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Full Length Research Paper

Physical properties and conveying characteristics of corn and barley seeds using a suction-type pneumatic conveying system

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In this research, physical properties of corn and barley seeds were first determined and then, to obtain the change in pressure drop, power consumption and mechanical seed damage as a function of air velocity during suction conveying of corn and barley, a suction-type pneumatic conveying system was designed and constructed and finally the pneumatic conveying characteristics of corn and barley seeds were determined under seven air velocities. The results indicated that the geometric and arithmetic mean diameters and sphericity of corn seeds were 80, 63 and 20%, respectively, more than the barley seeds. Pressure drop increased nonlinearly and linearly with an increase in air velocity for corn and barley seeds, respectively. However, power consumption was nonlinearly increased with air velocity for both seeds. Mechanical damage of both seeds increased linearly as the air velocity was increased. There was a turning point at which the pressure drop increased rapidly with an increase in air velocity. The lowest pressure drop for corn and barley occurred at the air velocity of 20 and 15 m s^{-1}, respectively. Therefore, for reducing the specific energy consumption and mechanical damage to corn and barley seeds at the conveying capacity of 15 ton h^{-1}, the air velocity in pneumatic conveying must be decreased below 20 and 15 m s^{-1}, respectively.

Key words: Pneumatic conveying, conveying characteristics, pressure drop, power consumption, mechanical damage.

INTRODUCTION

Application of pneumatic conveyer system is very comprehensive and a wide range of powder and granular materials can be transferred by this system. In agriculture, the high volume of harvested products such as grains and rice, processed materials, animal feed pellets, chemical fertilizers, food products such as flour, sugar, tea and coffee can be transferred by this way (Mills, 2004). Suction-type pneumatic conveying systems are commonly used for conveying materials from multiple sources to a single point. Suction-type pneumatic conveying systems are also widely used for drawing materials from open storage, where the top surface of the material is accessible. Suction systems, therefore, can be used most effectively for off-loading ships and trucks. Vacuum systems have the particular advantage that all gas leakage is inward, so that the injection of dust into the atmosphere is virtually eliminated (Mills et al., 2004). In order to design equipment for handling, cleaning, drying, aeration, storing, and processing of agricultural seeds, it is necessary to study the physical properties (Guner, 2007; Molenda et al., 2004).

Shape, size, volume, density, porosity are important in analysis of the behavior of the seeds in handling of the material. The porosity, terminal velocity and drag

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coefficient are the most important properties to determine the conveying pattern. Change in transport pattern from dense to dilute, resulted in increase of power consumption (Zhang et al., 2010). The fundamental step in the design of a pneumatic conveyor is the correct estimation of pressure drop along the conveying pipes. The pressure drop and power consumption increase with increasing air velocity (Guner, 2007). The percentage of damage to the seeds depends on conveying velocity, seed size, shape and moisture content. Minimizing seed damage is an important consideration in designing a system for loading and unloading, storage and conveying seeds which are used for planting. This is because during operations in this equipment, grains are subjected to impact between seeds and other surfaces which may result in mechanical damage (Baryeh, 2002).

Thus, the main objective of this part of the research which is reported here, is to determine the physical properties of corn and barley seeds and to obtain the change in pressure drop, power consumption and mechanical seed damage as a function of air velocity during suction conveying of corn and barley through a developed suction-type pneumatic conveying system.

MATERIALS AND METHODS

Among cereals, corn and barley were chosen for testing the developed system. Because they are the cereals with high transport volume and have prolate and oblate shape, respectively. The seeds were collected from animal feed storage silos in Isfahan, Iran.

Determination of physical properties

In this study, the physical properties of corn and barley seeds such as length, width, thickness, arithmetic mean diameter, geometric mean diameter, sphericity, volume, thousand seed mass, bulk density, true density, porosity, projected area were determined. The mass of seeds and thousand seed mass were measured by a digital scale to an accuracy of 0.01 g. To determine 1000 seed mass, 1000 randomly selected seeds from the bulk were weighed and averaged. To determine the moisture content of seeds ($M\%$), 10 g of each sample was weighed and placed in an oven at the temperature of 103°C, and a heating time of about 4 h. Then the sample was weighed and moisture content was calculated according to the following equation (ASAE, 1999):

$$M\% = \left(\frac{G_1 - G_2}{G_1}\right) \times 100 \quad (1)$$

Where G_1 and G_2 are total weight and dry weight, respectively. The size of the seeds was measured using a caliper to an accuracy of 0.01 mm. Ten seeds were randomly selected from each group and three linear dimensions namely the longitudinal axis containing the major dimension (length, *a*), the transverse axis containing the minor dimension (width, *b*), and the transverse axis containing the minimum dimension (thickness, *c*) were measured (Yalcin and Ozarslan, 2004; Kibar et al., 2008). Aspect ratio (R_a), arithmetic mean diameter (D_a), geometric mean diameter (D_g), sphericity ($\emptyset$), volume (V) and projected surface (S_p) values of ten seeds from each group were calculated using the following equations (Guner and Dursun, 2003).

$$R_a = \left(\frac{b}{a}\right)100 \quad (2)$$

$$D_a = \frac{(a+b+c)}{3} \quad (3)$$

$$D_g = (a \times b \times c)^{1/3} \quad (4)$$

$$\emptyset = \left(\frac{D_g}{a}\right)100 \quad (5)$$

$$V = \frac{\pi B^2 a^2}{6(2a-B)} \quad B = (bc)^{(1/2)} \quad (6)$$

$$S_p = \pi \frac{{D_g}^2}{4} \quad (7)$$

To determine the bulk density (ρ_b), seeds were uniformly poured from 15 cm height in a beaker and the seeds in the beaker were weighted. The bulk density of seeds was determined by dividing the mean seed mass to the beaker volume (Guner, 2007). The actual density of seeds (ρ_a) was determined by using the toluene displacement method.

In this method, some toluene (C_7H_8) was spilled in a mezor and the volume was recorded. Then a certain amount of seeds were weighed and poured into the mezor. The mezor was shaken to bubble out around the seeds and new volume was immediately read. The amount of displaced fluid volume by seeds was obtained and the actual density of seeds was determined by dividing the seed mass to the displaced fluid volume (Guner, 2007). After determining the bulk and actual density, the porosity (ϵ) was computed as follows (Singh and Goswami, 1996):

$$\epsilon = 100\left(1 - \frac{\rho_b}{\rho_a}\right) \quad (8)$$

The terminal velocities of the seeds (V_t) were measured using a wind column. A centrifugal blower was used to deliver air through a 70.3 mm inside diameter transparent tube positioned vertically. Air flow was regulated by adjusting the blower speed by a motor with frequency inverter. For each test, a sample was dropped into the air stream from the top of the air column. Air was blown upward to suspend the seed in the air stream. The air velocity near the location of the seed suspension was measured by Testo 512. mark electronic anemometer (Guner, 2007; Calısır et al., 2005; Tabak and Wolf, 1998). The dimensionless drag coefficient (C_d) characterizes the interaction between seed and airflow and was expressed by the following formula (Tabak et al., 2002; Tabak and Wolf, 1998):

$$C_d = \frac{2mg}{V_t^2 \rho_a s_p} \quad (9)$$

Design and development of suction-type pneumatic conveyor system

In order to determine pneumatic conveying characteristics of corn and barley seeds, suction-type pneumatic conveyor system was

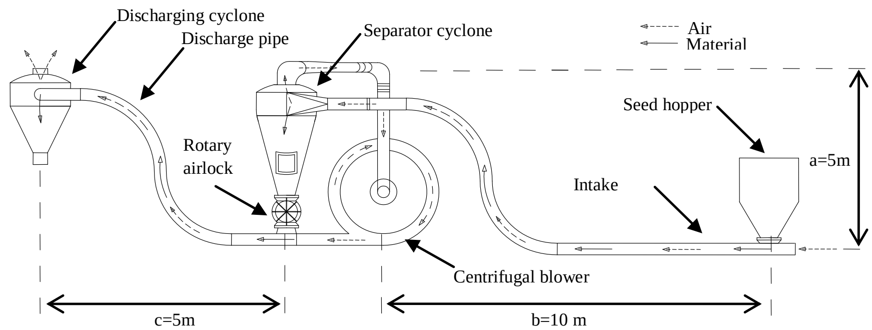

Figure 1. Layout of the pneumatic.

Figure 2. Pneumatic conveyor.

designed and developed. The system was designed for a capacity of 30 t h^{-1}. The pneumatic conveyor has a 15 m long horizontal pipe and a 10 m long vertical pipe with an inside diameter of 15.25 cm and four bends. The pneumatic conveying system consisted of a centrifugal blower, an electric motor, a seed hopper, a rotary airlock, a rotary airlock motor, intake and discharge pipes, a separator cyclone and a discharging cyclone (Figure 1). The choice of power source and vacuum blower was based on the ability of the blower to provide adequate suction and discharge pressures to overcome the pressure losses (air friction losses, losses due to acceleration of the grain, lift of the grain and the grain flow) in the system (Srivastava et al., 2006).

The centrifugal blower was used to deliver air through the system. The seed hopper served as a storage container for the material. The seeds to be conveyed are introduced into the system using a gate feeder under the hopper. The gate feeder was adjusted to feed seeds at constant rate. The separator cyclone was used to separate the seeds from the air. The rotary airlock was used to provide an airtight on cyclone. In the separator cyclone, the seeds fell downward and the air was exhausted out of the cyclone by the centrifugal blower. A transparent tube was used to observe the transport phenomena in the horizontal pipe. Different parts of the conveying system were installed on a chassis by using connecting pipes and fittings (Figure 2).

Determination of pneumatic conveying characteristics

After design and development of the conveyer, the effect of air velocities on pressure drop (kPa m^{-1}), power consumption (kW) and the percentage of seed damaged was evaluated. The pressure was measured at different sections of pipe by a pressure meter (model: Testo 512). Pressure drop was the difference between the two pressures at the two measurement sections. The pressure drop in the pipe refers to the pressure difference along the full length of the intake pipe, namely, between pressures at the first measurement section before the hopper feeder and the pressure before the cyclone. The air velocity was measured by velometer (model: Testo 512) installed at the inlet of the centrifugal blower (Raheman and Jindal, 2001).

To determine the conveying power consumption, voltage (V), current (I), and power factor (φ) drawn by the electric motor for the blower were measured using a voltmeter, an ampere meter, and power factor meter, respectively. Power consumption was calculated using the following equation:

$$P = \sqrt{3} \times V \times I \times \cos\varphi \qquad (10)$$

The mechanical damage was determined by the ratio of the damaged seeds mass to the whole seeds mass in each sample and expressed in mass percentage according to following equation (Guner, 2007):

$$S_d = \frac{M_d}{M_d + M_{ud}} 100 \qquad (11)$$

Where M_d and M_{ud} are damaged seeds mass and undamaged seeds mass, respectively.

Statistical analysis

Data on different parameters were analyzed in completely randomized design as factorial arrangement (conveying material with three levels of air only, corn and barley, air velocity with seven levels of 10, 15, 20, 25, 30, 35 and 40 m s^{-1}) and the effects of air velocity on pressure drop, power consumption and mechanical seed damage during suction conveying of corn and barley were evaluated by analysis of variance (ANOVA). Comparison of the means was performed by using least significant difference test at P < 0.05 level. Excel and SAS softwares were used for data analysis.

RESULTS AND DISCUSSION

The physical properties of the seeds are given in Table 1. The seed sizes of corn and barley vary within the dimensions ranges of 5.12 to 12.18 mm and 2.77 to 9.78

Table 1. Mean and standard deviation values of the seed physical properties.

Physical properties	Corn	Barley
Moisture content (%, w.b.)	10.55±0.40	5.97±0.38
Length (mm)	12.18±1.09	9.78±1.08
Width (mm)	8.78±0.47	3.41±0.27
Thickness (mm)	5.12±0.99	2.77±0.24
Arithmetic mean diameter (mm)	8.69±0.33	5.32±0.49
Geometric mean diameter (mm)	8.13±0.42	4.52±0.38
Sphericity (%)	67.35±0.6	46.36±2.6
Volume (mm^3)	208.36±51.39	29.19±7.44
Projected surface (mm^2)	52.07±5.37	16.12±2.75
Aspect ratio (%)	72.58±7.35	35.05±2.73
Thousand seed mass (g)	260.54±10.73	30.17±3.06
Bulk density (kg m^{-3})	650±10.64	648±13.01
Actual density (kg m^{-3})	1148±14.14	1297±17.96
Porosity (%)	43.32±1.38	50.03±1.13
Terminal velocity (m s^{-1})	13.85±0.53	7.84±0.45
Drag coefficient	0.55±0.04	0.4±0.02

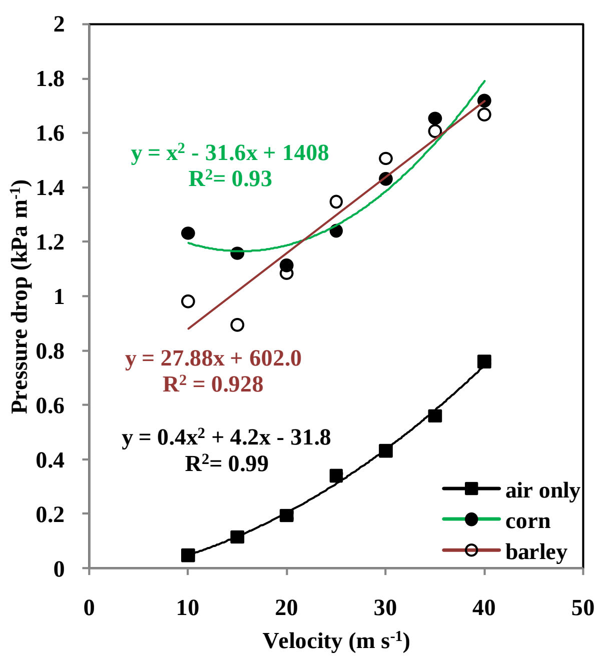

Figure 3. Effect of air velocity on the pressure drop at the conveying capacity of 15 ton h^{-1} seed, pipe with 15 m long and 15.25 cm inside diameter.

mm, respectively. Similar results have been reported by Guner (2007) for barley. He found that the mean sizes of barley seeds at 9% (d.b.) ranged from 2.58 to 9.54 mm. Table 1 shows that the arithmetic and geometric mean diameter of corn seeds are more than the barley seeds. Similar value for the geometric mean diameter of the barley as obtained in this study was reported by Guner (2007). The sphericity of corn (67.35%) was 20% more than the barley (46.36%). Guner (2007) also reported the sphericity of barley as 46.1%. The volume, projected surface and one thousand seed mass of corn are 7.14, 3.23 and 8.64 times the barley seeds. The mean value of the barley seed was 29.19 mm^3, whereas Guner (2007) found out that the volume of barley seed was 38.37 mm^3. One thousand seed mass value of barley was obtained as 30.17 g, while Guner (2007), and Dursun and Guner (2003) reported that higher values of 38.18 and 43 g, respectively. The bulk density, actual density and porosity of corn seeds at 10.55% (w.b.) are 1, 0.88 and 0.87 times the barley seeds at 5.97% (w.b.). The bulk density, actual density and porosity of barley were found to be 648, 1297 kg m^{-3} and 50.03%, respectively; whereas Guner (2007) reported values of 684, 995 kg m^{-3} and 31.25%, respectively. The bulk density of corn was 650 kg m^{-3}, whilst Guiney et al. (2002) reported the value of 778 kg m^{-3}.

The effect of air velocity (without seeds and with seeds) on pressure drop is presented in Figure 3. The pressure drop for air only, increased directly with the air velocity. This is in agreement with results obtained by Guner (2007). The pressure drop during the conveying seeds was first slightly decreased; then there was a turning point at which the pressure drop increased rapidly with an increase in air velocity. The lowest pressure drop for corn and barley occurred at the air velocity of 20 and 15 m s^{-1}, respectively. Our observations showed that at air velocity below the turning point, the material flow was in a dense phase and the material conveyed in a layer along the bottom of pipeline. At high air velocities (30 to 40 m s^{-1}), the seeds were distributed evenly and moved in suspension above the strand in the pipe and the material

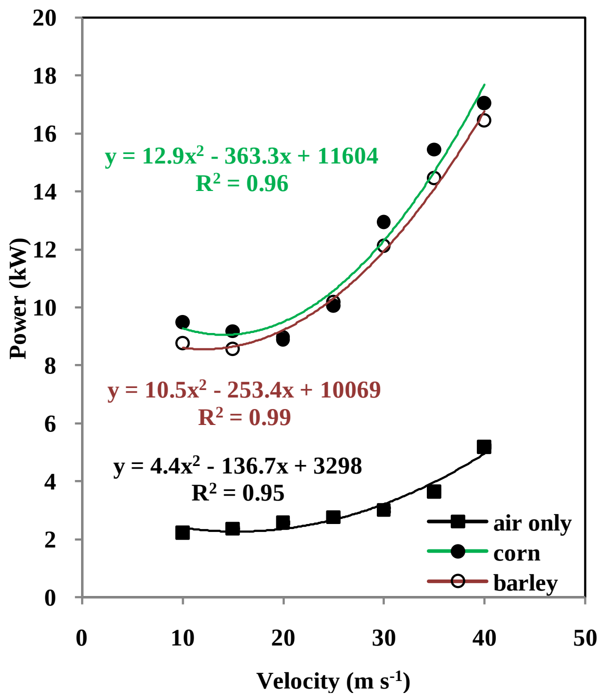

Figure 4. Effect of air velocity on the power consumption at the conveying capacity of 15 ton h^{-1} seed, pipe with 15 m long and 15.25 cm inside diameter.

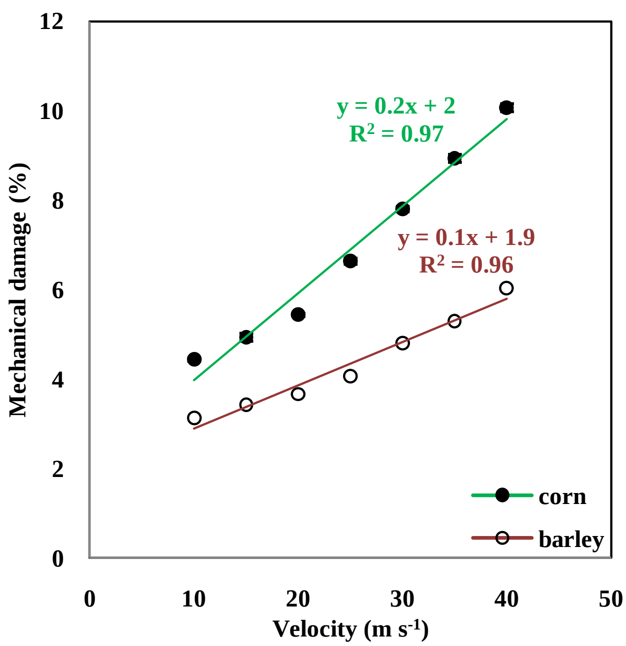

Figure 5. Effect of air velocity on mechanical damage to the seeds at the conveying capacity of 15 ton h^{-1} seed, pipe with 15 m long and 15.25 cm inside diameter.

flow was in a dilute phase. With increasing speed from 20 to 25 m s^{-1} for corn and 15 to 20 m s^{-1} for barley, there was a mixture of dense and dilute phase which is called the unstable zone. Conveying state in this zone changes between the suspension flow and strand. This is in agreement with results obtained by Jaworski and Dyakowski (2002) and Zhu et al. (2004). The suspended seeds impinging the strand will slow down to the strand velocity and be expelled from the suspension. Other seeds will be knocked out from the strand and accelerated by the air to the same velocity of the air in the suspension. Similar results have been reported by Wypych and Yi (2003) and Guiney et al. (2002).

The effect of air velocity (without seeds and with seeds) on the power consumption is shown in Figure 4. As can be seen, the power consumption for conveying seeds was at least 4 times the air only and was greatly influenced by the air velocity than the air only. It is logical that an increase in the pressure drop resulted in an increase in the power consumption. Similar results have been reported by Zhang et al. (2010). The effect of seed type on power consumption was not significant and the trend of change in power consumption for corn was similar to barley. The effect of air velocity on the mechanical damage is shown in Figure 5. The mechanical damage to the seeds increased linearly as the air velocity increased. The results are in agreement with the ones obtained by Guner (2007). The results showed that the damage is less for barley as compared to corn. According to impact equation, the impact force is related to body mass that impacts to a surface. Mass of a corn seed is more than barley, so the damage is more intensive for corn as compared to the barley. With an increase in air velocity from 10 to 40 m s^{-1}, the increase in mechanical damage for corn and barley varied from 4.4 and 3.1% to 10 and 6%, respectively.

With an increase in air velocity, the intensity of the material colliding with each other and the internal pipe surface, bends and cyclone surfaces will be increased; therefore, the mechanical damage to the seeds will increase as well. Then, the air velocity must therefore be regarded as a most critical factor in determining whether damage will occur or not. It is desirable, therefore, to work the lowest possible air velocity to keep the mechanical damage as low as possible, if we are conveying the seed used for planting. But the danger of blockage should be taken into consideration because the blockages can occur when the energy of air flow is insufficient to keep up the conveying process.

Conclusions

The results of this research can be summarized as follows:

1. When air alone was flowing through the developed conveying system, pressure drop increased with an increase in air velocity. The power requirement of pneumatic conveyor was also affected by air velocity;

2. The results indicated that there was a quadratic relation between the pressure drop as well as power consumption with the air velocity for corn seeds. The power consumption during the conveying seeds was first slightly decreased; then there was a turning point at which the power consumption increased rapidly with an increase in air velocity;
3. Most of the power consumption is due to seed moving in suspension mode;
4. Mechanical damage of seeds increased linearly as the air velocity increased;
5. The material flow in pneumatic conveying through a horizontal pipeline can exhibit one of three main flow modes: dense phase that the material convey in a layer along the bottom of the pipeline, dilute phase that material moves evenly in suspension above the strand in the pipe and mixture of dense and dilute phase which is called the unstable zone;
6. With change in flow pattern from dense to dilute phase, the pressure losses was increased due to acceleration and lift of the seeds;
7. The air velocity is an important critical factor in determining the power consumption and mechanical damage. Therefore, for reducing the power consumption and mechanical damage to the seeds, the air velocity in the developed pneumatic conveying must be decreased as long as the conveying capacity of the system is acceptable.

This study has answered several important questions about mechanical damage and power consumption in pneumatic conveying systems. However, several important areas require more extensive study. The effect of system length and elbows should be studied. Damage caused by the airlock feeder should be evaluated separately from damage caused by acceleration and deceleration of the seed. Mechanical damage and power consumption resulting from the use of pneumatic systems on other grains should be evaluated.

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