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Airflow resistance in soybean

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Abstract. Resistance of material to airflow is an important factor to consider in the design of a dryer or an aeration system. The airflow resistance of soybean was determined with the modified airflow resistance apparatus. It was found that pressure drop increased with increase in airflow rate, bulk density, bed depth and decreased with moisture content. Modified Shedd equation, Hukill and Ives equation and modified Ergun equation were examined for pressure drop prediction. Airflow resistance was accurately described by modified Shedd equation followed by Hukill and Ives equation and modified Ergun equation. The developed statistical model comprised of airflow rate, moisture content and bulk density could fit pressure drop data reasonably well.

Keywords: airflow resistance, pressure drop, soybean, models

INTRODUCTION

The soybean (*Glycine max* L.) has been reported to have originated in Eastern Asia. It contains about 20% oil and 40% protein. Soybean protein is rich in the valuable amino acid lycine (5%). A large number of Indian and Western dishes such as bread, chapati, milk, sweets, pastries *etc*. can be prepared with soybean. Production of soybean in India at present is restricted mainly to Madhya Pradesh, Uttar Pradesh, Maharashtra and Rajasthan. It is also grown on a small acreage in Andhra Pradesh, Karnataka, Nagaland and Gujarat. In India during 2007-08 area, production and yield of soybean is recorded as 8.88 mln ha, 9.99 mln t and 1 124 kg ha^{-1}, respectively (ISO, 2007).

The relationship between a drop in pressure and the rate of airflow through an agricultural product is important in the design of drying or aeration systems. Resistance to airflow is a function of both product and air properties (Khatchatourian and Oliveira, 2006). The air pressure, required to force air through a bed of grain, is dissipated continuously due to friction and turbulence. The pressure drop for airflow through any particulate system depends on the rate and direction of airflow, surface and shape characteristics of the grain, the number, size and configuration of the voids, the particle size range, bulk density, depth of product bed, method of filling bin, fines concentration and moisture content. The data on the airflow-static pressure relationship of a number of agricultural grains have been published (ASABE, 2007). Most of researchers have reported airflow resistance data for agricultural grains but for low ranges of airflow. The data on airflow resistance of agricultural crops are scarce for high airflow range as reported by Nimkar and Khobragade (2006).

The phenomenon of pressure drop in airflow through agricultural products has been widely investigated for various grains (Nimkar and Chattopadhyay, 2003; Rajabipour *et al.,* 2001) and root vegetables and other crops (Kashaninejad and Tabil, 2009; Reed *et al*., 2001; Shahbazi and Rajabipour, 2008; Verboven *et al.,* 2004). In most cases, data were analyzed by means of Shedd (1953) and Hukill and Ives (1955) equations. Both the models have been widely used because they found to fit many experimental data sets. However, the constants in these equations have a purely empirical nature without physical meaning. An alternative expression is the model of Ergun (1952) originally developed for packed beds of uniformly sized spheres; the equation contains a linear and a quadratic velocity term, which depends on bed porosity, particle diameter and fluid properties.

Earlier reported studies on airflow resistance of different agricultural grains as affected by various operating parameters were reviewed which showed that no design data on the resistance to airflow of soybean is available for high airflow ranges. Therefore, it is felt necessary to generate and

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*Corresponding author's e-mail: rnkenghe@yahoo.co.in provide data on airflow resistance of soybean to designers of drying systems for proper design of drying equipments. Therefore, the present investigation was planned with the following objectives:

- to determine pressure drop at different airflow rates through the clean grain beds of soybean at different levels of moisture content and bulk density,
- to compare suitability of mathematical relationships available for pressure drop prediction with the experimentally determined data,
- to develop a statistical model describing the relationship between airflow resistance and the various operating parameters for soybean.

MATERIALS AND METHODS

In order to interpret the results, modified Shedd equation, Hukill and Ives equation and modified Ergun equation were assessed for their fitness. The constant A of Shedd equation takes into consideration the factors such as shape, surface roughness of grain *etc*. which are difficult to measure. Shedd equation is:

$$V = \mathrm{A}\Delta P^{\mathrm{B}}, \tag{1}$$

where: V – airflow rate ($\mathrm{m^3\ s^{-1}\ m^{-2}}$), P – pressure drop ($\mathrm{Pa\ m^{-1}}$), A and B – constants for a particular grain.

Another equation was proposed by Hukill (1955) to represent the Shedd data and also to take care of the non-linearity of experimental data on a log-log plot. This equation has been recommended by ASABE (2007) in following form:

$$\Delta P = \frac{\mathrm{A}V^2}{\ln(1+\mathrm{B}V)}. \tag{2}$$

Modified forms of Ergun equation was also selected because it takes into account the important factor such as bed porosity, which is the most important factor for airflow resistance in packed bed. Modified forms of Ergun equation is:

$$\Delta P = \mathrm{A}V\frac{(1-\varepsilon)^2}{\varepsilon^3} + \mathrm{B}V^2\frac{(1-\varepsilon)}{\varepsilon^3}, \tag{3}$$

where: ε – bed porosity (decimal).

The modified airflow resistance apparatus consisted of airblow system, airflow measurement system, plenum chamber, test bin and pressure measurement system. In the modified apparatus, for static pressure measurement, three pressure taps at each level were connected to an inclined manometer, having least count of 1 mm, by means of 6 mm diameter polyethylene tubing through flat bottom glass air chamber so that pressure deviation at the section could be averaged. Kerosene of known density was used as a manometer fluid. The density values at different temperature of the manometer fluid (kerosene) were experimentally determined using standard procedure suggested by Mohsenin (1986). The noted density values determined at the temperature of 5, 10, 15, 20, 25, 30, 35, 40, 45 and 50°C were found to be 819, 817, 815, 813, 810, 807, 802, 791, 787 and 783 kg $\mathrm{m^{-3}}$, respectively. The setup could reproduce pressure drop observation with 5 Pa errors at the maximum airflow rate.

The test samples were conditioned by the method described by (Nimkar and Chattopadhyay, 2003). While conducting the experiments on airflow the conditioned test sample was removed from the refrigerator and left at room temperature for 6 h so as to equilibrate it with the ambient temperature before use. Test runs were carried out at three bulk densities obtained with loose, medium and densely packed grains and at this respective order. Firstly, the test bed was filled by a loose fill method as described by Sacilik (2004) .To obtain medium and dense packed bed conditions, initially, a required quantity of test sample was loosely filled and then the bulk density was gradually increased to the desired level by tapping the side walls with rubber hammer. After filling the test bin the top surface of the grain bed was leveled manually by using stroker specially developed for the purpose.

At each airflow rate, the test run with five sets of observations were conducted at each bulk density level. The tests were carried out starting initially from highest airflow rate and subsequently by proceeding to lowest airflow rates. The system was tested for air leakage for pressures upto 16 kPa using soap solution at all joints before start of each experiment. The velocity measurement was repeated after reloading of the grain bed for each replication. Relative humidity, atmospheric pressure and temperature were measured five times during each test run and the average were used for airflow rate calculations to standard condition of air at temperature (32.5°C) and pressure (101.325 kPa). The experiments were carried out at three different bulk densities for each moisture levels, *ie* 7.35, 13.20 and 19.05% d.b., for three bed depths (200, 400 and 600 mm). The experiments were carried out at all possible airflow ranges. Seventeen airflow rates ranged from $0.0411 \leq V \leq 1.1014\ \mathrm{m^3\ s^{-1}\ m^{-2}}$. No fluctuations were observed in the kerosene column indicating a fairly stable and uniform airflow through the air duct. Each pressure difference, measured by the inclined manometer, was divided by the distance of the two taps to obtain the pressure drop per meter depth. The average of five replications was expressed as pressure drop ($\mathrm{Pa\ m^{-1}}$) for each airflow rate.

For fitting the experimental data to the selected models, the entire span of airflow rates was considered as singular continuous airflow range and sub-divided into three sub-ranges of airflows ($0.0411 \leq V \leq 0.3019$, $0.3019 < V \leq 0.6902$ and $0.6902 < V \leq 1.1014\ \mathrm{m^3\ s^{-1}\ m^{-2}}$) to obtain more close results. These sub-ranges of airflows, *ie* low, medium and high were selected based on the physical observation of three prominent straight line segments with different slopes obtained in the log-log plot between airflow rate and pressure drop.

Fitted parameters (constant A and B), coefficient of determination (R^2) and standard error of estimate (S_y) were used to compare the relative goodness of fitting the experimental data with these models. The standard error of estimate expressed the average deviation between experimental and predicted values. Acceptability of the models for predicting the pressure drop was decided on the basis of percent data falling in different ranges of standard error of estimates (Spiegel, 1982).

The experimental data of soybean grain at each moisture and bulk density level were fitted to the selected three models by using non-linear least squares regression with MATLAB 7.1. The constants A and B for each of the model were estimated with multiple non-linear regression analysis technique using least square iterative procedure while fitting the experimental pressure drop values at each moisture level. The method of non-linear regression analysis was used to develop a statistical model to predict pressure drop across soybean grain by using the MATLAB 7.1.

RESULTS AND DISCUSSION

In order to characterize the grain sample at specified three levels of moisture content which formed the test sample for the experimentation, *insitu* bulk density, bulk porosity and moisture content were measured with the representative samples with five replications. It was observed that the values of bulk density, true density and bulk porosity were found linearly decreased with increase in moisture content. Similar results were reported for soybean (Kibar and Ozturk, 2008) and for bay laurel seeds (Yurtlu *et al.,* 2010). The variations in bulk density and bulk porosity values among replicated samples were found to be negligible. The maximum variation of moisture content among the different replicated samples was within 1.26%.

In order to interpret the results, three models, *ie* modified Shedd (Eq. (1)), Hukill and Ives (Eq. (2)) and modified Ergun (Eq. (3)) were used and hereinafter referred as Models I, II and III, respectively. The equations were fitted with mean pressure drop data recorded with 600 mm grain bed depth for complete airflow range as well as three sub-ranges of airflows. To study the comparative behavior of these three models, the estimated constants (A and B) along with coefficient of determination (R^2) and standard error of estimate (S_y) of the equation were estimated for complete airflow and three sub-ranges of airflows. The data and estimates have been presented in Table 1 along with their *in situ* bulk density, bulk porosity and moisture content. It was considered that full airflow as critical range; all the coefficient of determination of the equations was higher than 0.9942 for full airflow range of $0.0411 \leq V \leq 1.1014$ m^3 s^{-1} m^{-2}. Therefore, the magnitudes of standard error of estimates were utilized for comparing the relative precision of the models to predict airflow resistance of soybean. The average S_y values (mean values at three moisture levels) obtained by the models for complete airflow ranges with loose, medium and dense packed grain conditions were compared. For three sub-ranges of airflows, the average S_y values for only loose fill grain bed conditions were considered.

As regards the behavior of the selected models for the purpose of fitting the experimental airflow resistance data of soybean, it can be noted that for complete airflow range ($0.0411 \leq V \leq 1.1014$ m^3 s^{-1} m^{-2}), average values of standard error of estimate for loose fill condition were 126.90, 109.30, 94.90 Pa m^{-1} with models I, II, III, respectively. For sub-ranges of airflows of $0.0411 \leq V \leq 0.3019$, $0.3019 < V \leq 0.6902$ and $0.6902 < V \leq 1.1014$ m^3 s^{-1} m^{-2} average standard error of estimate values for loose fill conditions were found to be 38.38, 65.32, 63.00; 63.87, 60.34, 56.82 and 38.50, 40.48, 43.90 Pa m^{-1}, respectively for models I, II and III. (Table 1). These results indicated that for the purpose of predicting pressure drop in loosely filled soybean in these sub-ranges of airflows all the models were acceptable for predicting pressure drop.

While comparing for acceptability of these three models, the results indicated that 89% data sets were within 1S_y limit and 11% in ± 2 S_y limit for model-I. It was 78% in 1S_y limit and 11% each in ± 2 S_y and ± 3 S_y limit for model-II whereas, these data sets were 56% in 1S_y limit and 22% each in ± 2 S_y and ± 3 S_y limit for model-III. Considering complete and three sub-ranges of airflows the results also showed that with modified Shedd equation for complete airflow ranges, the percent data falling within 1 S_y limit was found 73.4%. For Hukill and Ives equation those were 68.7%, and for modified Ergun equation those were 67.1%, respectively. Hence, all these three models were acceptable for predicting pressure drop through soybean grains within the experimental airflow range of the study. This indicated that the modified Shedd equation is a better choice for predicting pressure drop through bulk soybean grain beds followed by Hukill and Ives equation and modified Ergun equation. Similar results were reported for bulk pistachio nuts (Kashaninejad and Tabil, 2009), walnuts (Rajabipour *et al.,* 2001), pulse grains (Nimkar and Chattopadhyay, 2003) and for beds of apples (Verboven *et al.,* 2004).

In order to relate the equation constants as characterizing the grain factor, the determined values of these constants A and B were studied. The study revealed that only constant A values of modified Shedd equation had a specific trend as its value decreased with the increase in moisture content in low, medium, high and complete airflow ranges. Therefore, constant A values were subsequently related to grain moisture content. For all range of airflows the values of constant A decreased with increase in moisture content, substantiating the negative effect of moisture content on pressure drop through soybean beds. Thus, it could be ascertained that for the design of drying or aeration system for soybean grains, the pressure drop of only dry material need to be considered as it would result in safe design. The trend of decrease in the value of constants A of modified Shedd equation with increase in moisture content indicating that

T a b l e 1. Physical properties and constant A and B in various models for complete range and three sub-ranges of airflows for soybean (*MC* = 13.20 % d.b.)

Bulk density (kg m^{-3})	Porosity %	Airflow range (m^3 s^{-1} m^{-2})															
		$0.0411 \leq V \leq 1.1014$				$0.0411 \leq V \leq 0.3019$				$0.3019 < V \leq 0.6902$				$0.6902 < V \leq 1.1014$			
		A	B	R^2	S$_y$ (Pa m^{-1})	A	B	R^2	S$_y$ (Pa m^{-1})	A	B	R^2	S$_y$ (Pa m^{-1})	A	B	R^2	S$_y$ (Pa m^{-1})
Modified Shedd equation																	
670	38.67	5027.4	1.622	0.9952	126.90	1503.8	0.605	0.9715	38.38	4844.9	1.600	0.9916	63.87	5058.6	1.693	0.9988	38.50
710	35.00	7069.8	1.708	0.9942	201.02	2157.4	0.638	0.9760	48.30	6521.4	1.601	0.9825	125.86	7113.4	1.819	0.9940	132.27
750	31.34	8834.9	1.712	0.9939	262.49	2542.8	0.597	0.9804	52.73	8551.4	1.694	0.9770	190.83	8874.9	1.793	0.9919	191.09
Hukill and Ives equation																	
670	38.67	13310	13.12	0.9964	109.30	-8729	-2.190	0.9175	65.32	13780	15.33	0.9925	60.34	16240	23.81	0.9987	40.48
710	35.00	24010	29.03	0.9952	184.40	-10480	-2.044	0.9332	80.57	18370	14.98	0.9839	120.90	39830	269.50	0.9940	132.50
750	31.34	30446	30.58	0.9947	244.00	-14600	-2.194	0.9180	107.90	31210	36.38	0.9781	186.30	43230	129.50	0.9919	191.20
Modified Ergun equation																	
670	38.67	231.55	333.15	0.9973	94.90	641.37	-542.35	0.9232	63.00	202.57	351.59	0.9934	56.82	223.17	339.78	0.9984	43.90
710	35.00	168.56	356.87	0.9964	159.44	540.94	-544.88	0.9373	78.03	181.28	329.55	0.9852	115.87	121.46	390.01	0.9939	133.71
750	31.34	133.77	304.22	0.9958	216.47	455.73	-434.12	0.9247	103.37	112.67	317.64	0.9798	179.02	112.47	320.38	0.9919	191.82

Mean values of five replications.

the constant A physically represented the resistance to airflow through soybean grains. Similar results have been reported for pulse grains (Nimkar and Chattopadhyay, 2003), marigold flowers (Reed, 2001), sugarbeet (Lope *et al.,* 2003), cottonseed (Tabak *et al.,* 2004) and for pelleted feed (Ray *et al.*, 2002).

While considering the effect of moisture content in mathematical model for predicting pressure drop through grain, the coefficient A of modified Shedd's equation was found linearly related to moisture content for full airflow as well as for three sub-ranges of airflows as given by the following relationship:

$$A = C + D\,MC \tag{4}$$

where: C and D – constants, *MC* – moisture content, % d.b.

The calculated values of constants C and D of Eq. (4). describing relationship of coefficient A, in modified Shedd's equation with moisture content are given in Table 2. For soybean at any level of moisture content in the range of 7.35 to 19.05% d.b. and for the complete, high, medium and low airflow ranges the constant A could be estimated by using Eq. (4). The results also revealed that in case of medium and dense packed grain conditions for soybean the estimated values of constant A of the equation were approximately 1.41 and 1.77 times, to that of loose fill condition.

Mean and standard deviation values of exponent B in modified Shedd's Eq. (1) for three levels of packing with the full airflow range as well as three sub-ranges of airflows are shown in Table 3. The results indicated that the exponent B could be assumed constant at mean value for all cases as the value of standard deviations were very low. The mean values of exponent B reported in Table 3 were nearly same to that of exponent B values given in Table 1. The result obtained followed similar trend with the results reported for pulse grains (Nimkar and Chattopadyay, 2003), pelleted feed (Ray *et al.,* 2002), wheat (Łukaszuk *et al.,* 2008) and for cottonseed (Tabak *et al.,* 2004).

The method of non-linear multiple regression analysis using least squares procedure was used to describe the relationship between pressure drop across soybean grain bed, airflow rate, bulk density and moisture content. For the specified grain conditions, the predicted pressure drop based on the Eq. (5) would help in selection of the blower for pulse dryer design. Values of experimental pressure drop were re-

Table 2. Constants C and D in Eq. (1) describing the relationship of coefficient A in modified Shedd equation with moisture content for soybean grain at different levels of packing and airflow ranges

Grain/Packing	Constants	Airflow range ($m^3 s^{-1} m^{-2}$)			
Soybean		$0.0411 \le V \le 1.1014$	$0.0411 \le V \le 0.3019$	$0.3019 < V \le 0.6902$	$0.6902 < V \le 1.1014$
Loose fill	C	5431	1570	5144	5479
	D	-32.63	-4.48	-21.77	-34.15
	R^2	0.9850	0.9390	0.9930	0.9830
Medium packed	C	7452	2235	6839	7504
	D	-30.13	-4.854	-20.47	-30.91
	R^2	0.9940	0.8550	0.8950	0.9930
Dense packed	C	9228	2615	8859	9266
	D	-27.98	-5.26	-18.28	-27.87
	R^2	0.9840	0.9930	0.7730	0.9840

Table 3. Mean and standard deviations of exponent B in modified Shedd (Eq. (1)) for soybean at different levels of packing and airflow ranges

Grain/Packing	Airflow range ($m^3 s^{-1} m^{-2}$)							
Soybean	$0.0411 \le V \le 1.1014$		$0.0411 \le V \le 0.3019$		$0.3019 < V \le 0.6902$		$0.6902 < V \le 1.1014$	
	Mean*	SD	Mean*	SD	Mean*	SD	Mean*	SD
Loose fill	1.619	0.014	0.599	0.034	1.609	0.010	1.685	0.054
Medium packed	1.702	0.006	0.645	0.020	1.612	0.013	1.800	0.021
Dense packed	1.715	0.003	0.590	0.029	1.707	0.018	1.794	0.009

*Explanations as in Table 1.

T a b l e 4. Coefficients of an estimated multiple regression model (Eq. (5)) to describe the airflow resistance of soybean

Airflow range (m^3 s^{-1} m^{-2})	Variables in nodels	Regression coefficients				R^2	S_y (Pa m^{-1})	% data in ± S_y limit (%)
		b_1 (Pa s m^{-2})	b_2 (Pa s^2 m^{-3})	b_3 (Pa s m^{-2})	b_4 (Pa s m kg^{-1})			
$0.0411 \leq V \leq 1.1014$	V	7505				0.8326	1080.4	69
	$V+V^2$	198.2	6454			0.8823	908.9	74
	$V+V_2+V$ M	-25098	6267	35.98		0.9821	355.8	71
	$V+V^2+V$ M+V ρb	-30059	6246	41.20	96.90	0.9930	223.8	67 (100)
$0.0411 \leq V \leq 0.3019$	V	2592				0.6972	156.7	57 (100)
	$V+V^2$	2584	22.67			0.6972	158.5	60 (100)
	$V+V_2+V$ M	-12287	293.1	20.89		0.9675	52.5	60 (100)
	$V+V^2+V$ M+V ρb	-14536	297.1	23.25	43.62	0.9853	35.7	64 (100)
$0.3019 < V \leq 0.6902$	V	7103				0.6785	551.2	70
	$V+V^2$	-6375	12821			0.6983	539.2	66 (100)
	$V+V^2+V$ M	-23650	12125	25.41		0.9580	203.2	74
	$V+V^2+V$ M+V ρb	-27018	11979	29.10	68.42	0.9863	117.1	72
$0.6902 < V \leq 1.1014$	V	12178				0.4931	1441	53 (100)
	$V+V^2$	-1431	7390			0.4948	1453	55 (100)
	$V+V^2+V$ M	-22778	3331	40.09		0.9406	503.1	62 (100)
	$V+V^2+V$ M+V ρb	-28711	3496	45.94	108.3	0.9896	212.7	64 (100)

Values in parentheses are percent data in ± 2 S_y limit.

gressed against each and all possible combinations of these variables in a step-wise approach. This technique allowed testing of the statistical validity of including each of the variables as a component of the model predicting airflow resistance. The results showed that with inclusion of each of the variables in the pressure drop predicting model, the value of R^2 was significantly increased whereas, the S_y value was decreased for the three sub-ranges from low to high level. The best fit values of coefficient b_1, b_2, b_3 and b_4 in the generalized form of a second degree polynomial were obtained and are shown in Table 4. The values of standard error of estimates were determined for judging the precision of the model. From the high values of coefficient of determination and percent data falling in ± 1 S_y limit, it was evident that the experi- mental data fitted the Eq. (5) reasonably well. The model that was found to describe airflow resistance was as follows:

$$\Delta P = b_1 V + b_2 V^2 + b_3 VMC + b_4 V\rho_b, \tag{5}$$

where: ρ_b – bulk density (kg m^{-3}); b_1, b_2, b_3, b_4 – regression coefficients.

In case of soybean it could be noted from the results as shown in Table 4 that for predicting pressure drop through the grain with the Eq. (5), the values of coefficient of determination for complete, low, medium and high airflow ranges were 0.9930, 0.9853, 0.9863 and 0.9896, respectively. In all cases the percent data were more than 96% upto ± 2 S_y limit. For soybean having moisture content ranging from 7.35 to 19.05% d.b., bulk density between 670 to 750 kg m^{-3}, and bulk porosity ranging between 31.34 to 38.67%; the model could predict pressure drop in the full airflow range ($0.0441 \leq V \leq 1.1014$ m^3 s^{-1} m^{-2}) with standard error of estimate of 223.8 Pa m^{-1} whereas, the values of standard error of estimate for the sub-ranges $0.0411 \leq V \leq 0.3019$, $0.3019 < V \leq 0.6902$ and $0.6902 < V \leq 1.1014$ m^3 s^{-1} m^{-2} were 35.7, 117.1 and 212.7 Pa m^{-1}, respectively.

The above results indicated that the statistical model was acceptable for prediction of pressure drop through soybean grain beds within the experimental limit.

CONCLUSIONS

1. Based on statistical analysis all the selected models were accurate enough for predicting pressure drop through soybean grain beds within the extremities. However, the modified Shedd equation was more precise followed by Hukill and Ives and modified Ergun equation.

2. Coefficient A of modified Shedd equation was linearly related to the grain moisture content and it represented the change in moisture content.

3. The statistical model developed for predicting pressure drop through soybean as affected by airflow rate, bulk density and moisture content was found to fit the experimental data reasonably well.

REFERENCES

ASABE, **2007.** Standards for resistance to airflow of grains, seeds, and other agricultural products, and perforated metal sheets. ASABE Press, St. Josepth, MI, USA.

Ergun S., 1952. Fluid flow through packed columns. Chem. Eng. Progress., 48, 89-94.

Hukill W.V. and Ives N.C., 1955. Radial airflow resistance of grain. J. Agric. Eng., 36(5), 332-335.

IOS, **2007.** Area and production of crops in India. Indian Official Statistics, Directorate of Economics and Statistics, New Delhi, India.

Kashaninejad M. and Tabil L.G., 2009. Resistance of bulk pistachio nuts (cv. ohadi) to airflow. J. Food Eng., 90(1), 104 -109.

Khatchatourian O.A. and Oliveira F.A., 2006. Mathematical modeling of airflow and thermal state in large aerated grain storage. Biosys. Eng., 95(2), 159-169.

Kibar H. and Ozturk T., 2008. Physical and mechanical properties of soybean. Int. Agrophysics, 22, 239-244.

Lope G., Tabil J., Kienholz H., Marshall Q., and Eliason V., 2003. Airflow resistance of sugar beet. J. Sugar Beet Res., 40(3), 110-113.

Łukaszuk J., Molenda M., Horabik J., Szot B., and Montross M.D., 2008. Airflow resistance of wheat bedding as influenced by the filling method. J. Agric. Eng. Res., 54(2), 50-57.

Mohsenin N.N., 1986. Physical Properties of Plant and Animal Materials. Gordon Breach Press, New York, USA.

Nimkar P.M. and Chattopadhyay P.K., 2003. Airflow resistance of pulse grains. J. Food Sci. Technol., 40(1), 28-34.

Nimkar P.M. and Khobragade B.V., 2006. Resistance of moth gram to airflow. Int. J. Food Sci. Technol., 41, 488-497.

Rajabipour A., Shahbazi F., Mohtasebi S., and Tabatabaeefar A., 2001. Airflow resistance in walnuts. J. Agric. Sci. Technol., 3, 257-264.

Ray S.J., Pordesimo L.O., and Wilhelm L.R., 2002. Airflow resistance of some pelleted feed. Trans. ASAE., 47(2), 513-519.

Reed S.D., Armstrong P.R., Brusewitz G.H., and Stone M.L., 2001. Resistance of marigold flower to airflow. Trans. ASAE, 44(3), 639-462.

Sacilik K., 2004. Resistance of bulk poppy seeds to airflow. Biosys. Eng., 89(4), 435-443.

Shahbazi F. and Rajabipour A., 2008. Resistance of potatoes to airflow. J. Agric. Sci. Technol., 10, 1-9.

Shedd C.K., 1953. Resistance of grains and seeds to airflow. J. Agric. Eng., 34(9), 616 -619.

Spiegel M.R., 1982. Outline of Theory and Problems of Statistics. McGraw-Hill Press, New York, USA.

Tabak S., Askarov B., Rashidov U., Tabak I., Manor G., and Shmulevich I., 2004. Airflow through granular beds packed with cotton seeds. Biosys. Eng., 88(2), 163-173.

Verboven P., Hoang M.L., Baclmans M., and Nicolaii B.M., 2004. Airflow through beds of apples and chicory roots. Biosys. Eng., 88(1), 117-125.

Yurtlu Y.B., Yesilogl U.E., and Arslanoglu F., 2010. Physical properties of bay laurel seeds. Int. Agrophys., 24, 325- 328.