Aerodynamic Properties of Wheat Kernel and Straw Materials

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ABSTRACT

Terminal velocity and drag coefficient of wheat kernel and straw materials (Canadian variety) have been experimentally measured by suspending the particles in an air stream. The effects of mass and moisture content of wheat kernel, node position and length of straw on terminal velocity were studied. The results showed that mass and moisture content have significant effects ($p<0.01$) on terminal velocity. By increasing mass of the kernel from 0.02 to 0.05 g and moisture content from 7 to 20 %(w.b.), its terminal velocity increased linearly from 7.04 to 7.74 m/s and 6.81 to 8.63 m/s, respectively. Drag coefficient of the wheat sample (0,96) showed this kernel was similar to a cylinder in an air stream. The terminal velocity of the straws with different node positions (node free, end node, and central node) and lengths (1 to 10 cm) were measured from 2.53 to 4.85 m/s. Terminal velocity increased by increasing length from 1 to 2 cm and decreased by increasing length from 2 to 10 cm. The results showed that terminal velocity and drag coefficient of wheat straw depended on node position and the end node position had the highest terminal velocity and the lowest resistant coefficient. For air separation of Canadian wheat and straw, the air flow should be less than 7.04 m/s and more than 4.85 m/s.

Keywords: Aerodynamic properties, terminal velocity, drag coefficient, wheat, straw

1. INTRODUCTION

Undesirable materials such as light grains, weed seeds, chaff, plant leaves and stalks can be removed with air flow, when grains, fruits and vegetables are mechanically harvested. In addition, agricultural materials are routinely conveyed using air stream in pneumatic conveyers. If these systems are not used properly, they could cause problems. For example, in a combine harvester, if the air speed is low, the materials would not be separated from each other and there will be extra foreign material with the product. If air speed is high, the product will be exhausted along with extra material and product loss will increase. For conveying agricultural material, the range of proper air streams should be used. With low air speed, there is stagnation in the system, or with high air speed, there is not only energy lost, but also grains may be broken.

The proper air speed can be determined from aerodynamic properties of agricultural materials. These properties are terminal velocity and drag coefficient. If an object is dropped from a sufficient height, the force of gravity will accelerate it until the drag force exerted by the air, balances the gravitational force. It will then fall at a constant velocity called the terminal velocity (Mohsenin, 1970):

$$M.g = \tfrac{1}{2}\rho.V_t^{\,2}.C_d.A \qquad (1)$$

Where, M is mass of the object (kg), g is gravitational acceleration (m/s^2), C_d is drag coefficient, ρ is air density (kg/m^3), A is projected area (m^2), and V_t is terminal velocity (m/s). From this equation, the drag coefficient of an object can be found from its terminal velocity:

$$C_d = \frac{2M.g}{\rho.V_t^{\,2}.A} \qquad (2)$$

Usually, a horizontal wind tunnel is used to measure drag coefficient of large objects. In this method, external parameters such as size and velocity are varied and values of drag coefficient are obtained over a wide range of Reynolds number. But for small particles (like grain seeds), the drag force cannot be measured directly by this method. So drag coefficient of agricultural materials are calculated from their terminal velocity (Eq.2) which is experimentally measured.

Carman (1996) measured the terminal velocity of lentil seeds at different moisture contents by free fall method. From the top of a dropping tube at various heights, a seed was allowed to fall. The duration of the fall was plotted as a function of vertical distance. The slope of the linear portion of the distance versus time curve indicated the terminal velocity of the seed. He found that as the moisture content of the lentil seed increased, its terminal velocity also increased linearly.

In another experimental method, a vertical wind tunnel is used for finding the suspension velocities of the particles in an air stream. Bilanski and Lal (1965) measured terminal velocities of wheat kernel and straw by a vertical wind tunnel. They found that the terminal velocity of the wheat kernel was between 8.8 and 9.2 m/s. The results showed that the straw with less than 6 cm length had the highest terminal velocity (4.9 m/s). Also they noticed that wheat and straw did not show a constant and stable behavior in air streams, because of their different shapes and densities. The terminal velocity of the Olympic wheat kernel was measured from 7.5 to 8.5 m/s by the wind tunnel floating technique (Shellard and Macmillan, 1978). Also the aerodynamic properties of a wide range of grains and straws were experimentally measured by finding the suspension velocities of the particles in an air stream (Gorial and O’Callaghan, 1990). The drag coefficient of grains, which is a function of Reynolds number, lay within the limits of a sphere (0.44) and of a cylinder (1.0) depending on the shape of the grain. The drag coefficient of straw was approximately 1.0, similar to a cylinder. The terminal velocity and drag coefficient of wheat kernel with 30.2 mg mass were reported 7.8 m/s and 0.85, respectively.

The purpose of this study was to measure the terminal velocity of wheat and straw materials in order to find the effects of mass and moisture content of wheat kernel, node position and length of straw on terminal velocity.

2. MATERIAL AND METHODS

2.1 Sample Preparation

The wheat and straw samples were selected from the Canadian variety, which is usually planted in the Khorasan province of Iran. The straws had a length of 10 to 100 mm with three different node position groups: node free, central node and end node. The means of mass (M) and diameter (D) of the straw samples (means of 5 samples in each group) are given in Table1.

Table 1. Specification of straw samples

Length (mm)	Node free		End node		Central node	
	M	D	M	D	M	D
10	0.028	3.69	0.063	4.16	0.07	3.69
20	0.068	3.83	0.14	4.07	0.16	3.57
40	0.098	3.86	0.17	4.34	0.118	4.06
60	0.242	3.87	0.284	4.26	0.266	3.42
80	0.216	3.43	0.406	4.18	0.325	3.7
100	0.308	3.73	0.51	4.04	0.32	3.67

M= mass (g) D= diameter (mm)

Five portions, each of 1 kg mass, were taken from different bulks of wheat kernel. These samples were mixed and from the mixture, three portions of 1 kg each were randomly taken. The samples were cleaned to remove foreign material and broken seeds and placed in three bags. From each bag, 300 seeds were picked randomly. Then all 900 seeds were mixed and 300 seed samples were randomly picked (Tabak and Wolf, 1998). The samples were weighed with an electronic balance capable of reading to 0.001 g (A&D, GF-400). They varied between 0.02 g and 0.05 g, so the masses of the kernel samples were divided into 3 fractions in steps of 0.01 g (0.02-0.03, 0.03-0.04 and 0.04-0.05 g). From each fraction 20 seeds were selected randomly.

The initial moisture content of the samples was 9.8% (d.b.). The density of the wheat kernel samples was 1267.02 kg/m^3 which were measured by the fluid (Toluene) displacement method (Mohsenin, 1970) with three replications. The volume of the seed kernel was calculated from its mass and density. Sphere diameter of equivalent volume of the samples was calculated. This diameter was used to calculate the projected area. After measuring terminal velocity of the samples, their drag coefficients were calculated from Eq. 2.

To study the effect of moisture content on wheat kernels, the samples were prepared at different moisture contents. Because most of the samples were in the mass fraction of 0.03 to 0.04 g, so this fraction was used for this part of the experiment. The required quantity of the wheat samples were soaked in distilled water for about 20 min. After soaking, they were allowed to equilibrate for about 24 h; they were lightly dabbed with blotting paper to remove surface water (Suthar and Das, 1996). The samples were dried in an oven at 90 °C for different periods to achieve seed moisture contents within the range of 7-20%. The final moisture content of the samples was determined using standard methods with an oven temperature of 130 °C for about 19 h (ASAE, 1999). By this method the wheat samples were prepared at 7.1, 13.8 and 20% (d.b.) moisture content.

2.2 Terminal Vlocity and Dag Coefficient Measurement

To measure the terminal velocity of the samples, a vertical wind tunnel was designed and fabricated based on the standard method which was used by Tabak and Wolf (1998) to measure aerodynamic properties of cottonseeds (Fig. 1). The square test section (W) was constructed with the dimension of 200 mm by 400 mm. The wind tunnel had a diffuser (A), with the wall inclined to the axes of the tunnel at an angle of 3°. Its length was five times bigger than the square test section (100 cm) and it was made of Plexiglas so that the suspended seeds could be seen from the outside. For measuring the terminal velocity of a particle, an equilibrium velocity field was required in the cross sections of the tunnel, where particles were suspended. To prevent the samples from falling into the bottom section, a net wire (B) with a size of 18 mesh (18M) was placed in the upstream end of the test section (W). The sample was loaded on this wire net through a hatch with a lid (C). The wind tunnel had an axial fan (D) driven by a 550 W a.c. motor. A flexible section (E) was used to avoid vibration in the wind tunnel. The velocity of the airflow in the wind tunnel was regulated by a diaphragm (F). A section, which consists of five layers of fine wire net screens (G), three layer of 50M and two layer of 40M mesh screens (G) with along honeycombs (H) were used to straighten the flow and reduce the turbulence. The nozzle (I) had the function of accelerating the low-speed air of the fan. Also it increased the uniformity of the air velocity in the test section. A hot-wire anemometer was used to measure air velocity in the test section. Based on the continuity flow law, the air velocity in different sections of the diffuser (A) was calculated from air velocity in the test section.

To measure terminal velocity, first the sample was loaded on the screen (B). Then the fan was turned on and the diaphragm was adjusted until the sample was suspended in the diffuser. The height of suspension was recorded and then the air velocity at that suspension point was calculated as terminal velocity (V_t). After measuring V_t, the drag coefficient (C_d) of the wheat kernel was calculated from Eq. 2, based on mass and equivalent diameter (Table 2). Because of unstable behavior of the straw samples in the wind tunnel, there was no specific frontal area of straw in the air stream. Therefore, instead of calculating C_d, the multiplication of C_d and A was calculated as resistance coefficient (Shellard and Macmillan, 1978).

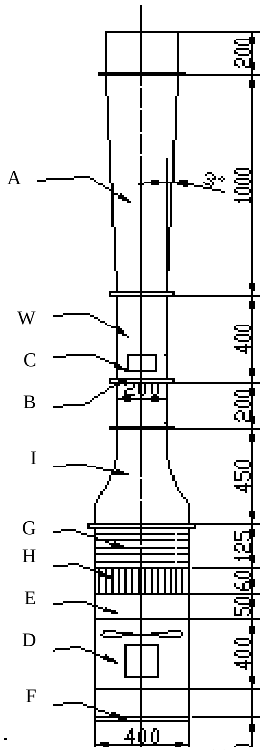

Figure 1. Cross section of vertical wined tunnel. (A) diffuser; (B) wire net; (C) lid hatch; (D) axial fan; (E) flexible section; (F) diaphragm; (G) mesh screens; (H) honeycomb; (I) nozzle; (W) support section

3. RESULTS AND DISCUSSION

3.1 The Effect of Wheat Mass on Terminal Velocity

The results of measured equivalent diameter (D_e), terminal velocity (V_t), calculated drag coefficient (C_d) and Reynolds number (R_N) of the wheat samples at the moisture content of 9.8% (w.b.) and different mass groups are given in Table 2. By increasing the mass of the kernel, its terminal velocity was increased. This result can be proved by Eq.1, that V_t has a direct relation with mass. Mass of kernel had significant effect ($p<0.01$) on terminal velocity (Table 3). The following linear relation ship between V_t and mass was found:

$$V_t = 35m + 6.1417 \qquad R^2 = 0.99 \qquad (3)$$

Where, V_t is terminal velocity (m/s) and m is mass (g). Table 4 shows the range of wheat kernel terminal velocity which was measured by other researchers. None of them had the same variety (Canadian) and moisture content (9.8%) of this study so the differences can vary in the size and density of the kernels.

3.2 The Effect of Moisture on Terminal Velocity

The results of analysis of variance (Table 5) showed that moisture content has significant effect ($p<0.01$) on wheat terminal velocity. Fig. 2 shows the effect of wheat moisture content on terminal velocity. By increasing moisture content from 7 to 20%, the terminal velocity was increased linearly from 6.81 to 8.63 m/s. This result was the same as found by other researchers for some other agricultural material (Tabak and Wolf, 1998; Gupta and Das,1997;

Suthar and Das, 1996; Carman, 1996). The reason for increasing terminal velocity by moisture content was because of increasing the kernel mass (Eq. 1). The linear equation of terminal velocity vs. moisture content was found as following:

$$V_t = 14.371MC + 5.9451 \qquad R^2=0.9 \qquad (4)$$

Where, *MC* is moisture content in decimal wet basis.

Table 2. Mean of aerodynamic properties of wheat samples at different mass groups (9.8% d.b. moisture content)

Properties	Mass groups (g)		
	0.02-0.03	0.03-0.04	0.04-0.05
D_e, mm	3.35	3.75	4.07
V_t, m/s	7.04	7.32	7.74
C_d	0.88	0.99	1.01
R_N	1615	1879	2157

Table 3. ANOVA table of wheat kernel mass

Source of Variation	df	Sum of Squares	Mean Square	F	Sig.
Mass	2	4.364	2.182	52.298	.000
Error	57	2.378	4.172E-02		
Total	60	3286.129			

Table 4. Measured wheat terminal velocity by different researchers

Gorial and O'Callaghan (1990)	Uhl and Lamp (1966)	Bilanski and Lal (1965)	Shellard and Macmillan (1978)
6.5-10	5.7-9	8.8-9.2	7.5-8.5

Table 5. ANOVA table of wheat kernel moisture content

Source of Variation	df	Sum of Squares	Mean Square	F	Sig.
Moisture	3	42.641	14.214	217.676	.000
Error	76	4.963	6.530E-02		
Total	80	4888.009			

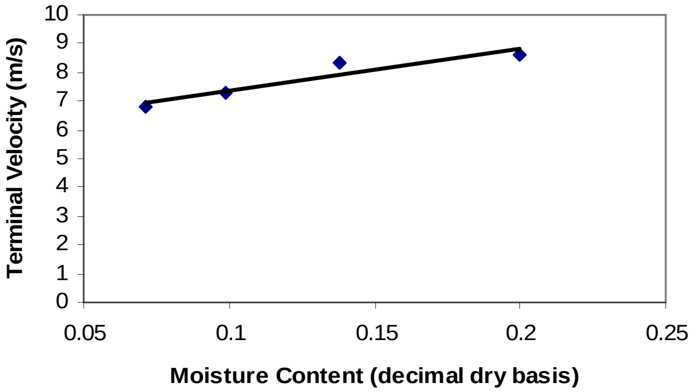

Figure 2. The effect of moisture content on terminal velocity of wheat kernel

3.3 The Calculation of Wheat Drag Coefficient

Drag coefficient of sphere and cylinder at the range of Reynolds number from 1000 to 3000 is 0.44 and 1, respectively (Fox and Macdonald, 1998). As the result in Table 2 shows, the mean of wheat kernel drag coefficient was 0.96, so it can be assumed that the wheat sample is similar to a cylinder in shape. Therefore, by calculating Reynolds number, drag coefficient of wheat kernel can be predicted from the curve C_d vs. R_N of the cylinder shape (Mohsenin, 1970)

3.4 Terminal Velocity and Resistance Coefficient of Wheat Straw

The results of measured terminal velocity of wheat straw at different lengths and node situations are given in Fig. 3. The maximum terminal velocity was for the 2 cm straw samples with end and central node position. By increasing straw length from 1 to 2 cm, for all the samples with different node positions, their terminal velocities increased. Because in this range, the effect of increasing the mass was more than that of increasing projected area (Eq. 1). But from 2 to 10 cm, the opposite result was obtained which may be due to the effect of increasing projected area. The straws with the node on the end had the highest V_t. This maybe caused by transferring the gravity from center to the end which caused it to float vertically within the air stream. In this case, V_t was increased because of decreasing the effective projected area in Eq. 1.

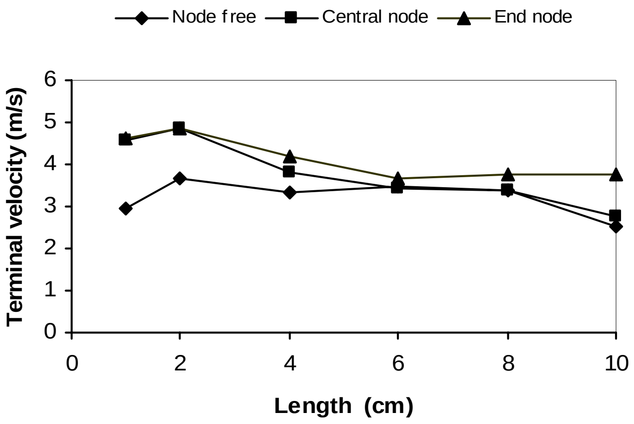

Figure 3. The effect of length and node positions on terminal velocity of wheat straw

Fig. 4 shows the resistance coefficients (A.C_d) for straw samples at various lengths and node positions. The node free straws had the highest and end node had the lowest resistance coefficients. It can also be seen that there was almost a linear relationship between the resistance coefficient and straw length.

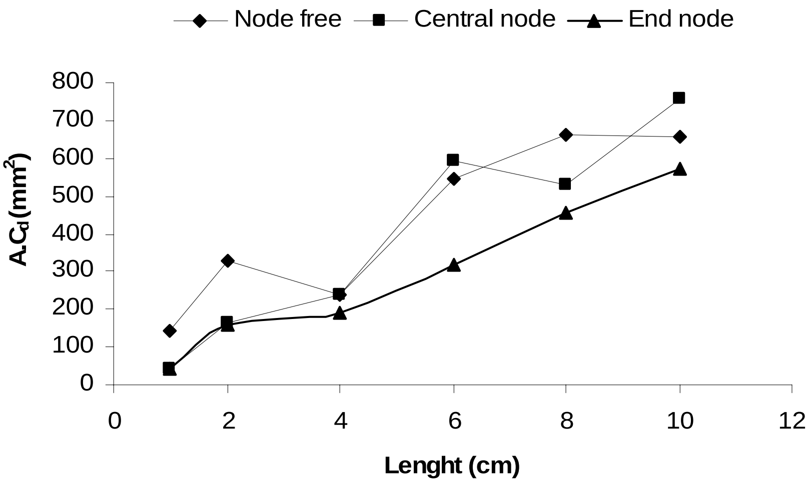

Figure 4. The resistance coefficient (A.C_d) of wheat straw as affected by length and node positions

4. CONCLUSIONS

The following conclusions can be drawn from the experiments:

- By increasing the mass of the kernel from 0.02 to 0.05 g and moisture content from 7 to 20% (w.b.), its terminal velocity increased linearly from 7.04 to 7.74 m/s and 6.81 to 8.63 m/s, respectively.
- Wheat kernel drag coefficient was 0.96, so it can be assumed that wheat is similar to a cylinder in an air stream.
- Terminal velocity and drag coefficient of wheat straw depended on node position and end node position had the highest terminal velocity and the lowest resistant coefficient.
- Because the minimum terminal velocity of wheat samples was 7.04 m/s and the maximum terminal velocity of wheat straws was 4.85 m/s, for air separation of Canadian wheat and straw, the air flow should be between 4.85 and 7.04 m/s.

5. ACKNOWLEDGMENTS

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