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AUGER DESIGN FOR UNIFORM UNLOADING OF GRANULAR MATERIAL: II. CYLINDRICAL CONTAINERS

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Auger Design for Uniform Unloading of Granular Material: II. Cylindrical Containers

M. F. Kocher, D. D. Jones

Abstract: The analysis presented can be used to determine the design equations for augers that produce uniform vertical flow of granular material through containers with cylindrical cross-sections. The augers so designed have a constant outside diameter and a variable root or shaft diameter. Installed in cylindrical grain bins they could be used to convert a batch-in-bin dryer to a continuous flow dryer. The analysis is an extension of the work of Jones and Kocher (1995) who designed and tested such an auger for containers of rectangular cross-section, and determined flow to be uniform for practical purposes. The analysis follows the same concept used by Shivvers (1973) to develop augers with variable outside diameter to provide uniform vertical flow of granular material through containers with cylindrical cross-section. Keywords: Augers, Design, Flow patterns, Granular flows, Grain bins, Container.

Jones and Kocher (1995) described the nonuniform flow that occurs with conventional augers and presented auger designs that provide uniform unloading of granular materials from containers with rectangular cross-sections. They described three changes that could be made to the conventional auger design to achieve the uniform flow characteristics. These three changes were variable outside diameter of the auger flighting, variable pitch of the auger flighting, and variable inside diameter (root or shaft diameter).

There are several possible options for using an auger with variable outside diameter to provide uniform unloading of a container with rectangular cross-section, but each option has a disadvantage. One disadvantage is that if a tube or trough of uniform diameter is used with this type of auger, a part of the tube or trough cannot be emptied with the auger. A variable outside diameter auger with maximum outside diameter equal to the width of the rectangular cross-section could be used. The disadvantage to this auger would be nonuniform unloading across the width of the container at the end opposite the auger outlet where the outside diameter of the flighting would be less than the width of the container. A variable outside diameter auger with minimum outside diameter equal to the width of the rectangular cross-section could be used. The disadvantage to this auger would be the outside diameter of the auger would be greater than the width of the rectangular cross-section for most of the length of the container. This auger would be larger in diameter than the other designs, requiring more material to manufacture and more space underneath the container.

One disadvantage of the variable pitch flighting was at the end opposite the auger outlet, the pitch of the flighting was small enough that particles lodged between the flighting rather than being transported by the auger. Another disadvantage was that manufacture of the variable pitch flighting was difficult. Of these three auger design possibilities, the variable inside diameter was preferred as being practical to manufacture and use for uniform unloading of containers with rectangular cross-section.

Shivvers (1973) patented a sweep auger with variable outside diameter for uniform unloading of granular material from cylindrical containers. The auger is a key component in continuous flow in-bin grain dryer systems marketed by Shivvers, Inc. and Nebraska Engineering Company. The design equation for the auger outside diameter was developed using the same continuity concept as presented in Jones and Kocher (1995) and this article. The design equation presented in Shivvers (1973) is equivalent to the one that would be developed using the methods in Jones and Kocher (1995) and this article, although the equation in Shivvers (1973) appears in a different form because different variables were used.

Sukup Manufacturing Co. and David Manufacturing Co. also use sweep augers with variable outside diameter as a key part in their continuous flow in-bin grain dryers. The augers they use have a stair-step function for outside diameter rather than a continuous function such as developed by Shivvers (1973), Jones and Kocher (1995) and in this article.

Jones and Kocher (1995) conducted tests with a conventional auger, a variable pitch auger, and a variable inside diameter auger and observed that the conventional auger did not produce uniform unloading of the container with a rectangular cross-section. For practical purposes, the variable pitch and variable inside diameter augers did produce uniform unloading of the same container.

Objectives
The designs presented in Jones and Kocher (1995) were developed to provide uniform unloading of containers with
rectangular cross-sections. The objective for this article is to develop the design analysis for augers with variable inside diameter to uniformly unload granular material from containers with other shapes. Specifically, this article presents the design of sweep augers with variable inside diameter for uniform unloading of cylindrical containers like grain bins. Such an auger, along with a system that provides uniform loading, could be used to convert a batch-in-bin dryer to a continuous flow dryer.

DEVELOPMENT OF DESIGN EQUATIONS

The design analysis presented in this article considers only the variable inside diameter auger as preferred by Jones and Kocher (1995). Use of the continuity concept in the design dictates that each vertical section of a horizontal auger must have enough room to hold the volume of material entering from the previous section (upstream) and accept the volume of material entering the auger from the container. This requirement is necessary to achieve uniform intake of material from the container along the length of the auger as well as provide grain conveyance. Consider an infinitesimally small (elemental) vertical section (of length $\Delta x$) of an auger (fig. 1). The downward velocity of material into the auger ($v$) is to be uniform along the length of the auger. The shape of the container affects the horizontal area through which grain will flow from the container into each elemental section of the auger. The volumetric flow rate ($L^3T^{-1}$) of material into a section of the auger from the container is calculated as the area through which grain will flow into this section of the auger multiplied by the desired downward velocity of material into the auger. The change in volumetric flow rate per unit length of the auger is equal to the volumetric flow rate of material from the container into the auger.

Let $x$ denote position along the length of the auger from the center of the grain bin ($x = 0$) to the outside perimeter of the grain bin ($x = L$). The sweep auger is to be designed to remove a uniform depth of grain from all areas of the bin and discharge that grain to an outlet at the center of the grain bin. Thus, grain flow in the auger will be from the perimeter of the bin ($x = L$) to the center ($x = 0$). The area through which grain will flow from the container into an elemental section of the auger is $\Delta A$ (figs. 2 and 3). The volumetric flow rate of material into and out of this section of the auger multiplied by the desired downward velocity of material into the auger. The change in volumetric flow rate per unit length of the auger is equal to the volumetric flow rate of material from the container into the auger.

The volumetric flow rate through this area into this section of the auger is $v_\Delta A$. The volumetric flow rate out of this section of the auger at $x$ must be equal to the sum of the volumetric flow rate from upstream in the auger at $x + \Delta x$ and the volumetric flow rate through the area $\Delta A$ (fig. 3).

$$q(x) = q(x + \Delta x) + v_\Delta A$$

where

- $q(x + \Delta x)$ = volumetric flow rate of material in the auger at $x + \Delta x$ down the length of the auger ($L^3T^{-1}$)
- $q(x) = $ volumetric flow rate of material in the auger at $x$ down the length of the auger ($L^3T^{-1}$)
- $x$ = distance down the auger, from the center of the bin to the outside perimeter ($L$)
- $\Delta x$ = increment of distance down the length of the auger ($L$)
Substituting from equation 1 for $A$ and rearranging yields:

$$q(x + \Delta x) - q(x) = -2 \pi v x \frac{\Delta x}{2}$$  

Taking the limit as $\Delta x$ approaches 0 yields:

$$\lim_{\Delta x \to 0} \left( \frac{q(x + \Delta x) - q(x)}{\Delta x} \right) = \lim_{\Delta x \to 0} \left( -2 \pi v x \right)$$

Using the definition of a derivative yields:

$$\frac{dq(x)}{dx} = -2 \pi v x$$

Rearranging and integrating:

$$q(x) = -2 \pi v \int_0^x 2 \pi v dx$$

Another expression for $q(x)$ is found by determining the flow within the auger as a function of the auger characteristics and the angular velocity at which the auger is operated.

$$q(x) = \pi \left[ (OD)^2 - (ID(x))^2 \right]$$

where

- $\omega$ = angular velocity of the auger around its centerline [rev T$^{-1}$]
- $P$ = constant pitch of the auger [L rev$^{-1}$]
- $OD$ = constant outside diameter of the auger [L]
- $ID(x)$ = inside diameter of the auger at $x$ along the length of the auger [L]

Setting the expressions in equations 7 and 8 equal:

$$\pi v L^2 - x^2 = \pi \left[ (OD)^2 - (ID(x))^2 \right]$$

Solving for $ID(x)$:

$$ID(x) = \sqrt{(OD)^2 - \frac{4vL^2}{\pi} x^2}$$

Note that the angular velocity ($\Omega$) of the sweep auger around the center of the grain bin floor (fig. 2) does not affect the shape of the inside diameter of the auger. The angular velocity ($\Omega$) only affects the amount of grain removed per revolution.

When designing a variable inside diameter auger using equation 10, it is important to select parameters $v$, $\omega$, and $P$ yielding an appropriate value for the quantity $4v/\pi P$. A practical auger requires that $ID(0)$ (at the outlet end of the auger) be greater than zero, so the quantity under the square root sign in equation 10 must be positive.

$$OD^2 - \frac{4vL^2}{\pi P} > 0$$

Rearranging this inequality yields the following dimensionless ratio (eq. 12) that dictates the feasibility of the auger design.

$$\frac{\omega P}{4v L} > 1$$

Figure 4 illustrates the influence of this ratio on the shape of the inside diameter. It is clear that when the ratio in equation 12 is less than 1.00, the design is impractical, since the inside diameter should be greater than zero for the entire length of the auger (0 $\leq x \leq L$). Ratio values slightly larger than 1.00 are probably impractical as the inside diameter at the outlet end of these augers may be smaller than the minimum shaft diameter. As the value of the ratio increases to infinity, the curvature of the inside diameter (derivative of the slope of the inside diameter with respect to $x$) decreases and approaches zero. This means the shape of the inside diameter approaches a linear taper as the ratio approaches infinity. The acceptable compromise between these extremes must be an intermediate ratio value.

Such an auger, along with a system that provides uniform loading, could be used to convert batch-in-bin dryers to continuous flow dryers. An example would be a
bin with diameter 9.1 m and a sweep auger of length 4.6 m. The auger could have an outside diameter of 20 cm and a pitch of 20 cm/rev. With an auger speed of 30 rpm and a desired downward velocity of the grain at 7 cm/h, the ratio
\[
\left(\frac{wP}{4v}\right) \left(\frac{OD}{L}\right)^2
\]
would have a value of 2.43 and the inside diameter as a function of length along the auger (calculated from eq. 10) would be as shown in table 1. Note that the downward velocity of the grain should be approximately equal to the speed of the drying front so the grain is removed from the dryer just as it reaches the desired moisture content.

The design of a sweep auger that rotates around the center of the circular floor of a cylindrical grain bin (fig. 2) has been used in this analysis. The geometry of other containers will require changes in the expression for the area through which grain will flow into the elemental section of the auger. The remainder of the analysis for other cross-sections parallels the analysis presented here. As an example, for uniform unloading of a rectangular bin the area \(\Delta A\) would be:

\[
\Delta A = w \Delta x
\]

Table 1. Example auger inside (root) diameter as a function of length along the auger for a sweep auger to convert a batch-in-bin dryer to a continuous flow dryer*

<table>
<thead>
<tr>
<th>Length along Auger, from Center of Bin to Outside Diameter (m)</th>
<th>Auger Inside (Root) Diameter (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>15.34</td>
</tr>
<tr>
<td>0.2</td>
<td>15.35</td>
</tr>
<tr>
<td>0.4</td>
<td>15.38</td>
</tr>
<tr>
<td>0.6</td>
<td>15.43</td>
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<tr>
<td>0.8</td>
<td>15.50</td>
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<tr>
<td>1.0</td>
<td>15.59</td>
</tr>
<tr>
<td>1.2</td>
<td>15.69</td>
</tr>
<tr>
<td>1.4</td>
<td>15.83</td>
</tr>
<tr>
<td>1.6</td>
<td>15.98</td>
</tr>
<tr>
<td>1.8</td>
<td>16.14</td>
</tr>
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<td>16.33</td>
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<tr>
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<tr>
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<td>16.97</td>
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<tr>
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<tr>
<td>3.0</td>
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<td>3.4</td>
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<td>3.8</td>
<td>18.65</td>
</tr>
<tr>
<td>4.0</td>
<td>18.97</td>
</tr>
<tr>
<td>4.2</td>
<td>19.30</td>
</tr>
<tr>
<td>4.4</td>
<td>19.65</td>
</tr>
<tr>
<td>4.6</td>
<td>20.00</td>
</tr>
</tbody>
</table>

* Bin diameter is 9.1 m, auger length is 4.6 m, auger outside diameter is 20 cm, auger flighting pitch is 20 cm/rev, auger speed is 30 rpm, and desired downward velocity of the grain is 7 cm/h.

Further testing of augers designed using this analysis will be necessary to evaluate their performance in terms of efficiency (power consumption and auger capacity) and damage caused to the granular material conveyed.

**SUMMARY AND CONCLUSIONS**

The analysis presented considers only design of variable inside diameter augers from the three possible auger configurations presented by Jones and Kocher (1995). Analyses for the other configurations parallel the analysis presented in this article. The analysis is based on the continuity concept which dictates that each elemental vertical section of a horizontal auger must have enough room to hold the volume of material entering from the previous section (upstream) and accept the volume of material entering the auger from the container. The equation for the inside diameter of sweep augers for uniform unloading of granular material from cylindrical grain bins was developed by applying the procedure to cylindrical containers:

\[
ID(x) = \sqrt{\frac{(OD)^2 - \frac{4wP}{\pi v} x}{wP}}
\]

Design of practical sweep augers is restricted with the following inequality:

\[
\frac{wP}{4v} \left(\frac{OD}{L}\right)^2 > 1
\]

Such an auger, along with a system that provides uniform loading, could be used to convert batch-in-bin dryers to continuous flow dryers.

**REFERENCES**


1166