Characterizing tortuous airflow paths in a grain bulk using smoke visualization

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INTRODUCTION

Aeration and drying practices are the common methods for preservation of grain quality during storage. The knowledge of resistance to airflow through grain bulks is critical in the design of grain aeration and drying systems (Crozza et al. 1995; Pagano et al. 2000; Lukaszuk et al. 2008; Kashaninejad et al. 2010; Shahbazi 2011). Traditionally, the airflow resistance has been empirically determined by measuring pressure drop along a bed of grain at different flow rates. Empirical curves of pressure drop for various grains have been established by many researchers and adopted as standards by the American Society of Agricultural and Biological Engineers (ASABE R2011.D272.3 2011). Navarro and Noyes (2002) indicated that the values of airflow resistance obtained from these empirical curves were based on the assumption that resistance to airflow is constant in grain bulks and independent of pore structures. This assumption contradicts the results reported by other researchers who showed that variables like grain kernel size, shape, bed height, porosity, airflow velocity, airflow direction, moisture content, filling methods, and pore structures all have significant effects on airflow resistance through grain bulks (Neethirajan et al. 2006; Lukaszuk et al. 2008; Shahbazi 2011). Wu and Yu (2007) developed an airflow resistance model for porous media that expressed airflow resistance as a function of porosity, particle size and shape. An important feature of the model was that airflow paths in the porous medium were considered to be tortuous.

Tortuous flow of air in porous media is often quantified by an important parameter known as tortuosity. The concept of tortuosity was first introduced by Kozeny (1927) and was later mathematically explained by Carman (1937). Tortuosity is commonly defined as the ratio (or the square of the ratio) of the effective length of the flow path through the porous media to the apparent length. This means that a straight channel has a tortuosity of one, while tortuous airflow through a grain bulk has a tortuosity value greater than one. Based on a literature review, Sobieski et al. (2012) summarized that tortuosity for porous beds consisting of spherical or quasi-spherical particles was in the range of 1.0 to 1.4. Accurately determining the effective flow path length is extremely difficult and simple and accurate direct measurements of tortuosity are still an active research area (Panneton et al. 2001). Theoretical models have been developed to predict the value of...
tortuosity in grain bulks but with limited success. Most of these models used the shortest length or the average of various flow path lengths as the effective length (Maciej and Zbigniew 2012; Sobieski et al. 2012). A variety of experimental methods have been used for indirect estimation of tortuosity. Based on descriptive models of sound propagation in porous media, analytical solutions linking the tortuosity to the measured dynamic density and compressibility could be obtained (Panetton et al. 2001). By measuring a quantity termed the formation factor obtained from the resistivity measurement of a given fluid in a porous medium of a known porosity, researchers have been able to indirectly estimate the values of tortuosity (Garrouch and Lababidi 2001; Attia 2005). Tortuosity may be indirectly estimated through diffusion measurements by relating the diffusion coefficient of a fluid in a porous media to the tortuosity (Barrande et al. 2007). Mercury intrusion porosimetry and ultrasonic reflectivity have been suggested by Webb (2001) and Fellah et al. (2003), respectively, for indirect determination of tortuosity.

Direct measurement of geometrical tortuosity in porous media is possible by image analysis. Vervoort and Cattle (2003) used image analysis to determine the correlation between tortuosity and pore properties (geometry and size) of soil. By analyzing scanning electron microscopy (SEM) images, Wu and Yu (2007) were able to directly measure the path lengths of flow in sodium chloride compacts to obtain quantitative information on tortuosity. Nakashima and Kamiya (2007) developed a suite of Mathematica programs to analyze micro-focus X-ray CT images to quantify the 3D pore connectivity and tortuosity of anisotropic porous rocks. To quantify the 3D microarchitecture of the inter-granular airspace in grain bulks, Neethirajan et al. (2008) used a high resolution X-ray computed tomography system to image grain samples, and based on the 3D images, they calculated such parameters as medial axis tortuosity, throat surface area and porosity.

Tortuosity reflects both the pore geometry and transport properties of porous media. Most research of using image analysis to determine tortuosity has been focused on the measurement of pore geometry without considering the flow. The objectives of this study were: (1) to combine image analysis and flow visualization to include both the pore geometry and flow in direct measurement of tortuosity and airflow paths in a grain bulk; and (2) to study the effect of the airflow rate and fill (bulk) density on tortuosity and flow behavior in the grain bulk.

**MATERIALS AND METHODS**

**Experimental setup**

A transparent box (simulated grain bin) of $27 \times 25 \times 2$ cm, made of 1.6 cm thick Plexiglas, was designed and constructed to conduct the experiment. The test box was designed to have a small thickness (2 cm) to simulate 2D flow and permit effective visualization of the smoke movement in the box (fig. 1). A similar box design was used for studying airflow by Carl and Craig (1999). The bottom of the box had a 1-cm diameter hole for introducing air into the grain contained in the box. The box was placed on a plenum ($25 \times 15 \times 9$ cm) that was used for mixing the smoke into the air stream to visualize airflow.

The grain used in this study was soybeans. Moisture content (8.82% w.b.) was determined by the standard oven method using temperature setting at 105°C for 72 hours as outlined in the ASABE standards (ASABE R2008.S352.2, 2008). The average mass of fifty (50) soybean kernels was measured by using an electronic balance with an accuracy of 0.001 g and the particle density 1178 kg m$^{-3}$ was calculated from ratio of the average mass to the average volume, which was measured by the water displacement method.

The effects of bulk density (or porosity) on tortuosity and flow velocity were studied by testing two different packing conditions: loose and dense fill. Loose fill was accomplished by using a funnel placed 20 cm directly above the test box to allow grain to free-fall into the box (fig. 2). The dense fill was achieved by vibrating the test box after filling. The test box was placed on a vibrating table and shaken for 30 s at a frequency of 15 Hz and amplitude of 0.623 mm (fig. 3). The bulk density obtained by vibration was 755 kg/m$^3$ while the bulk density for the direct funnel filling was 632 kg m$^3$.

The porosity was obtained to be 38% and 42% for the loose and dense fill, respectively, using eq. 1:

$$\phi = \left(1 - \frac{\rho_b}{\rho_p}\right) \times 100$$

(1)

where,

- $\phi$ = porosity of grain bulk (%),
- $\rho_b$ = bulk density (kg/m$^3$),
- $\rho_p$ = particle density (kg/m$^3$).

To study the effect of the airflow rate on airflow paths, three airflow rates (0.25, 0.45, and 0.60 L/s$^{-1}$) were tested. A range of flow rates were tried in preliminary tests and

![Schematic representation of the experimental set-up.](image)
these three rates were chosen to ensure efficient flow of smoke through the soybean bulk, within the capacity of the fan used (0.60 L/s). A fan (4D Coleman Pump, Norman, OK, USA) and an adjustable valve were used to obtain the desired airflow rates (fig. 1). The airflow rate was measured using a bubble flow meter (M-30, A.P. Buck Inc., Orlando, FL, USA).

**Flow visualization and analysis**

A smoke cartridge (S104x, Regin HVAC Product, Oxford, CT, USA) was used (burned) to generate coloured smoke for flow visualization. Cartridges containing different pigments could produce smokes of different colours when burned. Different colours (white, red and blue) were tried and the blue smoke resulted in the best images, thus selected for the experiment. The coloured smoke was introduced into the air stream in the plenum and then channeled into the grain bulk by opening the inlet valve (fig. 1). The movement of smoke was illuminated using a 500W halogen lamp (Slik Pro 700DX, Model – 8330T, Slik Cooperation, Hidaoka, Japan) placed 10 cm in front of the test box. A high-speed camera (Exilim EX-F1 Casio Computers Co., Ltd, Tokyo, Japan) was used to record digital videos of smoke movement at 60 frames per second. The recorded videos were first separated into frames using the commercial software VirtualDub (CRIM, QC, Canada) (fig. 4), and then sequences of individual frames were analyzed to construct the flow paths.

To analyze images of individual frames, image files of 512 by 384 pixels RGB extracted from recorded video frames were read into the ImageJ, an image processing Java-based software developed by the United State National Institute of Health (NIH, Bethesda, MD, US). The images were analyzed first by subtracting a background image of the grain bulk taken before the smoke was introduced to separate smoke from the grain. It should be noted that this background image was obtained with the same field of view and camera settings as that for images of smoke flowing through the grain bulk. Before subtraction, the background image and the image sequence were converted into 8-Bit images and then to inverted images to enhance the subtraction process in ImageJ (figs. 5 - 6).

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**Fig. 2.** Filling soybeans into the test box.

**Fig. 3.** Vibrating the test box after filling to achieve dense fill.

**Fig. 4.** An example of image frames (sequence) extracted from high-speed video.
Subtraction of the background image from the smoke image sequence produced a new image sequence that showed only the smoke (fig. 7).

To enhance the visibility of smoke in the image, the subtracted image sequence was then thresholded to further separate the flow of smoke from the grain itself and other image artifacts, creating binary images with intensity value of 1 (white) for the smoke and 0 (black) for other objects in the image (fig. 8).

The airflow (smoke) paths were then traced using the ImageJ manual tracking plug-in. Tracing started from the point at the bottom of the test box where the smoke was introduced. The bar scale function in the ImageJ was used for converting the image pixels to the actual size referenced to the test box size, resulting in a scale factor of 20.401 pixel cm$^{-1}$. The length of each airflow paths was measured and tortuosity was obtained by dividing the measured length of the airflow path by the apparent length using equation (2) below,

$$\tau = \frac{L_{\text{eff}}}{L_{\text{app}}}$$  

where,

$\tau$ = tortuosity,

$L_{\text{eff}}$ = effective length of flow path (m),

$L_{\text{app}}$ = apparent length of flow path (m).

The velocity of airflow was obtained from the distance traveled by smoke between two consecutive frames, divided by the time interval between the two consecutive frames (1/60s).

**RESULTS AND DISCUSSION**

As soon as the air entered the grain bulk, it started to branch (spread), resulting in multiple flow paths (fig. 9). In the following sections, the average tortuosity and flow velocity of all identified paths were first analyzed, and then the longest, shortest and fastest paths were discussed.
Average tortuosity
The average tortuosity values obtained in this study, for all identified flow paths, fell within the range of 1.0 to 1.6, which was similar to that estimated by Yu et al. (2006). And also the average tortuosity of the shortest paths was 1.14, which approximately equals the value of tortuosity for the shortest path obtained theoretically by Sobieski et al. (2012) and experimental values obtained with CT images by Neethirajan et al. (2006). The measured tortuosity values in this study were within the range of those calculated by various empirical equations (Table 1).

The average length of the airflow path increased as the flow rate increased, and this consequently led to increasing tortuosity. Specifically, as the flow rate increased from 0.25 to 0.60 L/s, the average tortuosity increased from 1.17 to 1.31 for the loose fill, and the corresponding change for the dense fill was from 1.20 to 1.38 (Table 2). The effect of flow rate on tortuosity was found to be statistically significant (P<0.05).

The higher values of tortuosity at higher airflow rates reflected longer, more complicated, and tortuous flow paths inside the grain bulk. This might be attributed to increased “branching” or “spreading” of the flow within the pores of the grain bulk as the flow rate increased. Given that the grain bulk had a fixed amount of pore space, when more air was forced through the bulk; it would flow through more branched paths. Smoke images showed that at 0.60 L/s the area covered by smoke (all flow branches) was 203.73 cm$^2$, whereas the covered area for 0.25 L/s was 122.34 cm$^2$ (fig. 10). This indicated that there were more flow branches for the higher flow rate (0.6 L/s) than the lower flow rate (0.25 L/s).

Table 1. Comparison of measured tortuosity values with empirical models ($\phi =$ porosity).

<table>
<thead>
<tr>
<th></th>
<th>Loose fill $\phi = 0.39$</th>
<th>Dense fill $\phi = 0.27$</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>1.23</td>
<td>1.30</td>
<td>Present study</td>
</tr>
<tr>
<td>$\tau^2=2-\phi$</td>
<td>1.27</td>
<td>1.32</td>
<td>Peterson(1958)</td>
</tr>
<tr>
<td>$\tau^2=1-ln\phi/2$</td>
<td>1.21</td>
<td>1.28</td>
<td>Akanni et al. (1987)</td>
</tr>
<tr>
<td>$\tau^2=1+Pln\phi/2$</td>
<td>1.21</td>
<td>1.54</td>
<td>Comiti and Renaud (1989)</td>
</tr>
</tbody>
</table>

Table 2. Average tortuosity at different flow rates and fill densities (*standard deviation)

<table>
<thead>
<tr>
<th></th>
<th>Flow rates (L/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.25</td>
</tr>
<tr>
<td>Loose fill</td>
<td>1.17±0.04**</td>
</tr>
<tr>
<td>Dense fill</td>
<td>1.19±0.02</td>
</tr>
</tbody>
</table>

Fig. 7. An example of subtracted image (the original image was inverted for visual illustration).

Fig. 8. An example of thresholded image (the original image was inverted for visual illustration).

Fig. 9. General pattern of air flow through the grain bulk (the original image was inverted for visual illustration).
Tortuosity has been considered by many researchers as a constant geometrical property (Hilmi and George 2000; Garrouch and Lababidi 2001; Barrande et al. 2007; Shang and Chen 2007; Arthur et al. 2011), however, the results of this study showed that tortuosity varied with flow rate. That is, tortuosity was not only a geometrical property that depends on the pore structure, but also was affected by the flowing fluid inside the porous medium. It is possible to have different values of tortuosity for different flow processes taking place in the same porous medium. Kaponen et al. (1996) stated that the preferred definition of tortuosity should be based on the flow context and the porous structure of the medium. Francisco and Peter (2011) and Manuel et al. (1999) reported that tortuosity was a function of the flow velocity because the flow path length was a function of the fluid flow, as well as the system microstructure. This same trend was observed by Yu et al. (2006) in their study of tortuosity in porous compacts; they concluded that the tortuosity values increased as the propagation speed increased. Different values of tortuosity could be obtained in the same porous medium depending on the flow rates (Francisco and Peter 2011). The increased tortuosity with increased flow rate observed in this study also supported the conclusion by several researchers that an increase in airflow rate results in higher resistance of airflow in grain bulks because the “tortuosity” of flow increases with the flow rate (Rajabipour et al. 2001; Jekayinha 2006; Kenghe et al. 2012).

The bulk density had a significant (P<0.05) effect on tortuosity (Table 2). For flow rates of 0.25, 0.45 and 0.60 L/s, the average tortuosity value increased from 1.17 to 1.20, 1.22 to 1.30, and 1.31 to 1.38 from loose to dense fill, respectively. This increase in tortuosity was a result of reduction in the pore size, which caused more “branching” of the flow (smoke) in the grain bulk (fig. 11). The total number of tracked smoke paths was 16 for the loose fill and 24 for the dense fill at 0.25 L/s (fig.11). This showed that the dense fill resulted in more branching or spreading of the flow paths than the loose fill at the same flow rate. Hilmi and George (2000) observed that tortuosity increased at greater degree of compaction of grain bulks.
because of greater degree of waviness in flow path caused by the application of higher pressure (compaction) to grain bulks.

Many researchers have reported that tortuosity increases as porosity decreases in porous media (Kaponen et al. 1996; Manuel et al. 1999; Barrande et al. 2007; Shang and Chen 2007; Cedric et al. 2009; Rahul et al. 2010; Arthur et al. 2011). For example, Cedric et al. (2009) measured tortuosities of sandstone and clay soil using X-ray and electron topographic reconstruction methods, and concluded that tortuosity increased with reduction in porosity.

**Airflow velocity at pore level**

The velocity of air flowing through the pores is one of the most important variables in defining porous media flow. The measured velocity at the pore level (pore velocity) was much higher than the nominal velocity determined as the airflow rate divided by the cross-sectional area (Table 3). For example, the measured pore velocity was 12.5 cm/s, while the nominal velocity was 5 cm/s for the dense fill at 0.25 L/s.

**Table 3. Airflow velocities at different flow rates and fill densities (*standard deviation).**

<table>
<thead>
<tr>
<th></th>
<th>Flow rate (L/s)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>0.25</td>
</tr>
<tr>
<td>Pore velocity (cm/s)</td>
<td></td>
</tr>
<tr>
<td>Loose fill</td>
<td>17.3</td>
</tr>
<tr>
<td>St.dev.*</td>
<td>3.0</td>
</tr>
<tr>
<td>Dense fill</td>
<td>12.5</td>
</tr>
<tr>
<td>St.dev.*</td>
<td>4.7</td>
</tr>
<tr>
<td>True velocity (cm/s)</td>
<td></td>
</tr>
<tr>
<td>Loose fill</td>
<td>10.7</td>
</tr>
<tr>
<td>Dense fill</td>
<td>13.8</td>
</tr>
</tbody>
</table>

Fig. 12. Effect of flow rate on tortuosity of the shortest, longest, and fastest path of shortest, longest and fastest path for loose fill.

Fig. 13. Effect of flow rate on tortuosity of the shortest, longest, and fastest path of shortest, longest and fastest path for dense fill.

0.25 L/s. Since the nominal velocity does not consider the cross-sectional area occupied by the particles, it is expected that nominal velocity is lower than the pore velocity. If only the pore space was considered as the available area for airflow, the average “true” velocity could be estimated as the nominal velocity divided by the porosity. This average true velocity was estimated to be 13.8 cm/s for the dense fill at 0.25 L/s, which was close to the average measured pore velocity (12.5 cm/s).

The pore velocity increased with the airflow rate as expected. As the flow rate increased from 0.25 to 0.60 L/s, the average pore velocity increased from 17.3 to 27.1 cm/s for the loose fill, and from 12.49 to 19.65 cm s\(^{-1}\) for the dense fill (Table 3). The ANOVA analysis results showed that the fill density had a significant (P<0.05) effect on the pore velocity. It was expected that the calculated “true” flow velocity increased with the density because of reduced pore space (flow area) (Table 3). However, it was observed that the pore velocity decreased as the fill density changed from loose to dense fill (Table 3). For 0.25, 0.45 and 0.60 L/s flow rates; the average flow velocity changed from 17.3 to 12.5 cm/s, 23.8 to 16.9 cm/s and 27.1 to 19.7 cm/s from loose to dense fill, respectively. The reduction in the flow velocity at higher density might be attributed to several reasons, including flow spreading. Because air (smoke) was introduced to the grain bed through a single point in the current study, reduction in pore space at higher density caused more “branching” of the airflow path (Fig. 11). In other words, individual flow channels were smaller, but there were more channels, and thus the total amount of pore space for airflow (flow area) could be more at higher...
density. It should be cautioned that this phenomenon would not occur if the air were introduced uniformly (instead of through a single point) to the grain bed.

**Multiple flow paths in grain bulk**

When air flows from one point to another point in a grain bulk, multiple paths are possible. In this section, the multiple flow paths in the grain bulk were categorized into the longest, shortest and fastest paths and their respective tortuosity and velocities were calculated. The influence of the flow rate and the bulk density on tortuosity and velocity of the shortest, longest and fastest path follow the similar trends as the average flow paths discussed earlier. That is, the tortuosity of all flow paths increased with flow rate. However, the effect of flow rate on the fastest path was more pronounced (figs. 12 and 13).

As the flow rate increased from 0.25 to 0.60 L s\(^{-1}\), the tortuosity of the shortest path increased by about 14% for the loose fill and 15% for the dense fill. The corresponding increases in tortuosity were 24% for the loose fill and 28% for the dense fill for the fastest path.

It was of interest to observe that the tortuosity of the fastest paths was very close to that of the shortest path at a lower flow rate. However, the tortuosity of the fastest path was very close to that of the longest path at the high flow rate (0.60 L s\(^{-1}\)). In other words, the shortest path was not always the fastest path inside the grain bulk. This observation is consistent with the observation made by Yu et al. (2006) in their study of flow path length as a measure of tortuosity. They observed that when the propagation speed was low the fastest path stayed rather straight and short and the tortuosity was only marginally higher than one.

Among the three characterized airflow paths (shortest, longest, and fastest paths), the fastest path had the highest flow velocity, and the difference in flow velocity between the shortest and longest paths was not significant (P>0.05) (figs. 14 and 15). The flow velocity increased with the flow rate for the fastest paths for both loose and dense fill densities, but decreased with the bulk density. However, the effect of flow rate and bulk density on the flow velocity was not apparent for the shortest and longest paths (figs. 14 and 15).

**CONCLUSION**

Smoke visualization coupled with imaging processing techniques provided a useful tool to investigate airflow through grain bulks at a microscopic (pore) level. Tortuosity was not only a geometry property varying with the pore structure, but also dependent on the characteristics of the flowing fluid inside the porous medium. Specifically, the tortuosity increased with not only the bulk density but also the flow rate.

Tortuosity of the fastest paths was close to that of the shortest path at a lower flow rate. However, at high flow rate, the tortuosity of the fastest path was close to that of the longest path. This implied that the shortest path was not always the fastest path inside a grain bulk. The airflow velocity at pore level was much higher than the nominal velocity. There was no significant difference in flow velocity between the shortest and longest paths.

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