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Terminal Velocity Determination for Component Separation of Biomass

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Abstract. Biomass processors request a technology that will separate node and internode segments so to enhance the end product or overcome production cost. Separation techniques that take advantage of density and aerodynamic differences use pneumatic methods that segregate by terminal velocity as in the case of classifiers and cyclones.

The objectives are to 1) determine terminal velocity differences between node and internode biomass segments of comparable diameter and volume, 2) evaluate the effects of switchgrass particle length and moisture content on terminal velocity of nodes and internodes, and 3) evaluate the effects of corn stalk pith, rind, and moisture content on terminal velocity of nodes and internodes.

Theoretical terminal velocity values for segment properties were calculated using equations published by Mohsenin in 1970. An experimental wind tunnel constructed vertically provided a means to directly measure terminal velocity. Calculated values are compared to measured results from the testing station. This comparison is then subjected to statistical analysis to define the difference between node and internode segments.

The proposed research will benefit the biomass processing industries by providing data that can be used to model for other botanical plant part separations in an area where resources are limited in the terminal velocity of segmented biomass. Only with a defined difference in segmented biomass can effective separation occur.

Keywords. Biomass, separation, node, internode, terminal velocity.

Introduction

Biomass processors request a technology that will separate node and internode segments so to enhance the end product or overcome production cost. Node and internode segments generally have similar properties except for the characteristics of density and surface smoothness. Separation techniques that take advantage of density and aerodynamic differences use pneumatic methods that segregate by terminal velocity as in the case of classifiers and cyclones.

Six physical separation principles that are currently used in biomass processing were reviewed so that the best method for separating biomass components could be selected. The principles included threshing which separates by a material's reaction to impact, vibratory which separates by a material's shape or surface texture, refiner which separates by a material's reaction to rubbing, electronic identification which separates by a material's appearance, hydrodynamic which separates by a material's buoyancy, and pneumatic which separates by material's behavior to air flow. Pneumatic separation has advantages over each of the other principles. Shattering of the material is at a minimal, unlike in threshing practices. Pneumatic methods can separate material of comparable shapes and surface textures, unlike in vibratory applications. Friction acting on the material is minimal, unlike refiner techniques. Pneumatic separation is not reliant on electronics that are sensitive to dust or grimy field conditions. And unlike hydrodynamic principles, the material is not subject to added moisture.

Rautiainen et al. (1999) defined pneumatic conveying as a "method of transportation of granular solids in a pipeline using a gas stream." When fractionated segments are conveyed in an air stream, terminal velocity is the basis of separation (Grochowicz 1980; Mohsenin 1986). The term *terminal velocity* was described simply by Jackson et al. (1996) as the "velocity of air that will suspend a given object." Grochowicz (1980) and Mohsenin (1986) stated more detail by saying "terminal velocity is equivalent to the velocity of a vertical air stream which ensures equilibrium between the weight… and upward force of air stream."

The biomass material selection criteria was based on the samples having sections that could clearing be defined as node or internode and the availability of samples. The biomass studied included wheat straw, switchgrass, and corn stalk.

The objectives of this study were to: 1) determine terminal velocity differences between node and internode biomass segments of comparable diameter and volume for switchgrass, wheat straw, and corn stalks, 2) evaluate the effects of switchgrass particle length and moisture content on terminal velocity differences between nodes and internodes, and 3) evaluate the effects of corn stalk pith, rind, and moisture content on terminal velocity differences between nodes and internodes.

Material and Methods

Samples

Dry wheat straw was cut into 1.27cm lengths. Dry and wet switchgrass was cut into 0.635cm, 1.27cm, and 2.54cm lengths. All corn samples were cut into 1.27cm lengths. For each biomass, there were samples of node and internodes. Each biomass group had nodes and internodes that were similar in diameter, length, and shape. This was measured so to have nodes and internodes of the same apparent volume. With the samples having the same volume, nodes of similar weight and internodes of similar weight made the final selection. In the case of switchgrass, three volumes were used. Wheat and switchgrass produced samples that were cylindrical in shape. Corn samples provided a different challenge due to its size. In order to be comparable to the switchgrass and wheat, the corn was cut into small chunks that had the same length, end area, and volume. The dimensions of the chunks were as close to the cylindrical shaped, however corn chunks appear more rectangular. Table 1charts the sample matrix.

Table 1. Sample Categories.

Biomass	Moisture Level	Length (cm)
Wheat Straw	Dry	1.27
Switchgrass	Dry	0.635, 1.27, & 2.54
	Wet	
Corn Pith	Dry	1.27
	Wet	
Corn Rind	Dry	1.27
	Wet	

The samples were hand cut and uniformity of the samples was stressed so that there would be the least amount of variability in the factors that contribute to terminal velocity. In real world applications, achieving crisp cuts on the ends of the biomass segments may prove tedious, though not impossible. It is unsure how the effects of jagged or tattered edges will play on the terminal velocity. This study represents the “best-case scenario” of segmentation of particles and the doorway to more research needs.

Theoretical Basis

Because the behavior of the biomass in a vertical wind tunnel was theoretical at best, two equations were selected to calculate terminal velocity, one for a cylindrical shape and one for a spherical shape. For spherical particles, theoretical terminal velocity was calculated as:

$$V_t = \sqrt{\frac{4\ g\ d_p\ (\rho_p - \rho_f)}{3\ Cd\ \rho_f}} \qquad \text{Equation 1}$$

Where: V_t = Terminal velocity (*m/s*)
g = Acceleration due to gravity = 9.8 m/s^2
d_p = Particle diameter (*m*)
ρ_f = Density of fluid = 1.205 kg/m^3 air at 1 $_{ATM}$ at 20°C (TETB, 2005)
ρ_p = Density of particle (kg/m^3)
Cd = Drag coefficient = 0.44 (Mohsenin, 1970)

For cylindrical particles, theoretical terminal velocity was calculated as:

$$V_t = \sqrt{\frac{g\ d_p\ \pi\ (\rho_p - \rho_f)}{2\ Cd\ \rho_f}} \qquad \text{Equation 2}$$

Where: V_t = Terminal velocity (*m/s*)
g = Acceleration due to gravity = 9.8 m/s^2
d_p = Particle diameter (*m*)

ρ_f = Density of fluid = 1.205 kg/m^3 air at 1 $_{ATM}$ at 20°C (TETB, 2005)
ρ_p = Density of particle (kg/m^3)
Cd = Drag coefficient = 1.20 (Mohsenin, 1970)

Once the samples were cut, measured, and culled for uniformity, the diameters and particle densities were plug into both sets of equations. An interesting query surfaced when calculating the particle densities. Should the density be calculated using the particle's apparent density or the particle's true density? The apparent density uses the outer volume of the segment, where the true density uses the outer volume minus the inner volume of the segment. Since wheat straw and switchgrass have hollow cores, two sets of densities were calculated and both sets were subjected to the two equations.

Equipment

The Terminal Velocity Testing Station (TVTS) was the machine developed to evaluate terminal velocity of stalk biomass. Figure 1 shows the schematic of the TVTS. It consists of a motorized blower fan, ductwork with damper, accessible plenum chamber, and a vertically mounted 3.05m clear PVC, 25.4cm diameter pipe with in-path straighteners.

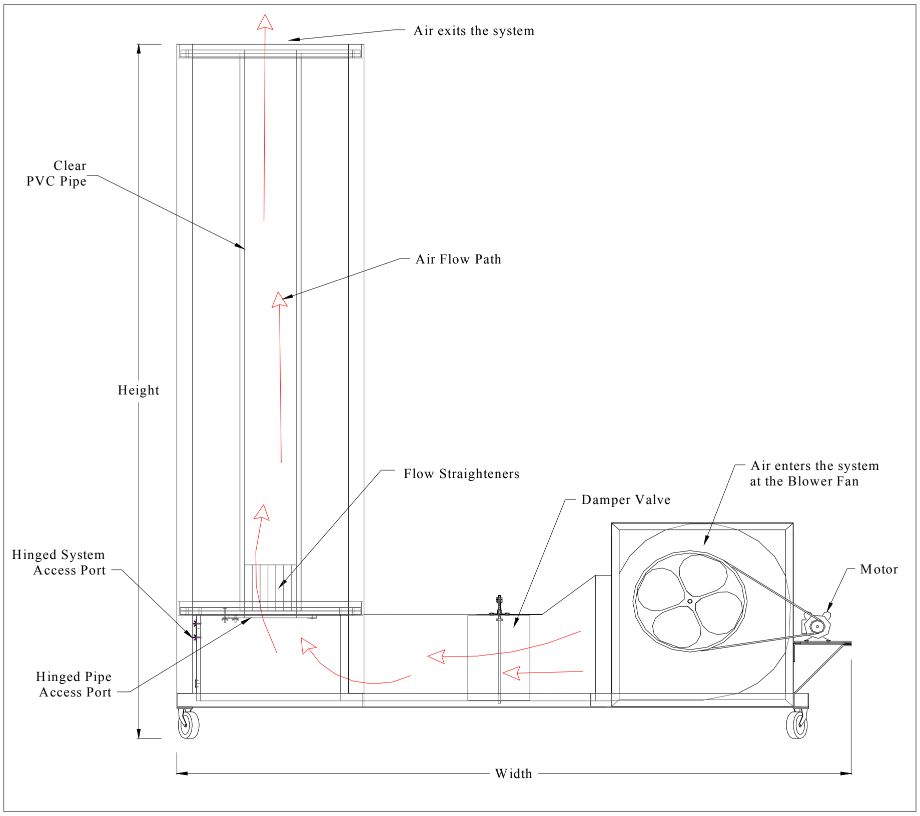

Figure 1. Schematic of the Terminal Velocity Testing Station, height = 3.81m, width = 3.35m, and inner pipe diameter = 25.4cm.

The airflow provided by the fan is directed to the plenum chamber through a section of duct work. This section houses a butterfly valve that is able to be adjusted and locked into a desired setting. The plenum chamber has two openings, an access panel into the chamber and a second port that allows access to the clear pipe. The second port has a screened opening that matches the 25.4cm diameter of the pipe. This port is simply a sample tray that fastens below the in-path straighteners. Once a sample is ready on the screen, the second port and access panel are shut to close the system. At the top of the pipe, the capping board also has a screened opening that matches the pipe diameter, thus opening the system to atmospheric pressure but not allowing the samples to escape.

The Reynolds number for the lowest speed and highest speed was calculated and illustrate that the flow at both is turbulent as defined by Mohsenin (1970) as the region where the Reynolds number is between 10,000 and 200,000. The Reynolds number is necessary for determining the drag coefficient (*Cd*) and thus the appropriate equation to use for calculating terminal velocity (V_t).

A ping pong ball was used to test the TVTS. Before the in-path straighteners, a ping pong ball placed inside the pipe would rotate rapidly while maintaining constant contact with the inner wall. This cyclonic action had to be prevented and the helix airflow had to be straightened in order to decrease wall interaction. When the ping pong ball was tested, there was still a depression in the airflow. However, the ball's contact with the pipe wall was minimal. The ball no longer spiraled around the edges, but instead bobbed vertically. Each time it came above the depression area at the source of the flow, it would descend and ascend once it came into the path of the faster current. The distance between the lowest descent point and the highest ascent point of the bobbing action could be decreased by decreasing the airflow. However, if the airflow was decreased too much, the ping pong ball would cease bobbing and simply descend. If the airflow was increased too much, the ball would ascend.

A hot wire anemometer was selected to measure air velocity. Nine locations at the top of the station where the pipe exhaust was where velocity readings were gathered. Since the diameter of the tube is the same from bottom to top, it is assumed that the air readings are the same through out the system.

With success of the ping pong ball test, biomass samples were tested one segment at a time. The segment, both node and internode, would exhibit the bobbing behavior just as the ball had done and with minimal wall interaction. However, the cylindrical particle rotated rapidly enough that if a slow-shutter speed camera took a photo, the particle would appear to be a sphere. Readings were gathered once the airflow was set at a speed that demonstrated the least bobbing behavior and observed over a few minutes not to ascend or descend the sample. Five readings were recorded for each of the nine locations and the 45 entries were averaged to give the terminal velocity. Terminal velocities were recorded in this manner for each of the biomass groups. The data gathered from the TVTS was subjected to statistical analyst done using SAS (2002).

Results

The TVTS terminal velocity results for the three biomass groups were compared to the four calculated results: spherical object terminal velocity calculated with the apparent particle density, spherical object terminal velocity calculated with the true particle density, cylindrical object terminal velocity calculated with the apparent particle density, and cylindrical object terminal velocity calculated with the true particle density. When only the calculated results were compared, there was a large difference between the apparent density and true density and a noticeable difference between spherical and cylindrical. The calculated results were the most comparable to the spherical object terminal velocity calculated with the apparent particle density. The airflow “saw” the segments as solid spherical objects. The reason being because the openings on the ends of the segments where perhaps too small for influential airflow to pass, so the segment acted solid instead of hollow. The spherical detection can perhaps be connected to the observation where the biomass spins rapidly enough to be a round.

Table 2 displays the TVTS readings compared to the solid spherical object calculations. The results illustrate that the TVTS provides satisfactory data to apply to the equation for a spherical object terminal velocity given by Mohsenin (1970).

Table 2. Terminal Velocities for the Combinations of the Three Biomass Groups.

Biomass	Location	Vt Readings from the TVTS (m/s)	Std. Dev.	Vt Calculated for Spherical Object (m/s)	Std. Dev.
1.27cm Dry Wheat Straw	Node	4.91	0.18	4.92	0.20
	Internode	3.35	0.16	3.37	0.15
2.54cm Dry Switchgrass	Node	6.59	0.22	6.61	0.22
	Internode	5.07	0.32	5.10	0.31
2.54cm Wet Switchgrass	Node	8.43	0.39	8.50	0.39
	Internode	5.93	0.40	5.99	0.39
1.27cm Dry Switchgrass	Node	7.50	0.33	7.58	0.31
	Internode	5.53	0.14	5.59	0.18
1.27cm Wet Switchgrass	Node	8.50	0.23	8.54	0.25
	Internode	6.23	0.31	6.29	0.30
0.635cm Dry Switchgrass	Node	7.58	0.23	7.60	0.22
	Internode	5.41	0.10	5.44	0.10
0.635cm Wet Switchgrass	Node	9.62	0.30	9.67	0.30
	Internode	5.92	0.27	5.95	0.26
1.27cm Dry Corn Pith	Node	4.01	1.09	3.72	0.32
	Internode	2.84	0.12	2.87	0.13
1.27cm Dry Corn Rind	Node	6.93	0.33	6.96	0.32
	Internode	5.83	0.15	5.87	0.15
1.27cm Wet Corn Pith	Node	7.51	0.41	7.54	0.41
	Internode	3.11	0.38	3.13	0.39
1.27cm Wet Corn Rind	Node	7.74	0.34	7.76	0.34
	Internode	7.63	0.29	7.66	0.29

Results of the difference in terminal velocity of biomass nodes and internodes is essential for pneumatic separation applications. Table 3 summarizes percentage difference between nodes and internodes of each biomass group. In each group, nodes prove to have greater terminal velocities than internodes, however the percent difference of wet corn rind segments is slight. The effects of length and moisture content on switchgrass terminal velocity are illustrated in

Table 2 and 3. Switchgrass segments of shorter length and higher moisture content display the greater difference in terminal velocity between node and internode. Interestingly, the 1.27cm cut segments of both dry and wet groups had a close percentage of difference. The effects of corn stalk pith and rind locations and the moisture content on terminal velocity. Wet corn pith locations show the greatest percent of difference with the node segments being 141.5% greater than internode segments.

Table 3. Percent Terminal Velocity Difference between Node and Internode.

Biomass	% Terminal Velocity Difference
1.27cm Dry Wheat Straw	Node is 46.57% Greater
2.54cm Dry Switchgrass	Node is 29.98% Greater
2.54cm Wet Switchgrass	Node is 42.16% Greater
1.27cm Dry Switchgrass	Node is 35.62% Greater
1.27cm Wet Switchgrass	Node is 36.44% Greater
0.635cm Dry Switchgrass	Node is 40.11% Greater
0.635cm Wet Switchgrass	Node is 62.50% Greater
1.27cm Dry Corn Pith	Node is 41.20% Greater
1.27cm Dry Corn Rind	Node is 18.87% Greater
1.27cm Wet Corn Pith	Node is 141.48% Greater
1.27cm Wet Corn Rind	Node is 1.44% Greater

Conclusion

Switchgrass with a high moisture content (52% w. b.) that was cut into 0.635cm segments had greater terminal velocity differences between node and internode sections. Corn pith with a high moisture content (43% w. b.) had greater node and internode terminal velocity difference than corn rind.

The research reported herein should benefit the biomass processing industries by providing data that can be used to model botanical plant part separations. Future study along the confines of this research may involve other biomass species, varying levels of moisture content, and/or the effects of not-so-clean-cut edges.

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