.4% and 25.8% (w.b.), respectively. Moisture content increased terminal velocity but decreased drag coefficient.

Key words: Airflow resistance, Legume and Terminal velocity.

INTRODUCTION

The aerodynamic properties of agricultural materials can be allocated into two groups: terminal velocity and airflow resistance. Terminal velocity is the maximum velocity which a freely falling seed can attain in atmosphere under downward gravitational force and upward airflow resistance force. Terminal velocity is an important aerodynamic property of granular agricultural materials for both their pneumatic conveying and pneumatic separation (Guner, 2007; Nalbandi *et al.*, 2010). The leaves and straws of crops generally have lower terminal velocity values than their seeds have. The cleaning of seeds from foreign materials such as weed seeds, straws, hulls and chaffs by pneumatic separation is widely used in agricultural production and agro-industry since it is relative cheap, effective and has high capacity (Shahbazi *et al.*, 2014; Zewdu, 2007). *Turgania latifolia* (a common weed) seeds were separated from wheat seeds by pneumatic separation since its seeds have lower terminal velocity values (6.775 to 6.877 m·s⁻¹) than wheat seeds (9.587 to 9.25 m·s⁻¹) have (Nalbandi *et al.*, 2010). Drag coefficient is the measure of drag or resistance of an object to moving air or water. The drag force is a function of terminal velocity, fluid density, projected area and drag coefficient (Gupta *et al.*, 2007). The piles of agricultural materials in silos resist the airflow because of their blockage of air way and their surface friction. Therefore, the air pressure should be increased at a level that airflow can overcome the resistance and pass through the pile at the prescribed flow rate. The necessary value of air pressure changes with operational features and material properties.

Important operational features are superficial air velocity and the depth of pile while the important material properties are moisture content and bulk density (Kenghe *et al.*, 2012; Masoumi and Tabil, 2008). Pressure drop per depth of pile increased with superficial air velocity in a nonlinear fashion and they can be related mathematically to each other (Hukill and Ives, 1955; Shedd 1953).

Faba bean (*Vicia faba* L.) seeds are commonly used as both food and feed sources since they are rich in protein, carbohydrate, dietary fibre, dietary minerals, B- group vitamins and phenolic compounds (Vidal-Valverde *et al.*, 1998; Baginsky *et al.*, 2013). The aerodynamic properties of faba beans have not been studied experimentally and modelled mathematically, yet. This study had two main research objectives. The first research objective was to determine the terminal velocity values of faba bean seeds having different moisture contents and represent the experimental data by a mathematical model. The second research objective was to determine the pressure drop values of faba bean seed piles for different superficial air velocities and moisture content values and represent the experimental data by two commonly-used mathematical models.

MATERIALS AND METHODS

Experimental material: Faba bean (*Vicia faba* L.) seeds were purchased from a local market in Tokat, Turkey. The samples were manually cleaned from foreign materials and broken, infected and immature seeds. The initial moisture content of faba bean seeds was determined by oven drying at 105 °C for 24 hours. Dry seeds were rewetted as described

*Corresponding author's e-mail: sefatarhan@hotmail.com. ¹Gaziosmanpasa University, Faculty of Engineering and Natural Sciences, Department of Mechatronics Engineering, Tokat, Turkey.

by Altuntas and Yildiz (2007) to get the wet seeds at a moisture content of 25.8%.

Experimental setup: The experimental unit consists of a centrifugal fan, a plenum and a cylindrical container (Figure 1a). The plenum was made from galvanized iron sheet with the dimensions of 55×55×55 cm. Three perforated sheets were placed 5 cm away from each other and 5 cm away from the top of plenum to equalize air pressure and straighten the airflow stream coming from the fan. The perforated sheets had 116 holes of 5 mm diameter per 100 cm² total area. The 25-cm outer diameter and 125-cm long cylindrical container was made from galvanized iron sheet and its bottom was covered by perforated sheet. A hole was drilled just above its bottom to insert pressure probe through it. This cylindrical container was used for the airflow resistance tests. The 8.5-

cm inner diameter and 115-cm long transparent cylindrical pipe was used for the terminal velocity tests (Figure 1b). The bottom of pipe was covered by perforated sheet. Two holes were drilled on the transparent cylindrical pipe 2.5 cm and 30 cm away from its top. The upper hole was used to insert the anemometer probe while the lower hole was used to drop a faba bean seed into air stream coming upward from the air distribution room.

Determination of dimensions of faba bean seeds:

The length, width and thickness of 100 randomly selected faba bean seeds were measured using a digimatic caliper having 0.01 mm accuracy (Figure 2). The geometric mean diameter (D_g) and sphericity (\bar{O}) of seeds were calculated by using the following equations (Altuntas and Yildiz, 2007):

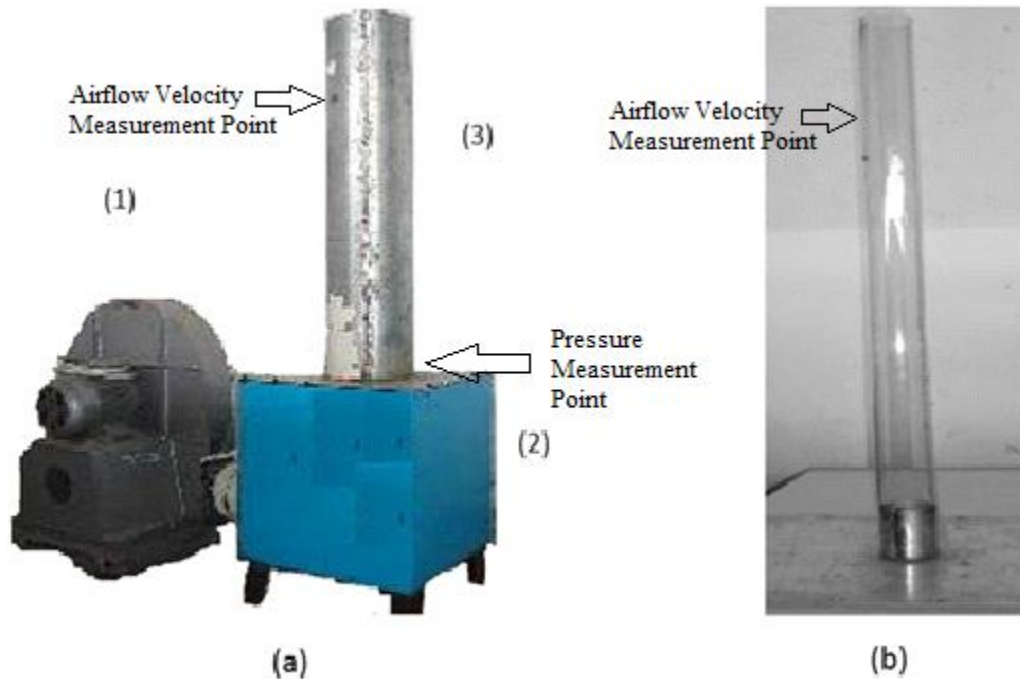


Fig 1: Experimental set up (a): 1 is centrifugal fan; 2 is plenum; 3 is cylindrical container, (b): The transparent cylindrical pipe used for the test of terminal velocity.

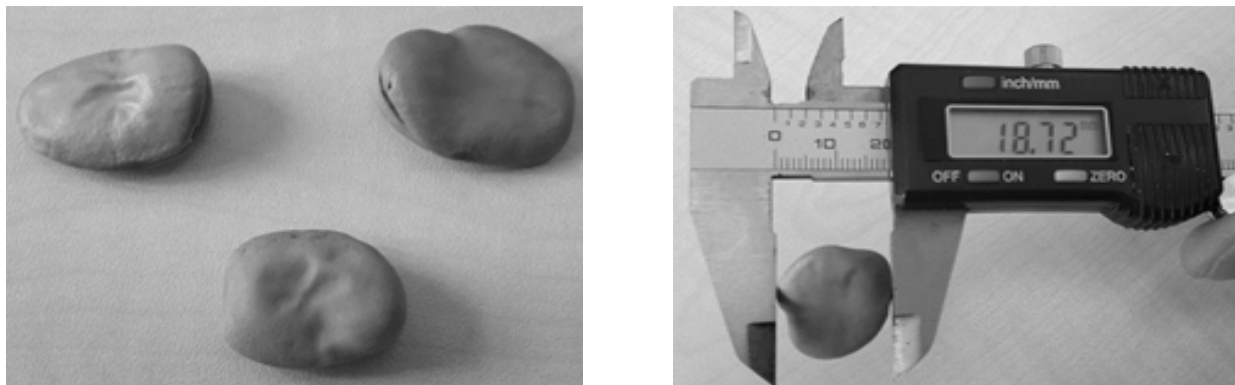


Fig 2: Faba bean seeds

$$D_g = (L \times W \times T)^{1/3} \quad (1)$$

$$\Phi = \left[\frac{(L \times W \times T)^{1/3}}{L} \right] \times 100 \quad (2)$$

L is length, W is width and T is thickness (mm).

The true density of seeds was measured by using the liquid displacement method. The randomly selected sample whose total weight had been measured previously was poured into a 100 ml glass cylinder filled with ethanol. The sample weight was divided by the displaced ethanol volume. Bulk density was determined by using a weight per hectoliter tester. Using the true densities of seeds and the bulk densities of seed piles, the porosities of these seed piles were calculated by the following equation (Altuntas and Yildiz, 2007):

$$P = \left(1 - \frac{\rho_b}{\rho_t} \right) \times 100 \quad (3)$$

ρ_b and ρ_t are the bulk densities of seed piles (kg m^{-3}) and the true density of seed (kg m^{-3}), respectively. 1000-seed mass was determined by weighing 100 randomly selected seeds and multiplying it by ten. All weight measurements were done by using a digital electronic balance with 0.01 g sensitivity (Sartorius BA3100P, Germany). To determine repose angle, a 50-mm long polyvinyl cylindrical pipe of 30 mm diameter was placed on a clean surface and filled with seed samples. A cone shape of seed samples was obtained by raising slowly and removing the cylinder. The radius and the height of the cone were measured. The repose angle was calculated using the following equation.

$$\alpha = \tan^{-1} \left(\frac{L}{R} \right) \quad (4)$$

L is the cone height and R is the cone radius (mm).

Determination of airflow resistance of faba bean seed piles: Faba bean seeds were loosely filled into cylindrical container by free fall from the top of container. The pile was 50 cm deep and had an evenly distributed upper surface. After free filling the container with faba bean seeds, the centrifugal fan was run at the selected lowest rpm of the electrical motor. Static pressure values at the bottom of piles were determined by using a probe made from the steel tube. One end of the tube was grounded into a taper and welded shut. A series of four holes with diameters of 0.12 cm were drilled into the probe at a 1.27 cm distance from the tapered end. These holes were 90° away from each other, and were used to measure average static pressure at a certain point. The probe was connected by a plastic tubing to a digital manometer whose range and resolution were 0 to 200 mbar and 0.01 to 0.1 mbar (Testo 520, Germany), respectively. The probe was inserted through the hole at the bottom of the

container to determine static pressure values at the different points on the bottom of pile. The probe of hot wire anemometer was inserted through the hole that was 100 cm high from the bottom of the container. The probe was kept horizontally parallel to the upper surface of pile and used to measure the speed of airflow (i.e. superficial air velocity) coming upward from the pile at different points on the same horizontal cross section of the container. The range and resolution of the hot wire anemometer (Testo 425, Germany) were 0 to 20 $\text{m} \cdot \text{s}^{-1}$ and 0.01 $\text{m} \cdot \text{s}^{-1}$, respectively. Eight different rpm levels of the electric motor were used in this experiment. After the completion of the first replication, the seeds were emptied from the container and were refilled for the later replication. There were three replications for the airflow resistance tests of seed piles.

Mathematical modeling of airflow resistance of faba bean piles: Modified Shedd's equation was formulated as;

$$P = a \times Q^b \quad (5)$$

P is pressure loss per unit of depth, $\text{Pa} \cdot \text{m}^{-1}$; Q is superficial air velocity $\text{m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, a and b are model parameters.

Hukill-Ives equation was formulated as;

$$P = \frac{c \times Q^2}{\ln(1 + d \times Q)} \quad (6)$$

c and d are model parameters.

SigmaPlot program was used to fit the experimental data to these equations and determine the models parameters; a, b, c and d. The coefficient of determination (R^2) values of curve fitting process were used to evaluate the fitting performance of the models.

Determination of terminal velocity of faba bean seeds: Randomly-selected ten faba bean seeds were used for terminal velocity measurement. The transparent cylindrical pipe was used for the experiment of terminal velocity (Figure 1b). First, the fan was operated at its maximum speed. A faba bean seed was dropped into the pipe from the lower hole on the pipe (30 cm below from the top of pipe). If the sample was carried away from the pipe by the air stream in the pipe, the speed of the fan was gradually reduced. When the sample moved up and down in the pipe, the speed of airflow was measured by the hot wire anemometer inserted into the pipe at the upper hole 2.5 cm below from the top of pipe. The relative humidity and dry bulb temperature of ambient air were measured during tests by the digital Thermo Hygrometer (HI 8564, Hanna, Italy). Its sensitivity values of temperature and relative humidity were 0.1 °C and 0.1%, respectively.

The drag coefficient (C_d) of faba bean seeds was calculated using the following equation (Gupta *et al.*, 2007):

$$C_d = \frac{2 \times g \times m \times (\rho_t - \rho_{\text{air}})}{\rho_{\text{air}} \times \rho_t \times V_t^2 \times A_p} \quad (7)$$

C_d is drag coefficient; m is mass of single faba bean seed (kg); g is gravitational acceleration ($m \cdot s^{-2}$); ρ_{air} is air density ($kg \cdot m^{-3}$); A_p is projected area of seed (m^2); V_t is terminal velocity ($m \cdot s^{-1}$).

The projected area of faba bean seed normal to the direction of the motion (A_p) was calculated by using the following equation (Gupta *et al.*, 2007);

$$A_p = \left(\frac{\pi}{4}\right) \times L \times W \quad (8)$$

The value of drag coefficient was calculated by using the mean values of variables in Equation 7.

RESULTS AND DISCUSSION

Physical properties of faba bean seeds: The moisture contents of dry and wetted faba bean seeds were determined to be 11.4 % and 25.8% (w.b.), respectively. Important dimensional and gravimetric properties of faba bean seeds were given in Table 1. The increase of moisture content from 11.4% to 25.8% increased slightly the length, width, thickness, geometric mean diameter, sphericity, projected area, porosity, angle of repose, 1000-seed mass of faba bean seeds while slightly decreased their true density and bulk density. Similar changes for these physical properties of faba beans seeds except true density with moisture content were found by Altuntas and Yildiz (2007). The average faba bean seed considered in this study is larger and heavier than the average faba bean seeds considered in the previous two studies (Altuntas and Yildiz, 2007; Haciseferogullari *et al.*, 2003). For instance, the average length and 1000-seed mass of faba bean seeds are 21.74 mm and 1655 g for 11.4% (w.b.) in this study while the average length and 1000-seed mass of faba bean seeds are 18.40 to 19.77 mm and 1140.15 to 1332.67 g for 9.89% to 25.08% (d.b.) in the study completed by Altuntas and Yildiz (2007) and the average length and 1000-seed mass of faba bean seeds are 20.39 mm and 1349.34 g for 10.90 % (d.b.) in the study completed by Haciseferogullari *et al.* (2003). The differences of faba bean seed dimensional and gravimetric properties among the results of three studies can be caused by agricultural practices and uncontrolled genetic variations.

Air resistance determination of faba bean seeds: Increasing the amount of air passed through faba bean seed piles per second resulted in nonlinear increase of pressure drop (Figure 3). It means that much more fan power is needed to pass the air through the piles at higher superficial air velocities. The moisture content did not affect the airflow resistances of faba bean seeds to airflow at different superficial velocities. In literature, it was reported that the pressure drop decreased with the increase of moisture content (Kenghe *et al.*, 2012; Masoumi and Tabil, 2008). The reason for the difference between the results of the current study and the previous studies can be the differences among the dimensional properties of agricultural materials.

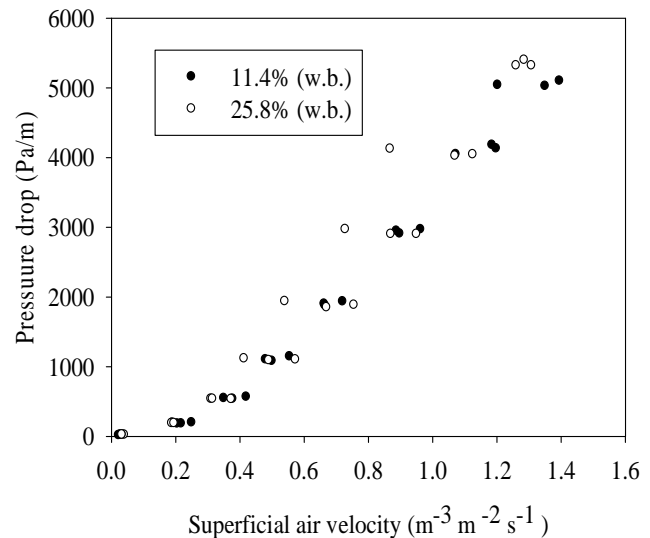


Fig 3: Airflow resistances of faba bean seed piles

The experimental data points and the prediction curve drawn with Modified Shedd's equation for 11.4% and 25.8% w.b. were given in Figures 4a and 4b, respectively. All predictions made with Modified Shedd's equation stayed mostly within the range of experimental data points for both moisture contents. The experimental data points and the prediction curve drawn with Hukill-Ives equation for 11.4% and 25.8% w.b. were given in Figures 4c and 4d, respectively. All predictions made with Hukill-Ives equation stayed also mostly within the range of experimental data points for both moisture contents. The R^2 values of Modified Shedd's equation are 0.9839 and 0.9597 for the moisture contents of 11.4 % or 25.8% w.b. respectively while the R^2 values of Hukill-Ives equation are 0.9818 and 0.9583 for the moisture contents of 11.4 % or 25.8% w.b. respectively. Based on these results, either equation can be used to model

Table 1: Some physical properties of faba bean (*Vicia faba L.*) seeds

Physical Properties	Moisture Content (% w.b.)	
	11.4 (0.126)	25.8 (2.79)
Length (mm)	21.74 (2.21)	21.92 (2.31)
Width (mm)	14.96 (1.35)	15.13 (1.42)
Thickness(mm)	5.92 (0.82)	5.99 (0.88)
Geometric mean diameter (mm)	12.40 (0.97)	12.53 (1.04)
Sphericity (%)	57.32 (3.86)	57.39 (3.97)
Projected area (mm ²)	257.1 (46.1)	(262.2) (48.5)
1000 seeds mass(g)	1655 (44)	1808 (16)
True density (kg/m ³)	1094 (14)	1049 (15)
Bulk density (kg/m ³)	760 (2.9)	723.9 (3.1)
Porosity (%)	30.60 (1.17)	31.00 (1.18)
Angle of repose (°)	14.68 (0.94)	15.93 (0.63)

The numbers given in parentheses are the standard deviations of experimental data.

mathematically the airflow resistances of faba bean seeds. The model parameter values of both equations were given in Table 2. Using these model parameter values with their equations, the necessary air pressure at the bottom of silos can be estimated for a given superficial velocity and depth.

Determination of terminal velocity of faba bean seeds:

The data about ambient air thermodynamic properties were given in Table 3. In the same table, the mean values of terminal velocity measurements and the calculated values of drag coefficient were also given. The terminal velocity increased with moisture content. Similar results were also reported for safflower seeds, sunflower seeds and coffee cherries/beans (Afonso Junior *et al.*, 2007; Gupta *et al.*, 2007; Kara *et al.* 2012). The increase of terminal velocity with moisture content may have been caused by the increase of

seed mass. The drag coefficient value of faba bean seeds decreased with moisture content. It was reported that the drag coefficient values of sunflower, Makhobeli, triticale and wheat seeds also decreased linearly with moisture content (Gupta *et al.*, 2007; Shahbazi *et al.*, 2014). The mean drag coefficient values of Makhobeli, triticale and wheat seeds were reported to be 1.12, 0.92 and 0.85, respectively (Shahbazi *et al.*, 2014).

Table 2: Model parameter values

Model parameters		Moisture Content (% w.b.)	
		11.4	25.8
Modified Shedd' equation	a	3289	3654
	b	1.53	1.50
Hukill-Ives equation	c	6715	6799
	d	6.87	5.53

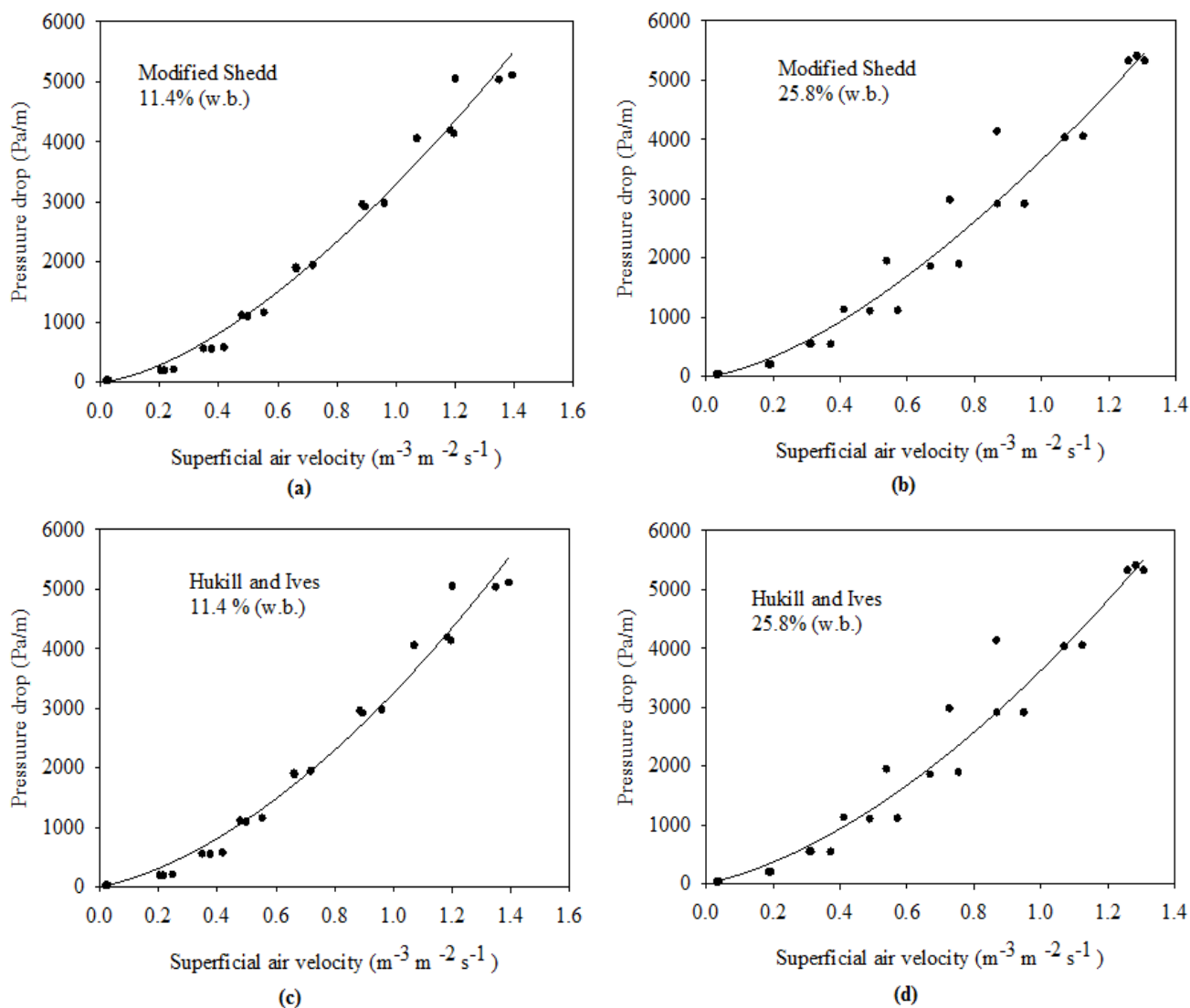


Fig 4: Fitting performances of models to experimental data

Table 3: Results of terminal velocity experiments

Data	Moisture Content (% w.b.)	
	11.4	25.8
Relative humidity of ambient air (%)	50	60
Dry bulb temperature of ambient air(°C)	21.6	25.3
Elevation of Tokat (m)	608	608
Atmosphere pressure in Tokat (kPa)	94.22	94.22
Volumetric weight of air (kg/m ³)	0.909	0.928
Terminal velocity(m/s)	11.68 (0.37)	12.86 (0.38)
Drag coefficient	1.02	0.88

The numbers given in parentheses are the standard deviations of experimental data.

CONCLUSIONS

Terminal velocity and airflow resistance of faba bean seeds were experimentally studied and mathematically modelled. The terminal velocity values were determined to be 11.68 and 12.87 m·s⁻¹ for the moisture contents of 11.4% and 25.8% (w.b.), respectively. Drag coefficients were calculated to be 1.02 and 0.88 for the same moisture contents. Terminal velocity increased but drag coefficient

decreased as the moisture content increased. The airflow resistances of faba bean seed piles were mainly affected by superficial air velocity. Modified Shedd's equation and Hukill-Ives equation were well fitted to the experimental pressure drop data for the superficial air velocities in the range of 0.0225 to 1.395 m³·m⁻²·s⁻¹. Either equation can be used to design aeration systems for the storage and drying bins of faba bean seeds.

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