1998

DESIGN OF TAPERED AUGERS FOR UNIFORM UNLOADING PARTICULATE MATERIAL FROM RECTANGULAR CROSS-SECTION CONTAINERS

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ABSTRACT. *The design equation for an auger to provide uniform unloading of particulate material from a container with a rectangular cross-section (Jones and Kocher, 1995) was revised to account for the minimum flighting height that could effectively unload particles with a known average smallest diameter. A minimum flighting height that was about 64% of the average smallest diameter of the particles was experimentally determined to obtain mean slopes of the top surface of the material not significantly different from zero for screened soybeans. A linear taper that best fit the square root curve for the inside diameter of the auger was determined by minimizing the integral of the squared area differences between the linear taper and the square root curve. The maximum difference between the auger radii as determined with the square root curve and linear taper functions was less than 0.3 mm, significantly less than the 4.7 mm average smallest particle diameter for the screened soybeans used. An auger constructed following this design (linear tapered inside diameter with a minimum flighting height) provided uniform unloading of particulate material from a container with a rectangular cross-section, as evidenced by mean slopes of the top surface of the material being maintained not significantly different from zero, until the top surface dropped to within 30 cm of the top of the auger flighting.*
Keywords. *Auger, Design, Flow patterns, Granular flows, Particulate materials.*

Unloading particulate material from a container with a rectangular cross-section using a conventional screw conveyer (auger) in the bottom of the container causes non-uniform downward movement of the particles being transferred. When transport is the only concern, the non-uniformity is acceptable. However, in some processing operations, such as a continuous-flow grain drying system or a potato processing system, it is advantageous for the particles to have equal residence time while flowing downward through the container. In these applications conventional augers are not well suited for the unloading mechanism.

For an auger in the bottom of a container to provide uniform flow, the auger must be able to accept additional material into the auger along the entire length of the auger. Conventional augers are not designed for this purpose. At each point along the auger there is only enough room to convey material from upstream, which leaves no room to accept additional material from the container. An auger developed to uniformly unload material requires the conveying volume of the auger to increase along its length.

Article was submitted for publication in September 1997; reviewed and approved for publication by the Food & Process Engineering Institute of ASAE in June 1998.

Journal Series No. 12047, Agricultural Research Division, University of Nebraska-Lincoln. Commercial product names are given for description only and do not imply endorsement over similar products.

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The development of design equations for augers to uniformly unload cylindrical containers was first presented by Shivvers (1973). One application for these augers is in unloading round grain bins. Shivver's auger design used a constant pitch and shaft (or root) diameter, with an increasing flighting height (or outside diameter) to create uniform downward flow of the material being conveyed.

Jones and Kocher (1995) developed auger designs for uniformly unloading containers with rectangular cross-sections resulting from a combination of work presented by O'Brien (1965) and Shivvers (1973). O'Brien (1965) used an auger with increasing outside diameter in the bottom of a feed wagon to uniformly mix granular components stored in sequential compartments of the wagon.

The first set of equations developed by Jones and Kocher (1995) was for an auger with uniform outside diameter and pitch, with the inside diameter decreasing down the length of the auger. Decreasing the inside diameter served as the means to increase the conveying volume of the auger, along the length of the auger. Their second set of equations was for an auger with uniform flighting height and inside diameter, with the pitch increasing down the length of the auger. The outside diameter was held constant for both of these auger designs to allow use of a conventional U-trough housing in the bottom of a container with a rectangular cross-section (Jones and Kocher, 1995). The auger design with the decreasing inside diameter was preferred because of the difficulty in constructing the increasing pitch auger flighting and a tendency for particles to lodge in the flighting at the end opposite the outlet, where the flighting pitch was very small.

Tests were performed with a decreasing inside diameter auger to determine if downward material flow was uniform as evidenced by the slope of the top surface of the material in the container being maintained at zero as the material was unloaded (Jones and Kocher, 1995). The slope of the top surface of the material in the container unloaded with the decreasing inside diameter auger was much closer to zero than with a conventional auger. Despite the visual appearance of uniform unloading with the decreasing inside diameter auger, the top surface slope was significantly different from zero.

Jones and Kocher (1995) indicated the non-zero surface slope was likely a result of the discrepancy between the assumed zero particle diameter used in development of the design equation and the non-zero diameter of the soybeans used in their test. They stated that at the end opposite the auger outlet, the zero particle diameter assumption resulted in a flighting height of zero. They reasoned that the auger could not push soybeans towards the auger outlet at locations along the length of the auger where the flighting height was much less than the diameter of the soybeans.

The design equation for the decreasing inside diameter auger presented by Jones and Kocher (1995) was:

$$ID(x) = \sqrt{[OD]^2 - \frac{4 \times v \times OD \times x}{\pi \times \omega \times P}} \qquad (1)$$

where (fig. 1):

- x = distance along the auger starting (x = 0) at the end opposite the auger outlet (cm)
- ID(x) = inside (shaft, or root) diameter of the auger as a function of x, at distance x along the length of the auger (cm)
- OD = outside diameter of the auger (cm)
- v = downward flow velocity of material flowing into the auger ($cm \cdot min^{-1}$)
- ω = angular velocity of the auger [$rev \cdot min^{-1}$]
- P = pitch of the auger [$cm \cdot rev^{-1}$]

This square root function for the decreasing inside diameter describes a curve for the inside diameter as a function of length along the auger.

Jones and Kocher (1995) also derived a dimensionless ratio from the design equation. They showed that the minimum practical value for the dimensionless ratio was 1.0. Increasing the value of the dimensionless ratio resulted in a decrease in the curvature of the inside diameter along the length of the auger. Jones and Kocher (1995) suggested that it may be practical to approximate the square-root function curve with a linear taper for larger values of the dimensionless ratio.

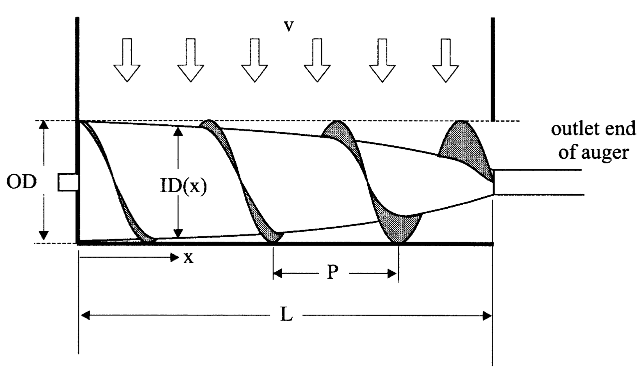

Figure 1–Schematic diagram of the decreasing inside diameter auger for uniform unloading particulate material from a rectangular cross-section container showing dimension variables pertinent to the design.

Objectives

The objectives of this study were: (1) to revise the decreasing inside diameter auger design equation (eq. 1) to account for the non-zero particle size of the particulate material; (2) determine the best fit linear taper to replace the square-root function curve describing the auger inside diameter; and (3) determine the capability of this linear tapered inside diameter auger with a minimum flighting height to uniformly unload a container with a rectangular cross-section.

Equation Development

Jones and Kocher (1995) developed an equation for the design of augers that would generate uniform vertical flow of particulate material through containers or boxes having a rectangular cross-section. They preferred auger designs with uniform outside diameters so the geometry of the conventional U-trough housing would not be affected. The preferred design had a uniform pitch for the flighting and a decreasing shaft or flighting inside (root) diameter. The equation developed (eq. 1) resulted from an assumption that no material would enter and be transported along the auger at x = 0 [auger “inlet” (end opposite the auger outlet)] when the auger inside diameter (shaft or flighting root diameter) was equal to the outside diameter [ID(0) = OD].

The design equation developed by Jones and Kocher (1995) was developed for situations with infinitesimal particle diameter. The design equation must be revised to accommodate situations with real, finite particle diameters. Consider the conservation of mass flow rate into and out of an infinitesimally small vertical section of an auger (fig. 2). The downward flow velocity of material into the auger (v) must be constant along the length of the auger to achieve the desired uniform flow. Note that q(x) is the volumetric flow rate ($cm^3 \cdot min^{-1}$) of the material in the auger, along the length of the auger, at location x.

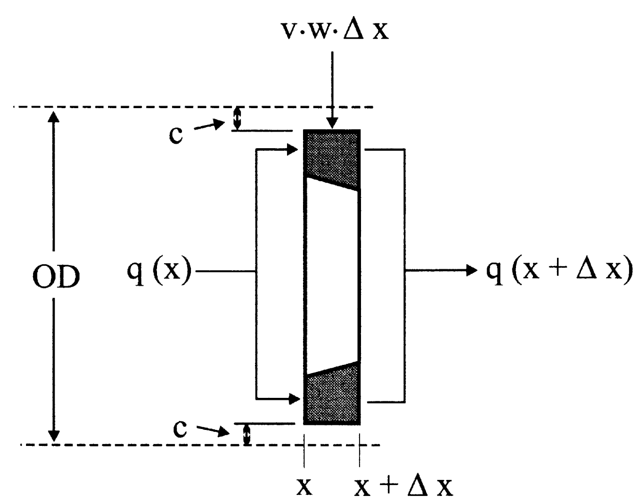

Figure 2–Schematic diagram of an infinitesimally thin vertical section of a horizontal auger in the bottom of a rectangular cross-section container, showing the volumetric flow rates into and out of the section necessary for uniform downward flow of the material above the auger.

Therefore:

$$q(x + \Delta x) = q(x) + v \times w \times \Delta x \tag{2}$$

where

- $q(x + \Delta x)$ = volumetric flow rate of material in the auger, along the length of the auger, at distance $x + \Delta x$ along the length of the auger ($cm^3 \cdot min^{-1}$)
- $q(x)$ = volumetric flow rate of material in the auger, along the length of the auger, at distance x along the length of the auger ($cm^3 \cdot min^{-1}$)
- Δx = incremental distance along the length of the auger (cm)
- w = width of the container (cm)

Note that having the width of the container equal to the auger outside diameter (w = OD) should result in uniform downward flow across the width of the container, as well as the desired uniform downward flow along the length of the container. Rearranging equation 2 and taking the limit as Δx approaches zero yields:

$$\frac{d}{dx}[q(x)] = v \times w \tag{3}$$

To account for non-zero particle diameter, consider a conventional auger moving particles with 10 mm diameter. An auger with a flighting height of 1 mm would not be expected to move those particles along its length. As greater flighting heights are tried, we would expect to find a minimum flighting height, likely between 4 mm and 10 mm, such that particles would be moved along the length of the auger. Another way of considering the minimum flighting height is that real particles because of their real, finite diameter, may displace outward slightly, around the edge of the flighting, rather than being pushed by the edge of the flighting along the length of the auger to the outlet. The minimum flighting height could also be considered the portion of the flighting height that is not effective in moving real particles along the length of the auger.

A different expression for q(x) is found by determining the flow within the auger as a function of the auger characteristics and the angular velocity (ω) of the auger around the centerline of its shaft. Note that flighting height represents a radius, so twice the flighting height represents a diameter, and referring to figure 2, q(x) can be written as:

$$q(x) = \frac{\pi}{4}\left\{ [OD - 2 \times c]^2 - [ID(x)]^2 \right\} \omega \times P \tag{4}$$

where c is minimum flighting height required to just start moving the particles along the length of the auger (cm). Differentiating and combining with equation 5 yields:

$$v \times w = -\frac{\pi}{4}\, \omega \times P \times 2 \times ID(x) \times \frac{d}{dx}[ID(x)] \tag{5}$$

Isolating the variable ID(x) yields:

$$2\, ID(x)\, d[ID(x)] = -\frac{4 \times v \times w}{\pi \times \omega \times P} \times dx \tag{6}$$

Recalling the boundary conditions and solving the differential equation:

$$\int_{OD - 2 \times c}^{ID(x)} 2 \times ID(x) \times d[ID(x)] = \int_0^x -\frac{4 \times v \times w}{\pi \times \omega \times P} \times dx \tag{7}$$

yields:

$$ID(x) = \sqrt{[OD - 2 \times c]^2 - \frac{4 \times v \times w \times x}{\pi \times \omega \times P}} \tag{8}$$

The quantity under the square root sign must be positive for real solutions, resulting in the following inequality:

$$\frac{[OD - 2 \times c]^2\ \pi \times \omega \times P}{4 \times v \times w \times L} > 1 \tag{9}$$

Jones and Kocher (1995) also mentioned that it may be practical to approximate the square root function in equation 8 with a linear taper as larger values of the ratio in equation 9 flattened the curve of the square root function. This may be especially true for real particles if the difference between the square root function and the linear taper function is significantly smaller than particle diameter.

The sum of the squared area differences between the square root and linear taper functions was minimized to determine an equation for a best-fit linear taper. The inside radius (one half the inside diameter) can be determined from equation 10:

$$r(x) = \frac{1}{2}\sqrt{[OD - 2 \times c]^2 - \frac{4 \times v \times w \times x}{\pi \times \omega \times P}} \tag{10}$$

where r(x) is the square root function for the auger inside radius as a function of x, at distance x along the length of the auger (cm). With the linear taper, the inside radius would be:

$$R(x) = mx + b \tag{11}$$

where

- R(x) = linear taper function for the auger inside radius as a function of x, at distance x along the length of the auger (cm)
- m = slope of the auger taper, or change in auger inside radius per unit change in auger length ($cm \cdot cm^{-1}$)
- b = inside radius of the auger at x = 0 (the end of the auger opposite the auger outlet) (cm)

Note that ideally b would be equal to [(OD/2) – c], such that the inside radius of the auger at x = 0 would make the auger flighting height at that point equal to the minimum flighting height necessary to move particles along the length of the auger.

At any distance x along the length of the auger, the difference in area between the square root function and the linear taper function would be:

$$\Delta A(x) = \pi\{[R(x)]^2 - [r(x)]^2\} \qquad (12)$$

where $\Delta A(x)$ is the difference in area between the square root and linear taper functions for the auger inside radius as a function of x, at distance x along the length of the auger (cm^2). Squaring the area difference yields:

$$[\Delta A(x)]^2 = \pi^2\{[R(x)]^2 - [r(x)]^2\}^2 \qquad (13)$$

The sum of the squared area differences can be obtained by integrating the squared area differences along the length of the auger:

$$\frac{1}{\pi^2}\sum_{x=0}^{L}\left[\Delta A(x)\right]^2 = \int_0^L \left\{ \left[R(x)\right]^2 - \left[r(x)\right]^2 \right\}^2 dx \quad (14)$$

Substituting equations 10 and 11 into equation 14 and determining the integral yields:

$$\int_0^L \left\{ \left[R(x)\right]^2 - \left[r(x)\right]^2 \right\}^2 dx = \frac{m^4 L^5}{5} + m^3 bL^4 + \frac{v\,w\,m^2 L^4}{2\pi\omega P} + 2m^2 b^2 L^3 - \frac{\left[OD - 2c\right]^2 m^2 L^3}{6} + \frac{4\,v\,w\,m\,b\,L^3}{3\pi\omega P} + \left(\frac{v\,w}{\pi\omega P}\right)^2 \frac{L^3}{3} - \frac{\left[OD - 2c\right]^2 mbL^2}{2} + \frac{v\,w\,b^2 L^2}{\pi\omega P} + 2\,mb^3 L^2 - \frac{v\,w\left[OD - 2c\right]^2 L^2}{4\pi\omega P} + \frac{\left[OD - 2c\right]^4 L}{16} - \frac{\left[OD - 2c\right]^2 b^2 L}{2} + b^4 L \quad (15)$$

To find the linear taper parameters (values for the slope m and intercept b) giving the best fit of the linear taper to the square root function, the derivatives of the integral of the squared area differences must be set equal to zero:

$$\frac{d}{dm}\left\{ \frac{1}{\pi^2}\sum_{x=0}^{L}\left[\Delta A(x)\right]^2 \right\} = 0 = \frac{4\,m^3 L^5}{5} + 3\,m^2 bL^4 + \frac{v\,w\,m\,L^4}{\pi\omega P} + 4\,mb^2 L^3 - \frac{\left[OD - 2c\right]^2 m\,L^3}{3} + \frac{4\,v\,wbL^3}{3\pi\omega P} - \frac{\left[OD - 2c\right]^2 b\,L^2}{2} + 2\,b^3 L^2 \quad (16)$$

and:

$$\frac{d}{db}\left\{ \frac{1}{\pi^2}\sum_{x=0}^{L}\left[\Delta A(x)\right]^2 \right\} = 0 = m^3 L^4 + 4\,m^2 bL^3 + \frac{4\,v\,wmL^3}{3\pi\omega P} - \frac{\left[OD - 2c\right]^2 m\,L^2}{2} + \frac{2\,v\,wbL^2}{\pi\omega P} + 6\,mb^2 L^2 - \left[OD - 2c\right]^2 b\,L + 4\,b^3 L \quad (17)$$

Solving these two cubic equations numerically for the auger linear taper slope, m, and intercept, b, yields the taper with the minimum sum of the squared area differences between the taper and the square root function.

EQUIPMENT

A linear tapered inside diameter auger with a minimum flighting height was designed using the following values in equations 16 and 17 to obtain the construction dimensions.

w = 13.2 cm
L = 61 cm
OD = 13.2 cm
P = 13.7 $cm\cdot rev^{-1}$
ω = 20 $rev\cdot min^{-1}$
v = 15 $cm\cdot min^{-1}$
c = 0.3 cm

These values resulted in the dimensionless ratio in equation 9 being equal to 2.7 for this auger. The values for the slope, m, and intercept, b, in equation 11 were determined to be –0.0207 and 6.3 cm, respectively. This resulted in a final value for c, the minimum flighting height, of 0.3 cm.

As stated earlier, the linear taper may work as well as the square root curve for the inside radius of the auger to provide uniform unloading as long as the maximum difference between the inside radii calculated by these two approaches is significantly less than the diameter of the particles being conveyed. The maximum difference between the inside radii as calculated by these two methods was less than 0.3 mm for this auger.

One turn of conventional flighting was added to the outlet end of the linear tapered inside diameter auger with a minimum flighting height. The additional turn of flighting prevented the material in the container from free flowing out of the container while the auger was not in operation. The additional turn also moved the material away from the outlet hole to reduce any restriction on the material once it was outside of the container.

The evaluation of the linear tapered inside diameter auger with a minimum flighting height was conducted by placing the auger in a U-trough in the bottom of a container with a rectangular cross section (fig. 3). The container measured 60 cm long × 15 cm wide × 89 cm deep. The drive system for the auger consisted of an electric motor and mechanical transmission so the auger could be operated at 20 rpm.

Necessary preparation of the particulate material was accomplished by screening with a mechanical separator. The separating machine was a replica of an oscillating separator designed by Deere and Co., Moline, Illinois, and evaluated by Finner et al. (1978). The large particles and small or broken pieces were removed to achieve the desired particle size for the soybeans. The top screen was made of

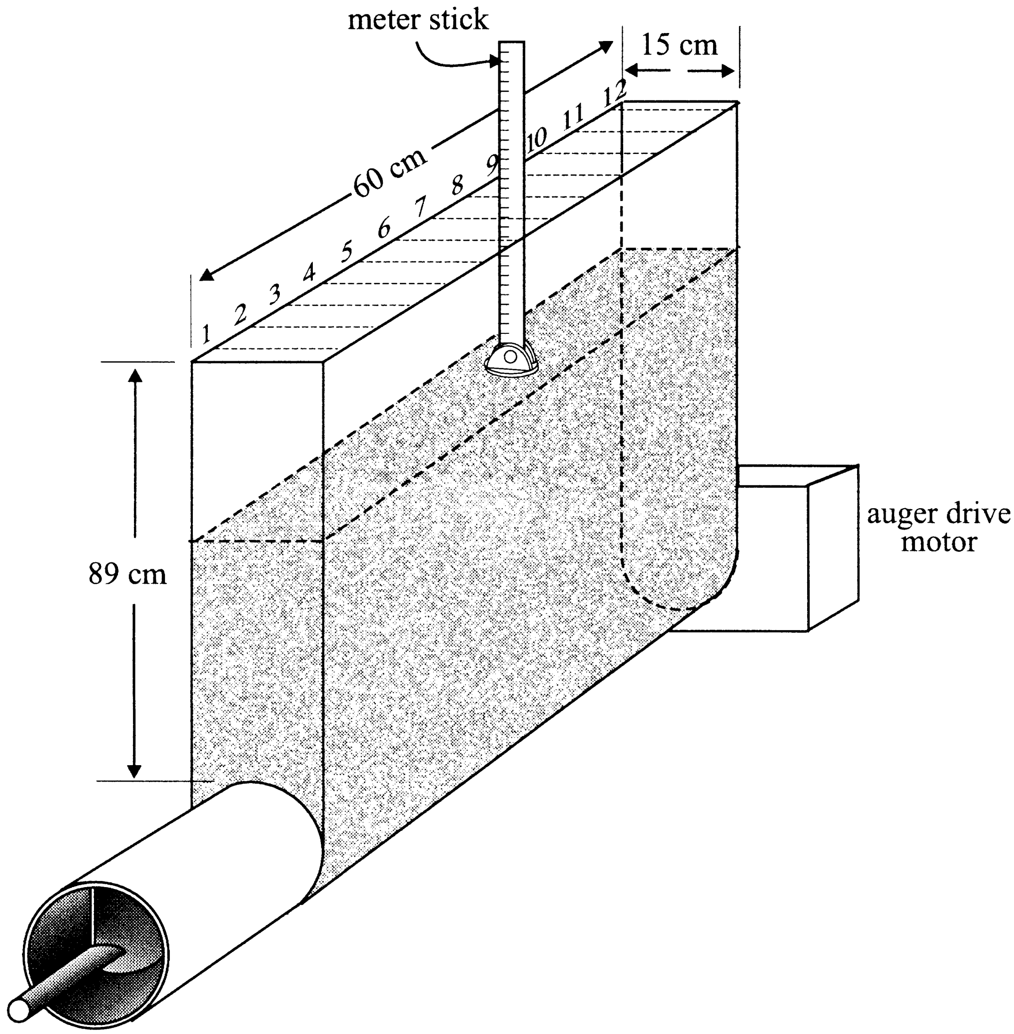

Figure 3–Schematic diagram of the apparatus used to test the uniformity of downward flow for particulate material in a container with a rectangular cross-section, unloaded using a linear tapered inside diameter auger with a minimum flighting height.

0.91-mm-thick perforated steel, with holes that were 6 mm in diameter and staggered by 8 mm. The bottom screen was a punched aluminum plate with 4-mm square holes. The mechanical separator was operated for one minute with each batch.

Testing Methods

In order to test the validity of the concept regarding minimum flighting height, the minimum flighting height had to be determined for the particulate material used. The process used to make this determination began with an initial guess for the minimum flighting height as being slightly greater than particle radius. The linear tapered auger was constructed with this minimum flighting height and was tested unloading particles of three different sizes (grain sorghum, soybeans, and garbanzo beans).

Samples of each particulate material were obtained for particle size determination. The particle dimension of interest was the smallest diameter as this dimension was expected to be related to the minimum flighting height with which the particles would just start moving. The smallest diameter of each particle in each sample was measured using a caliper. For each particulate material, the minimum, maximum, average and standard deviation of the smallest diameters was determined. The particle dimension used was the average of the smallest diameter, referred to as particle size for the remainder of this article.

Before the system was run for data collection, the particulate material was placed in the container and the auger was operated until the flow out of the auger outlet was visually judged to be uniform. This was done to ensure that material had completely filled the volume between the auger and the U trough. The drive motor was then turned off and the container was filled so the top surface of the material was parallel to the horizontal top of the container (fig. 3). The top surface of the material was approximately 72 cm above the top edge of the auger flighting.

The distance between the surface of the particulate material and the top of the container was measured to the nearest 0.6 cm using a meter stick with an attached round base plate (fig. 3). The base plate was 4 cm in diameter and pinned to the meter stick so it could pivot slightly at the bottom of the meter stick. When the measurements were taken, the round plate on the end of the meter stick was allowed to rest on the surface of the particulate material with the meter stick oriented vertically, and at a right angle to the horizontal axis of the auger. Measurements were taken 2.5 cm from the drive end of the container and at 5-cm intervals along the length of the container. This resulted in 12 measurements along the length of the container, of the distance from the top of the container to the top surface of the material, at each time interval. These distances were subtracted from the 89 cm height of the top of the container above the auger flighting to obtain the heights of the top surface above the top of the auger flighting.

The auger was operated for 30-s time intervals. At the end of each time interval, the auger was stopped and the distance between the top of the container and the top surface of the particulate material was measured. The auger operation intervals were continued until the auger flighting could be seen through the top surface of the particulate material. During the intervals of auger operation, the rotational speed of the auger was also measured using a hand-held digital tachometer in the optical operation mode. This procedure was followed for each of five replications for all materials during testing.

A least squares linear regression analysis was performed on the top surface heights for each time interval with each replication and each material to determine the slope of the top surface. Both slope and intercept parameters were calculated with the regression procedure. The slopes of the calculated regression lines for each time interval and each material were analyzed using a t-test to determine if the mean surface slope for each particulate material was significantly different from the ideal slope of zero. This analysis followed the same procedure described by Jones and Kocher (1995). The two tailed t-test was used with an alpha value of 0.05 and a t_{crit} value of 2.132.

The average slope of the top surface after 1 min of unloading was determined for each of the three particle sizes as described above. A least squares linear regression was performed with average slope of the top surface as a function of particle size. The particle size that should give an average slope of the top surface equal to zero was determined from the regression equation. Particles of that size were obtained (screened soybeans) and used with the auger to test the validity of the concept regarding minimum flighting height. The same test procedure described above was also used with this particulate material (screened soybeans).

Results and Discussion

The average of the smallest diameters for a sample of 20 soybeans was 5.2 mm (table 1). These soybeans were placed in the rectangular container and unloaded using the linear tapered inside diameter auger with a minimum flighting height. The average slope of the top surface after 1 min of operation was slightly greater than zero (table 2).

The averages of the smallest diameters for the grain sorghum and the garbanzo beans were 1.8 mm and 8.5 mm, respectively (table 1). The mean slope of the top surface of the grain sorghum after 1 min of auger operation to unload the material was negative, while the mean slope of the top surface of the garbanzo beans after 1 min of auger operation was positive (table 2). Figure 4 shows that the relationship between the mean slope of the top surface of the material after 1 min of auger operation and particle size appeared to be linear. A regression analysis was performed and the particle size that would have resulted in a slope of the top surface of zero was determined to be 4.6 mm. This resulted in the 3-mm minimum flighting height for the tapered auger being about 64% of the particle size.

Table 1. Results of the particle size determinations for the particulate materials unloaded from the rectangular cross-section container using the linear tapered inside diameter auger with a minimum flighting height

Particulate Material	No. Particles Measured	Particle Smallest Diameter (mm) Min.	Avg.	Max.	S.D.
Grain sorghum	20	1.07	1.75	2.54	0.377
Soybeans	20	4.73	5.23	5.58	0.248
Garbanzo beans	20	7.51	8.51	9.48	0.527
Screened soybeans	150	3.53	4.74	5.54	0.386

Table 2. Particulate material, particle size (average smallest diameter), and average slope of the top surface for each particulate material one minute after the start of unloading from the rectangular cross-section container using the tapered inside diameter auger with a minimum flighting height

Particulate Material	Particle Size	Slope at 1:00 min.
Grain sorghum	1.8 mm	–0.038
Soybeans	5.2 mm	0.0147
Garbanzo beans	8.5 mm	0.208

A quantity of soybeans was obtained by screening to remove the large, small, and broken soybeans. The average of the smallest diameters from a sample of 150 of the screened soybeans was 4.7 mm (table 1). The screened soybeans were placed in the rectangular container and unloaded using the linear tapered inside diameter auger with a minimum flighting height. The mean of the slopes of the top surface of the material obtained from these replications was not significantly different from zero for the first three time intervals (table 3). These results showed that it was possible to achieve a top surface slope of zero using an auger built with a linear tapered inside diameter and a minimum flighting height.

The top surface slope equal to zero was not maintained at the cumulative auger operation times of 2 and 2.5 min. At those times the top surface of the material was less than 30 cm above the top of the auger flighting. The depth of the container was increased to allow longer cumulative operation times. The container was filled so the top surface of material was approximately 98 cm above the top edge of

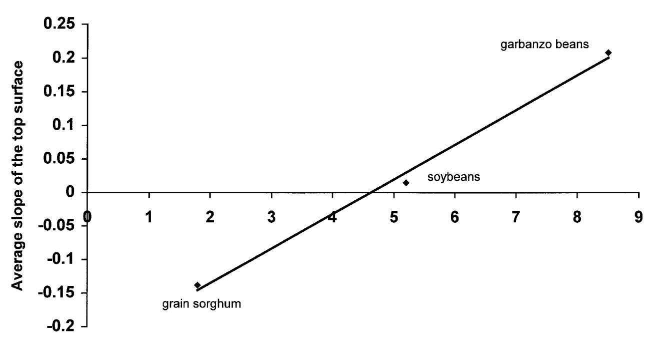

Figure 4–Average slope of the top surface for three particulate materials in a rectangular cross-section container after one minute of unloading using the linear tapered inside diameter auger with a minimum flighting height. Regression equation: Average slope of the top surface = 0.0516 mm^{-1} × (particle size) – 0.238. Coefficient of determination (r^2) = 0.9942.

Table 3. Slopes of the top surface and t-values obtained when the linear tapered inside diameter auger with a minimum flighting height was used to unload the screened soybeans from the rectangular cross-section container, at each 30 s interval after the start of unloading (the container was filled to approximately 72 cm above the top of the auger flighting at the start of each replication)

	Replication Number					Average	t Obs
Time	1	2	3	4	5	Slope	Value
0:30	0.000	0.022	0.000	0.009	0.000	0.006	1.429
1:00	–0.018	0.013	0.000	0.039	–0.039	–0.001	–0.067
1:30	0.000	0.000	0.000	0.022	0.022	0.009	1.633
2:00	0.022	0.062	0.034	0.052	0.042	0.043	6.16*
2:30	0.065	0.054	0.061	0.094	0.067	0.068	9.998*

* t values significantly different from zero (t_{crit} = 2.132, n = 5, and α = 0.05).

the auger flighting and parallel with the horizontal top of the container. The screened soybeans were unloaded from this taller rectangular container and the slopes of the top surface of the material were determined (table 4). Again, the average slopes of the top surface at the last two time intervals (top surface of the material less than 30 cm above the top of the auger flighting) were significantly different from zero. This indicated that the auger was able to produce uniform downward flow of material in the container, until the top surface of the material dropped to within 30 cm of the top of the auger flighting. It is hypothesized that with a top surface of the material within 30 cm of the top of the auger flighting, the forces generated by the auger in the soybeans were sufficient to disrupt the uniform downward flow.

The slope of the top surface of the screened soybeans after 1 min of unloading from the taller rectangular container was significantly different from zero, and negative (table 4). The slope of the top surface was not significantly different from zero after the first 30-s unloading interval. Also, after the next three 30-s unloading intervals, the slope of the top surface was not increasingly negative, but was again not significantly different from zero. In addition, the slope of the top surface after one minute of unloading in the previous test (table 3) was not significantly different from zero. This led to the conclusion that the slope of the top surface of the screened soybeans after one minute of unloading from the taller rectangular container (table 4) was significantly different from zero by random chance in this experiment.

Table 4. Slopes of the top surface and t-values obtained when the linear tapered inside diameter auger with a minimum flighting height was used to unload the screened soybeans from the rectangular cross-section container, at each 30 s interval after the start of unloading (the container was filled to approximately 98 cm above the top of the auger flighting at the start of each replication)

	Replication Number					Average	t Obs
Time	1	2	3	4	5	Slope	Value
0:30	0.000	0.000	0.000	–0.012	–0.012	–0.005	–1.630
1:00	–0.040	–0.018	–0.036	–0.040	–0.039	–0.034	–8.11*
1:30	–0.012	0.000	–0.006	0.000	0.018	0.000	0.000
2:00	0.000	0.012	0.000	0.000	0.010	0.004	1.610
2:30	0.000	0.022	0.009	–0.006	0.049	0.015	1.530
3:00	0.022	0.040	0.058	0.021	0.058	0.040	4.92*
3:30	0.042	0.081	0.085	0.047	0.077	0.066	7.26*

* t values significantly different from zero (t_{crit} = 2.132, n = 5, and α = 0.05).

Conclusions

Conclusions from this experiment were:

1. The design equation for an auger to provide uniform unloading of particulate material from a container with a rectangular cross-section (Jones and Kocher, 1995) was revised to include a minimum flighting height that could effectively unload particulate material with a known average smallest diameter (see eq. 8). A minimum flighting height that was about 64% of the average smallest diameter of screened soybeans produced mean slopes of the top surface of the screened soybeans not significantly different from zero.
2. A linear taper that best fit the square root curve for the inside diameter of the auger was determined by minimizing the integral of the squared area differences between the linear taper and the square root curve (see eqs. 16 and 17).
3. An auger constructed following this design (linear tapered inside diameter with a minimum flighting height) provided uniform unloading of particulate material from a container with a rectangular cross-section, as evidenced by the slope of the top surface of the material being maintained not significantly different from zero, until the surface dropped to within 30 cm of the top of the auger flighting.

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