Vibration effect on pore structure of grain bulks

C. Nwaizu
Graduate Student, Department of Biosystems Engineering, University of Manitoba, Winnipeg, MB, R3T 5V6, Canada

Q. Zhang
Professor, Department of Biosystems Engineering, University of Manitoba, Winnipeg, MB, R3T 5V6, Canada

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ABSTRACT. Knowledge of pore structure inside grain bulks is important for determining airflow resistance of grains. In this study, an image analysis procedure was used to study the effect of vibration on the number, size, and interconnectivity of pores in the horizontal and vertical directions of a grain bulk in a lab scale grain bin filled with soybeans. ImageJ, an image processing Java-based software developed by the United State National institute of Health was used for the image analysis. It was observed that the mean pore area was 0.041 cm$^2$ ± 0.009 before vibration, and decreased to 0.02 cm$^2$ ± 0.007 after vibration, or a 51% reduction for the vertical direction. And for the horizontal direction, mean pore area was 0.043 cm$^2$ ±0.01 before vibration, and 0.017 cm$^2$ ±0.003 after vibration, or a 60% reduction. Bulk density was 635 kg/m$^3$ (porosity, $\phi=39\%$) before vibration and 755 kg/m$^3$ (porosity, $\phi=27\%$) after vibration. Pore channels (airflow path) were more connected inside the grain bulk before vibration than after vibration with fragmentation index of about 55.46% and 58.83% higher after vibration than before vibration in the horizontal and vertical bed directions respectively.

Keywords: Grain bulks, Airflow resistance, Pore structure, Porosity, Pore space
INTRODUCTION

The pore structure of agricultural products is complex and highly variable. Knowledge of pore structure is essential for the determination of air flow resistance (Wojciech et al., 2013), in predicting fluid transport in agricultural bulk solids (Bear, 1989; Celia et al. 1995) and in validating mathematical models of drying, aeration, or fumigation pattern for stored grain (Smith and Jayas, 2004).

Imaging techniques have been used to study the internal structure of bulk solids. Hans and Quisenberry (2007) used image analysis procedure to determine spatial distribution of macro pores and to identify individual pores, measure size and location in soil. Laser scanning confocal microscopy (LSCM) was used to image the micro geometry of porous geological and engineering materials for heat transfer processes in complex porous media (Fredrich, 1999). Smith (1993) used the nuclear magnetic resonance (NMR) to determine the pore size distribution of porous solids. Recently, Neethirajan et al. (2008) used the X-ray CT to scan the internal micro-structure of grain bulks to explain the reason why the air flow resistance is lower in the horizontal direction than in the vertical direction.

Grain stored in silo, elevators or in processing storage systems is often subject to change in bulk density due to vibration or filling procedures, and this consequently affects the pore structure of grain bulks. However, no study has been carried out to study the effect of vibration (compaction) of the stored grains on the pore size and interconnectivity. The objective of this study was to use image processing techniques to study changes in the pore interconnectivity and size inside grain bulks due to vibration (compaction).

MATERIALS AND METHODS

Materials

A rectangular lab-scale bin (box) (27 × 25 × 2 cm) made of 1.6 cm thick Plexiglas was designed and constructed to conduct the the experiments. The grain used in this study was soybeans. The grain moisture content was determined by using the standard oven method as outlined in the ASABE Standard: 105°C for 72 hours (ASAE R2008.S352.2, 2004). The moisture content was obtained as 8.82 % wb (web basis). Other measured physical properties of the soybeans used in this study are summarized in Table 1. These property values were similar to those reported by Kibar and Ozturk (2008) and Kenghe et al. (2012) at a moisture content of 8.0 and 8.7%, respectively.
Table 1. Physical properties of Soybean grain sample

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture Content (%)</td>
<td>8.82</td>
</tr>
<tr>
<td>Average Length (m)</td>
<td>$6.2 \times 10^{-2}$</td>
</tr>
<tr>
<td>Average Volume ($m^3$)</td>
<td>$1.8 \times 10^{-1}$</td>
</tr>
<tr>
<td>Equiv. diameter (m)</td>
<td>$6.9 \times 10^{-2}$</td>
</tr>
<tr>
<td>Sphericity</td>
<td>0.7</td>
</tr>
<tr>
<td>Average mass of kernel (kg)</td>
<td>$2.2 \times 10^{-4}$</td>
</tr>
<tr>
<td>Particle Density ($kg/m^3$)</td>
<td>1028</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>39†</td>
</tr>
</tbody>
</table>

†Before vibration

**Experimental Procedure**

The test box was filled with the grain (soybeans) by using a funnel that was placed 20 cm from the top of the test box (fig. 1). The grain developed a heaped surface after filling. The box was vibrated on a vibrating table for 30 seconds at 15 Hz and amplitude of 0.623 mm (fig. 2).

![Figure 1. Filling soybeans into the box to achieve loose fill.](image)
A digital camera (Exilim EX-F1 Casio Computers Co., Ltd, Tokyo, Japan) mounted on a tripod stand was placed 10 cm in the front of the test box to obtain digital images. Images (512×384 pixel RGB) of the bulk grain inside the test box were captured before and after vibration in three replicates. ImageJ (NIH, Bethesda, MD, US) a public domain Java-based image processing software was used in analyzing the images.

The RGB images were first converted into 8-bit images (fig. 3), and then thresholded to further separate the pores from the grain kernel and other image artifacts, creating binary images with intensity value of 1 (white) for kernels and 0 (black) for pores in the images (fig. 4).

Figure 2. Vibrating the test box after filling to achieve dense fill.

Figure 3. Convection of RGB image into 8-bit image
From the thresholded images of the grain bulk before and after vibration, the individual pore area (2D) was measured using ImageJ along (vertical direction) the grain bed starting from the bottom of the bin to the depth of the filled grain, and also across (horizontal direction) the grain bed starting from the bin center to the bin wall. Also the number of the extended pore, that is the number of the pores that are well connected with two or more pores were indicated and counted before and after vibration along (vertical direction) the grain bed starting from the bottom of the bin to the depth of the filled grain, and also across (horizontal direction) the grain bed starting from the bin center to the bin wall. The distance from the bin bottom to the top the grain filled inside the bin was 9cm, while the distance from the bin center to the bin wall was 12.5cm.

The Fragmentation Index (FI) was calculated to quantify the inter connectivity of pore spaces inside grain bulks. FI was based on the ratio of the areas and perimeters of pores (Hahn et al., 1992; Neethirajan et al., 2008):

\[
FI = \left( \frac{P_1 - P_2}{A_1 - A_2} \right)
\]

where

- \( FI \) = fragmentation index
- \( P_1 \) = pore space perimeter before dilation (pixel)
- \( P_2 \) = pore space perimeter after dilation (pixel)
- \( A_1 \) = pore space area before dilation (pixel\(^2\))
- \( A_2 \) = pore space area before dilation (pixel\(^2\)).

A lower fragmentation index signifies better connected pore channels (air path), while a higher value of fragmentation index signifies disconnected pore channel.

Analysis of variance was carried out with SAS statistical software to test for the effect of vibration (compaction) and bed directions on the measured pore characteristics (pore area, number of extended pore and pore connectivity).
RESULTS AND DISCUSSION

Bulk density before and after Vibration

Vibration caused the grain to settle and the heap was flattened by vibration (fig. 5). This settling led to increase in bulk density. The bulk densities measured in three replications before and after vibration are illustrated in fig.6. On average the bulk density obtained by vibrating the test box after filling (dense fill) was 20% higher than that before vibration (loose fill) (755 Kg m\(^{-3}\) vs. 632 Kg m\(^{-3}\)).

Figure 5. Photographs of grain in bin before vibration and after vibration.

Figure 6. Bulk density of the grain bulk before and after vibration (Error bars represent standard deviations).
Effect of vibration on pore space (area)

The variation of pore space (area) along (vertical) and across (horizontal) the grain bed before and after vibration was examined. It was apparent that the mean pore space area of the grain bulk before vibration was higher than that after vibration in both the vertical and horizontal bed directions. As the grain bulk became denser due to vibration, the pore space area reduced. Before vibration, mean pore space area was 0.041 cm$^2$ ± 0.009, and 0.02 cm$^2$ ± 0.007 after vibration for the vertical bed direction. And for the horizontal bed direction, mean pore area was 0.043 cm$^2$ ± 0.01 before vibration, and 0.017 cm$^2$ ± 0.003 after vibration. It was also observed that the pore space area increased from the bottom to the top of the test box for the vertical bed direction before and after vibration (fig. 7).

![Figure 7. Distribution of pore space (area) along the bed (vertical direction) before and after vibration (Error bars represent standard deviation).](image)

And, for the horizontal direction, the pore space area did not vary much across the bin. (fig. 8).
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Figure 8. Distribution of pore space (area) across the bed (horizontal direction) before and after vibration (Error bars represent standard deviation).

The ANOVA statistical test ($\alpha = 0.05$) results indicated that pore space area changed as a result of vibration. However, there was no significant difference in the measured mean pore areas between the horizontal and vertical directions (Table 2).

Table 2. ANOVA results for the effect of vibration and bed direction on pore space area

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration</td>
<td>1</td>
<td>0.012618</td>
<td>0.012618</td>
<td>4.50</td>
<td>0.0408</td>
</tr>
<tr>
<td>Bed direction</td>
<td>1</td>
<td>0.001230</td>
<td>0.001230</td>
<td>0.44</td>
<td>0.5117</td>
</tr>
<tr>
<td>Interaction</td>
<td>1</td>
<td>0.003705</td>
<td>0.003705</td>
<td>1.32</td>
<td>0.2577</td>
</tr>
<tr>
<td>Error</td>
<td>36</td>
<td>0.100855</td>
<td>0.005851</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>39</td>
<td>0.118408</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Effect of vibration on pore connectivity

The average calculated fragmentation index was $6.36 \pm 2.2$ before vibration, and $14.28 \pm 4.2$ after vibration for the vertical directions (fig. 9).
And for the horizontal direction, the average fragmentation index was 5.62 ± 0.9 before vibration and 13.65 ± 1.2 after vibration (fig. 10). This means that pore channels after vibration for both the horizontal and vertical directions were more disconnected than the pore channels before vibration for both the horizontal and vertical directions.
The ANOVA statistical test ($\alpha = 0.05$) results indicated that the fragmentation index changed significantly as a result of vibration. However, there was no significant difference in the average fragmentation index measured between the horizontal and vertical directions (Table 3).

### Table 3. ANOVA results for the effect of vibration and bed direction on pore connectivity

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration</td>
<td>1</td>
<td>504.242</td>
<td>504.242</td>
<td>62.90</td>
<td>0.001</td>
</tr>
<tr>
<td>Bed direction</td>
<td>1</td>
<td>0.05329</td>
<td>0.05329</td>
<td>0.01</td>
<td>0.9355</td>
</tr>
<tr>
<td>Interaction</td>
<td>1</td>
<td>1.96249</td>
<td>1.96249</td>
<td>0.24</td>
<td>0.6238</td>
</tr>
<tr>
<td>Error</td>
<td>36</td>
<td>288.605</td>
<td>168.753</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>39</td>
<td>794.863</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Comparing the number of extended pore on vertical to horizontal direction

Extended pores are the pores that are well connected with two or more pores inside the grain bulk. ImageJ was used in counting the numbers of the extended pores before and after vibration before and after vibration. The result indicated that the number of the extended pores before vibration in both the horizontal and vertical bed directions is greater than the number of the extended pores after vibration in both the horizontal and vertical bed directions (Table 4).

### Table 4. Average number of extended pores along (vertical) and across (horizontal) bed direction.

<table>
<thead>
<tr>
<th></th>
<th>Number of extended pores</th>
<th>Ratio of number of pore (Horizontal to vertical)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Horizontal direction</td>
<td>Vertical direction</td>
</tr>
<tr>
<td>Before vibration</td>
<td>7403±97.2</td>
<td>6710±42.0</td>
</tr>
<tr>
<td>After vibration</td>
<td>6487±50.2</td>
<td>6357±71.8</td>
</tr>
</tbody>
</table>

It is interesting to note that the ratio of the number of the extended pores in the vertical direction to the horizontal bed direction was 0.90 before vibration. This indicated that the number of the extended pores in the horizontal bed direction was more than that in the vertical direction before vibration. Therefore, flow through the horizontal bed direction will experience less resistance compare to the flow through the vertical direction. But this ratio increased to 0.98 after vibration. This means that vibration might lessen the difference in airflow resistance between the horizontal and vertical directions.
CONCLUSION
This study demonstrated that the compaction of the soybean grain due to vibration affect both the pore space and the internal pore connectivity. There was a significant reduction in pore space after vibration, and in pore connectivity as measured by the fragmentation index. There were more elongated pores in the horizontal direction than in the vertical direction before vibration, but the difference became negligible after vibration. This means that vibration might lessen the difference in airflow resistance between the horizontal and vertical directions.

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REFERENCES


