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X-ray Computed Tomography Image Analysis to explain the Airflow Resistance Differences in Grain Bulks

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X-ray computed tomography (CT) is a technique that uses X-ray images to reconstruct the internal microstructure of objects. A high-resolution X-ray CT system with a resolution of 120 μm was used to scan slices of grain bulks. Grain bulks of wheat, barley, flax seed, peas and mustard were scanned along horizontal and vertical directions. The X-ray CT images were analysed to explain the airflow resistance difference along the horizontal and vertical directions of grain bulks. Total airspace, airpath distribution and size of airpaths were determined from the images. Morphological information of the airpaths from the tomographic images showed that the size and number of airpaths vary between horizontal and vertical directions of many grain bulks. Airpath area and airpath lengths along the horizontal direction were 100% higher than in the vertical direction for wheat, barley and flax seed bulks, where as for pea and mustard bulks, they were only 30% higher in the horizontal direction than in the vertical direction. The numbers of airpaths along the horizontal direction for wheat, barley and flax seed, respectively, were 92%, 145% and 187% more than along the vertical direction. In pea and mustard bulks, however the increase in the number of airpaths was only 28% and 17%. The ratio of total airspace area to the total number of airpaths in the grain bulk is the best predictor for the difference in the airflow resistance in horizontal and vertical directions in the grain bulk.

1. Introduction

Cereals and oilseeds are a major source of food for humans and most domesticated animals throughout the world. In North America, grains are normally stored in free-standing bins varying in capacity from 25 to 250 t. The key to safe storage of grain is to store clean, dry grain in insect free structures and to maintain grain temperatures as cool as possible. To achieve this, air is often forced through a grain bulk either to dry or to cool the grain.

The airflow rate through the packed grain bed determines the rate of drying or cooling. To design grain cooling and drying systems, information on the airflow resistance of grains is needed. The determination of this resistance is essential for designing an energy-efficient forced ventilation system (Matthies & Peterson, 1974). The airflow pressure drop relationships are basic inputs to the mathematical models for predicting the pressure pattern and airflow distribution within the stored grain mass (Brooker *et al*., 1974; Jayas *et al*., 1990).

The resistance to airflow through grains is affected by several factors such as air velocity and viscosity, moisture content of the grain, shape and size of kernels, grain surface roughness characteristics, configuration of voids, amount, size and distribution of foreign materials, method of filling and direction of airflow. Several researchers have conducted experiments to determine the effect of these parameters on the resistance to airflow through grains (Kumar & Muir, 1986; Jayas *et al*., 1987, 1991; Alagusundaram *et al*., 1992). They also determined that there is a difference in airflow resistance between horizontal and vertical directions in seed bulks.

Until now, no scientific effort has been made to explain why there is a difference in airflow resistance between horizontal and vertical directions of grain bulks. Some plausible explanations have been reported in the literature (Jayas *et al.*, 1987) providing new knowledge on the importance of airflow direction and packing on resistance of grains to airflow.

X-ray computed tomography (CT) is a non-destructive technique that measures variations in material density. X-ray CT can be used as an alternative way to determine both porosity and pore size distribution within an object (Tollner, 1993). Microstructure of an entire airpath inside grain bulks can be measured down to details comparable to the resolution of the instrument. Thus, the airpath distribution can be determined from the X-ray CT images of grain bulks.

The objective of this study was to explain the reason behind the airflow resistance difference along the horizontal and vertical directions of different grain bulks.

2. Materials and methods

2.1. *Sample preparation*

Five types of grains were selected for CT scanning based on their shape to give potentially different airflow paths. These were hard red winter wheat (referred to as wheat, hereafter), barley, flax seed, peas and mustard. Of these samples wheat, barley and flax seed are oblong in shape while peas and mustard are almost spherical. All the grain samples were further sifted manually to remove stone, straw and chaff particles.

The sample containers were made of acrylic material, which is radiometrically translucent to the X-rays. The resolution of the X-ray CT image depends on the size of the sample. For smaller seeds like flax seed and mustard, the resolution of the image must be higher to get a clear image. Hence, two sizes of sample containers were used for scanning. Wheat, barley and peas were filled in three separate 15 cm side cubic acrylic containers while flax seed and mustard were filled in two, 7·5 cm side cubic containers. The grains were filled in the containers from the top. To ensure that the orientation of the kernels inside the container does not change while scanning, the containers were shaken well for compaction after filling and cotton was placed on the top of each sample before covering with the lid. During grain filling in the container, the kernels near walls may orient differently than in the middle of the container. Therefore, for wheat, barley and peas the samples were scanned at the middle of the container for a 50 mm thickness (slice thickness × number of slices *i.e.*, $0{\cdot}25 \times 200 = 50$ mm) in both the horizontal and vertical directions and for mustard and flax seed, the samples were scanned for 43 mm thickness (slice thickness × number of slices *i.e.*, $0{\cdot}125 \times 350 = 43$ mm). The samples were scanned in both the horizontal and vertical directions of packed grain bulks (*Fig. 1*).

2.2. *Acquisition of X-ray computed tomography images*

The X-ray CT images used in this study were obtained at the High-Resolution X-ray CT Facility at the University of Texas, Austin. The seed bulks were scanned using the Bio-imaging Research X-ray CT scanner. The X-ray source was operated at 420 kV and 1·8 mA. The samples were scanned along the horizontal direction first and then the containers were rotated 90° for vertical scanning. Table 1 shows the resolution and slice thicknesses of images of different grain bulks.

2.3. *Comparison of bulk density*

The actual bulk densities of the grain samples were calculated using the mass of the grain required to fill the

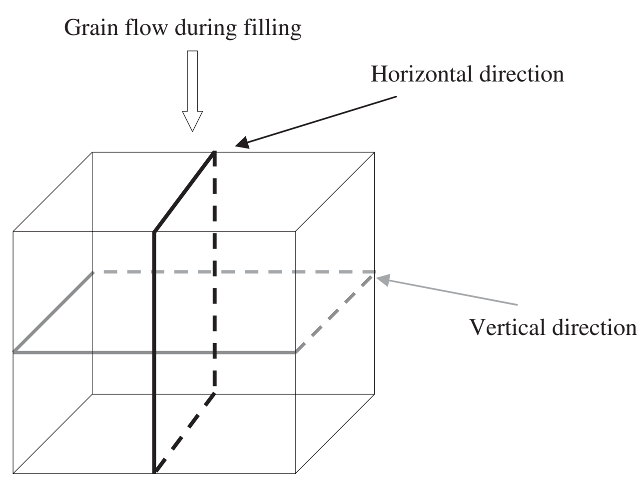

Fig. 1. Schematic showing the relationship between the direction of grain filling and directions of airflow

Table 1
Summary of image characteristics of different grain bulks

Grain type	*Image resolution, µm*	*Slice thickness, mm*	*Number of slices*
Wheat	200	0·25	200
Barley	200	0·25	200
Flax seed	120	0·125	350
Peas	200	0·25	200
Mustard	120	0·125	350

container and the volume of the container. The bulk densities of the grain samples were also calculated from the images. The actual bulk density, and the bulk density calculated from the images were compared with the bulk density of the grains reported in the literature.

2.4. *Image analysis*

Algorithms were developed in MATLAB (version 6.5, The Mathworks Inc, Natick, MA) to analyse the images and to measure the airflow paths. The following image-processing techniques were used to quantify the airflow paths inside the grain bulks:

(i) image cropping to select the region of interest;
(ii) thresholding to remove grain from the air space;
(iii) blob colouring to identify different air paths;
(iv) skeletonisation to determine the length of individual airpaths; and
(v) feature extraction of each airflow path to determine their characteristics.

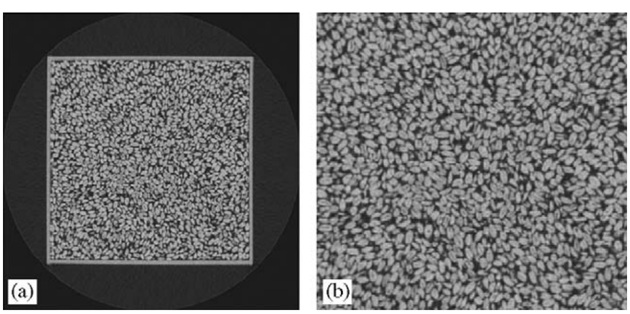

Fig. 2. Single slice of a X-ray computed tomography (CT) scan of a wheat bulk: (a) before cropping and (b) after cropping

2.4.1. *Image cropping*

Each slice of the image was 1024 by 1024 voxels in size. The original CT image of grain bulks included the CT ring and walls of the container. But the region of interest for this study was only the grain and the airspace. Therefore, the CT ring and the sample container wall were removed from the image. Each slice of the original image was cropped and a square sub-image was selected. The sub-image consisted of the maximum number of voxels excluding the rings of scanner and the container wall in the image. *Figure 2* shows the X-ray CT image before cropping and the sub-image of a wheat slice after cropping. The sub-image sizes were 635 by 635 voxels.

2.4.2. *Thresholding*

In this work the images were thresholded (*i.e.* the separation of bright objects against dark backgrounds or *vice versa* using intensity differences) using Otsu's adaptive technique to separate airspace and grain (Yang *et al.*, 1996). The resulting white voxels in the image represent the airflow paths. The histogram and the thresholded images are shown in *Fig. 3*.

2.4.3. *Blob colouring*

The thresholded image was blob coloured to study the distribution and size of airflow paths. A connected component labelling algorithm was written for blob analyses of the X-ray CT images. This algorithm was implemented on the thresholded image. The total number of individual airflow paths was measured based on the number of blob colours in the image. Different colour objects in the image represent different airpaths. A blob-coloured image of the X-ray CT wheat image is shown in *Fig. 4*.

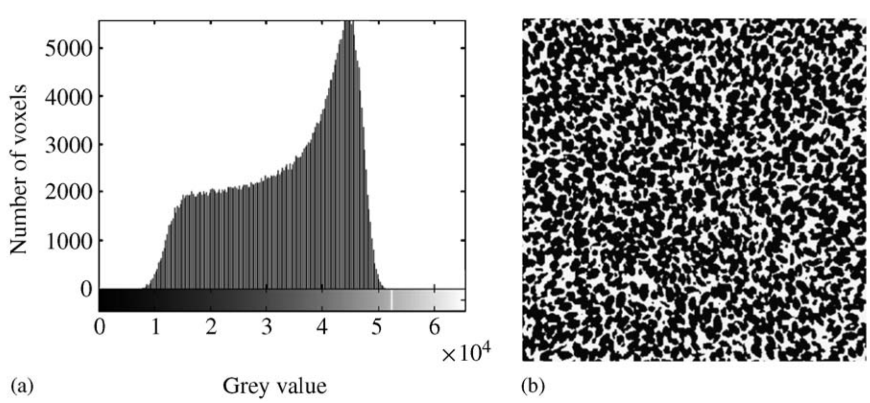

Fig. 3. Object segmentation for a single slice of X-ray computed tomography: (CT) wheat image (a) histogram; and (b) thresholded image

2.4.4. *Skeletonisation*

The skeleton of the X-ray CT image is produced by the morphological thinning algorithm on the thresholded image. The skeleton is useful because it provides a simple and compact representation of a shape that preserves many of the topological and size characteristics of the original shape of airpaths inside grain bulks. The algorithm successively eroded away voxels from the boundary while preserving the end points of line segments. This erosion was done until no more thinning was possible, at which point what was left approximated the skeleton. The obtained skeleton image was a single-stranded sub-set of the original binary image. The length of the individual airflow paths inside grain bulks was determined by summing the voxels in individual skeletons. The skeleton of the X-ray CT wheat image is shown in *Fig. 5*.

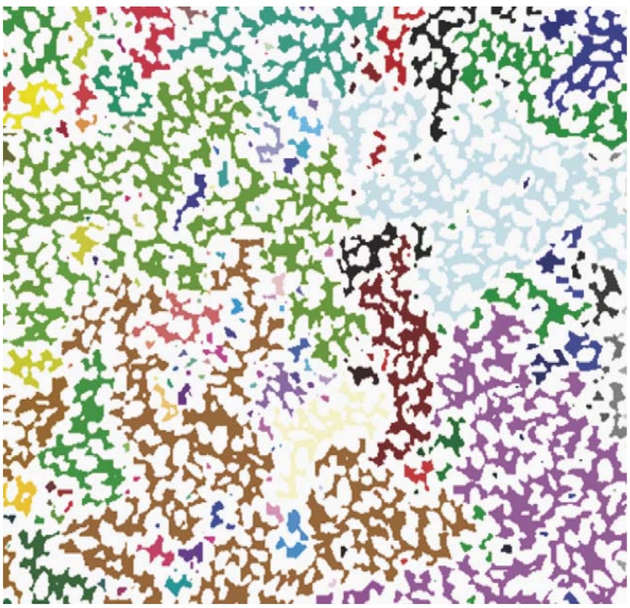

Fig. 4. Blob-coloured image of a typical X-ray computed tomography (CT) wheat image

2.4.5. *Feature extraction*

The features extracted from the X-ray CT grain images were: (i) total grain surface area from the thresholded image; (ii) total airspace area from the thresholded image; (iii) total number of airflow paths from the blob-coloured image; (iv) areas of the individual airflow paths from the blob-coloured image; (v) length of individual airflow paths from the skeletonised image.

The grain sample images for all five grains were analysed by using the above image-processing techniques and features for each grain bulk were extracted for both the horizontal and vertical directions. An independent group *t*-test was done to check the difference between the means of area of airflow paths and the number of airflow paths in both horizontal and vertical directions for all grains (SAS version 8.2, Statistical Analysis Systems, Cary, NC).

3. Results and discussion

Bulk densities of all the grains determined from the images and from the samples compared well with the

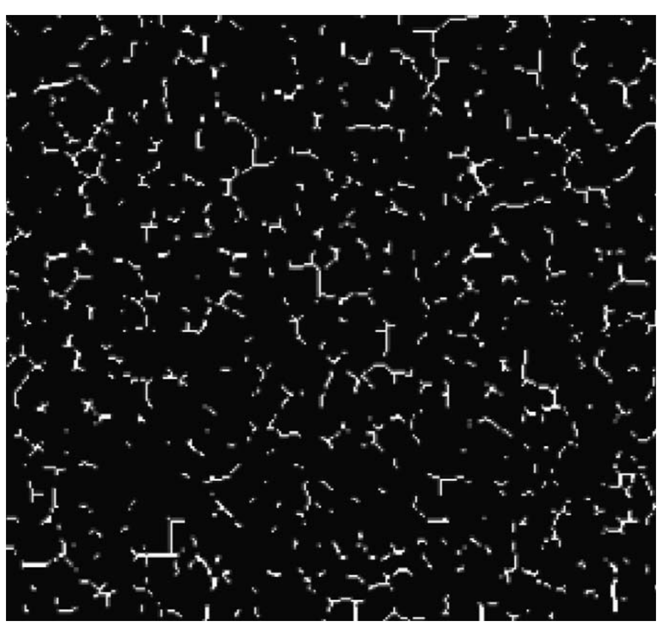

Fig. 5. A sample of the skeletonised wheat image; white lines represent airpaths in grain bulk

Table 2
Comparison of calculated bulk densities of grain samples with the reported values

Grain type	*Calculated bulk density, kg/m³*		*Reported bulk density of the dried seeds, kg/m³*	*Reference*
	Image	*Sample*		
Wheat	750	760	772	Kumar and Muir (1986)
Barley	590	603	610	Kumar and Muir (1986)
Flax seed	625	637	642	Irvine *et al.* (1992)
Peas	364	375	379	Alagusundaram *et al.* (1992)
Mustard	670	684	690	Velasco *et al.* (1998)

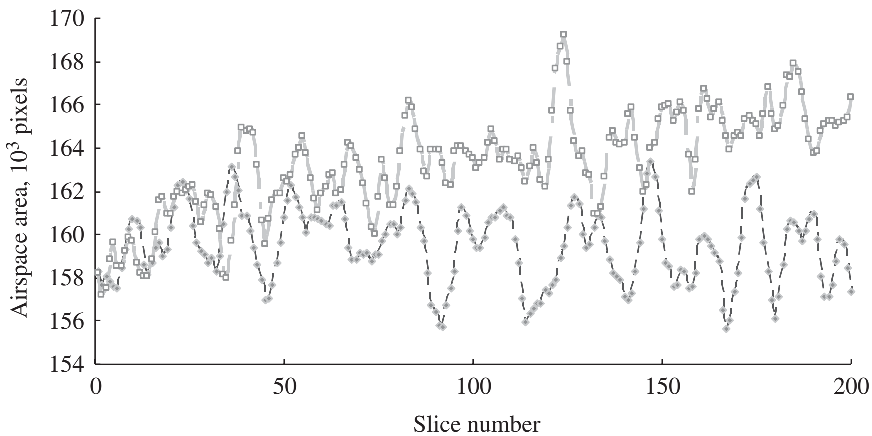

Fig. 6. Distribution of airspace area in different slices of wheat bulk along horizontal and vertical directions; slice 1 corresponds to bottom of the container for vertical direction — —◆— —, horizontal direction; ——□— —, vertical direction

Table 3
Total airspace area and number of airpaths for wheat, barley and flax seed

Grain type	*Total airspace area, pixels*		*Number of airpaths*	
	Horizontal direction	*Vertical direction*	*Horizontal direction*	*Vertical direction*
Wheat	159465 ± 1705	163296 ± 2304	478	249
Barley	163364 ± 1938	170023 ± 2633	504	205
Flax seed	115390 ± 5106	136851 ± 4297	537	188

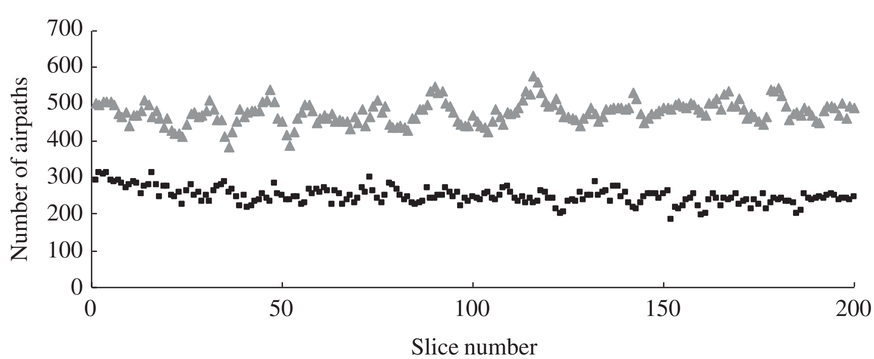

Fig. 7. Number of airpaths in horizontal and vertical directions in different slicies of a wheat bulk; ▲, horizontal direction; ■, vertical direction

reported bulk densities (Table 2). The similar bulk densities imply that samples used in this study are representative of bulk grains in storage bins.

3.1. *Analysis of wheat, barley and flax seed images*

The distribution of airspaces in horizontal and vertical directions in different slices of the wheat bulk is shown in *Fig. 6*. There is compaction of grain from the bottom to the top of the sample container as the airspace area is increasing from slice 1 to slice 200 for the vertical direction. This trend was not observed for the horizontal direction. The compaction was observed in the vertical direction for barley and flax seed as well. Independent group *t*-test between means of airflow path areas of horizontal and vertical directions of wheat, barley and flax seed bulk showed that they were statistically different (probability, $P > 0{\cdot}05$) (Table 3).

The distribution of number of airpaths in horizontal and vertical directions of a wheat bulk is shown in *Fig. 7*. The distribution of area of individual airpaths in wheat bulk is shown in *Fig. 8*. The number of airpaths of the same area in the horizontal direction is almost double that in the vertical direction of the wheat bulk. In the vertical direction, there are larger airpath areas which are not present in the horizontal direction of the wheat bulk [*Fig. 8*(*b*)]. The same trend is observed for both the barley and flax seed bulk (Table 3).

The distribution of the length of airpaths in the horizontal and vertical directions of wheat bulk is shown in *Fig. 9*. The number of smaller airpaths of the same length in the horizontal airspace was almost double that in the vertical airspace for wheat, barley and flax seed bulk. For example, in the horizontal

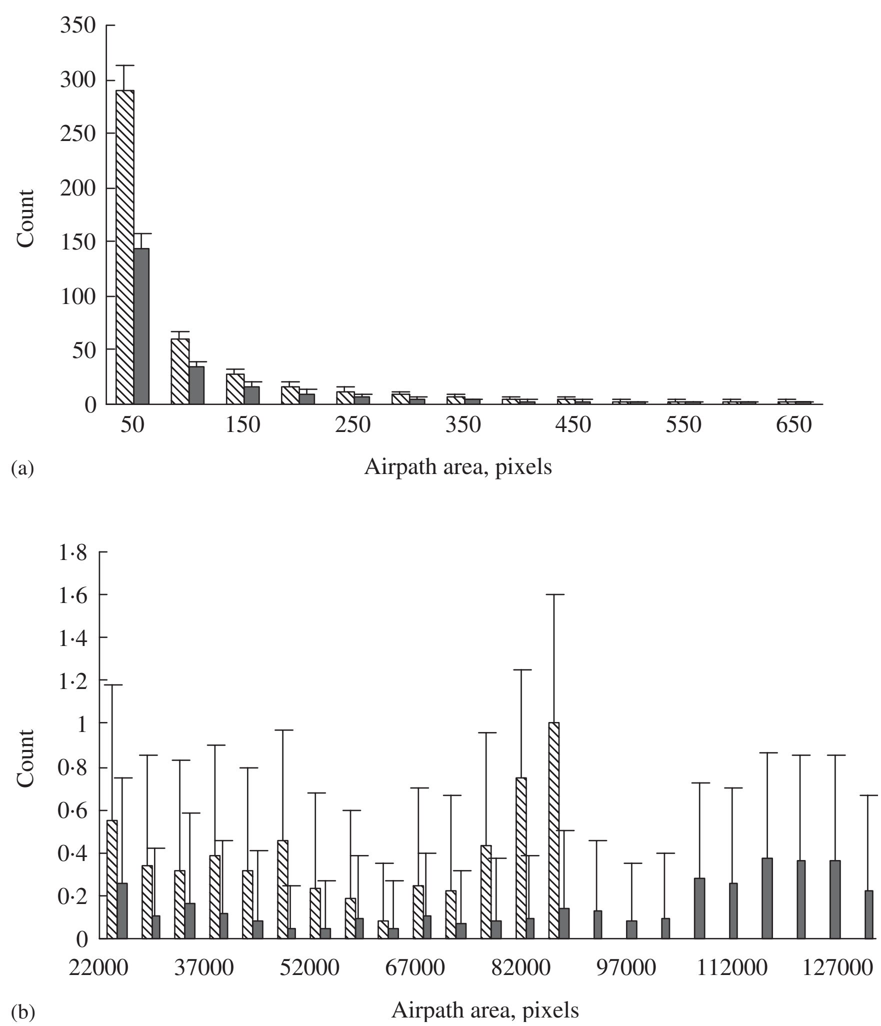

Fig. 8. Frequency distribution on the area of airpaths in horizontal direction (▧) and vertical direction (■) of a wheat bulk: (a) smaller airpath areas and (b) larger airpath areas

airspace of wheat, the number of airpaths with 20 voxel length was 320 whereas in the vertical airspace of bulk wheat, the number was only 160. Smaller area airpaths are distributed uniformly in the horizontal airspace than in the vertical airspace of the wheat bulk [*Fig. 8*(*b*)]. Hence the air can pass through the grain bulk with less resistance in the horizontal direction than in the vertical direction of the grain bulk. This is the reason for the lower airflow resistance in the horizontal direction than in the vertical direction. Airpaths with longer lengths are more numerous in the vertical airspace than in the horizontal airspace of the wheat, barley and flax seed bulk. This is the reason for larger total airspace area in vertical airspace compared to the horizontal airspace.

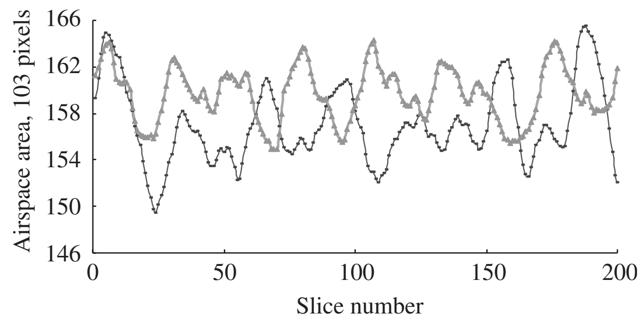

Fig. 10. Distribution of airspace area in different slices of pea bulk along horizontal and vertical directions; slice 1 corresponds to bottom of the container for vertical direction ——, horizontal direction; —▲—, vertical direction

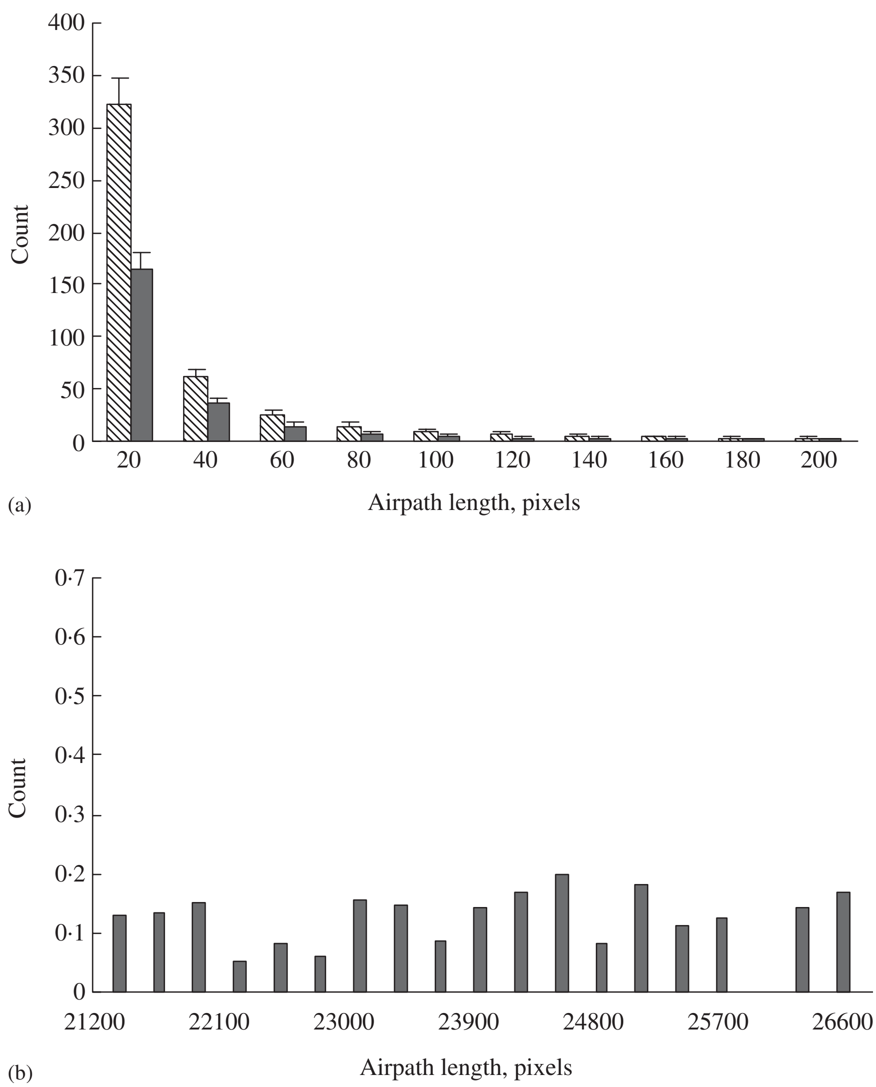

Fig. 9. Frequency distribution on the length of airpaths in horizontal direction (▧) and vertical direction (■) of a wheat bulk: (a) smaller airpath lengths and (b) larger airpath lengths (none observed in horizontal direction)

3.2. *Analysis of peas and mustard images*

The distribution of horizontal and vertical airspaces in a pea bulk is shown in *Fig. 10*. The mean value of the airspace area in horizontal direction in the pea bulk is 157 017 voxels which is equal to the mean airspace area of 159 666 voxels in the vertical direction. Similarly the mean airspace area in the horizontal direction of mustard is 133 289 voxels which is equal to the mean airspace area of 133 228 in the vertical direction.

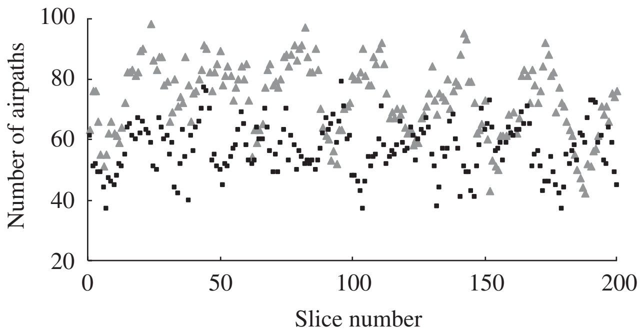

Fig. 11. Number of airpaths in horizontal and vertical directions of different slicies of a pea bulk; ▲, horizontal direction; ■, vertical direction

The distribution pattern of airspace area in a pea and mustard bulk is almost the same in both the horizontal and vertical directions. *Figure 10* shows the distribution of airspace area in pea bulk. There is no compaction of grains from slice 1 to 200 for the vertical direction in the pea and mustard bulk as noted for oblong seeded bulks. This means that all the pea and mustard seeds are equally spaced among themselves during packing in both the horizontal and vertical directions to airflow. Independent group *t*-tests between means of airflow path areas between horizontal and vertical airspace of pea and mustard bulk showed that they are statistically different ($P > 0{\cdot}05$).

The distribution of number of airpaths in horizontal and vertical directions of pea bulk images is shown in *Fig. 11*. The number of airpaths is greater in the horizontal direction than in the vertical direction for pea

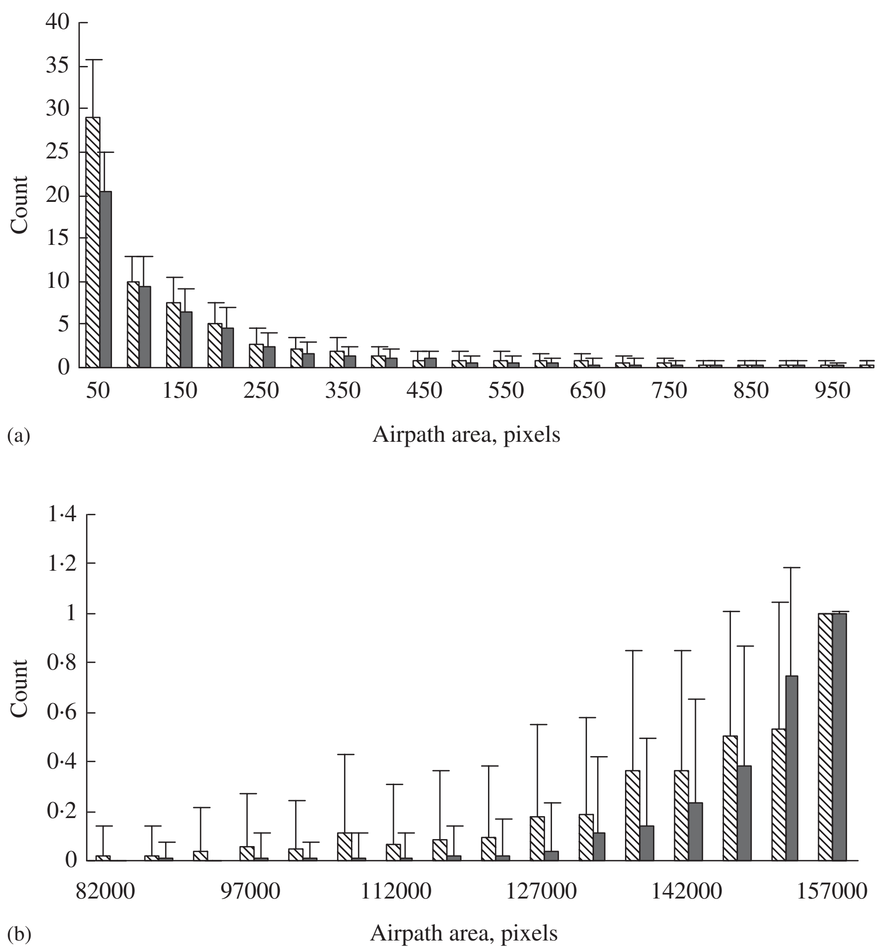

Fig. 12. Frequency distribution on the area of airpaths in horizontal direction (▧) and vertical direction (■) of a pea bulk image: (a) smaller airpath areas and (b) larger airpath areas

and mustard bulks. The mean value of the number of airpaths in horizontal direction is 72 while the mean value in the vertical direction is 59 in the pea bulk. The numbers of airpaths along the horizontal direction are 28% and 17% more than vertical direction for pea and mustard bulk, respectively. But for wheat, the increase is 92%.

The distribution on area of airpaths in horizontal and vertical directions of pea bulk is shown in *Fig. 12*. Almost same area of airpaths is present in both horizontal and vertical directions of the pea and mustard bulks.

There is almost the same length of airpaths distributed uniformly in both the horizontal and vertical directions of pea bulk (*Fig. 13*). The same pattern is observed for both the larger and smaller airpath lengths in the airspaces of pea bulk. Unlike peas, more number of larger airpaths is in the vertical direction of the mustard bulk than in the horizontal direction.

3.3. *Comparison of airflow resistance for oblong and spherical bulk seeds*

The difference between the horizontal and vertical airspace area for wheat, barley and flax seed are 2·5%, 4% and 18%, respectively while for the spherical kernels such as peas and mustard, the difference is only 0·98 and 0·99%. Airpath area and airpath lengths along the horizontal direction are 100% higher than in the vertical direction for wheat, barley and flax seed bulk. However, the airpath area and airpath lengths are only 30% higher in the horizontal direction than in the vertical direction for pea and mustard bulks.

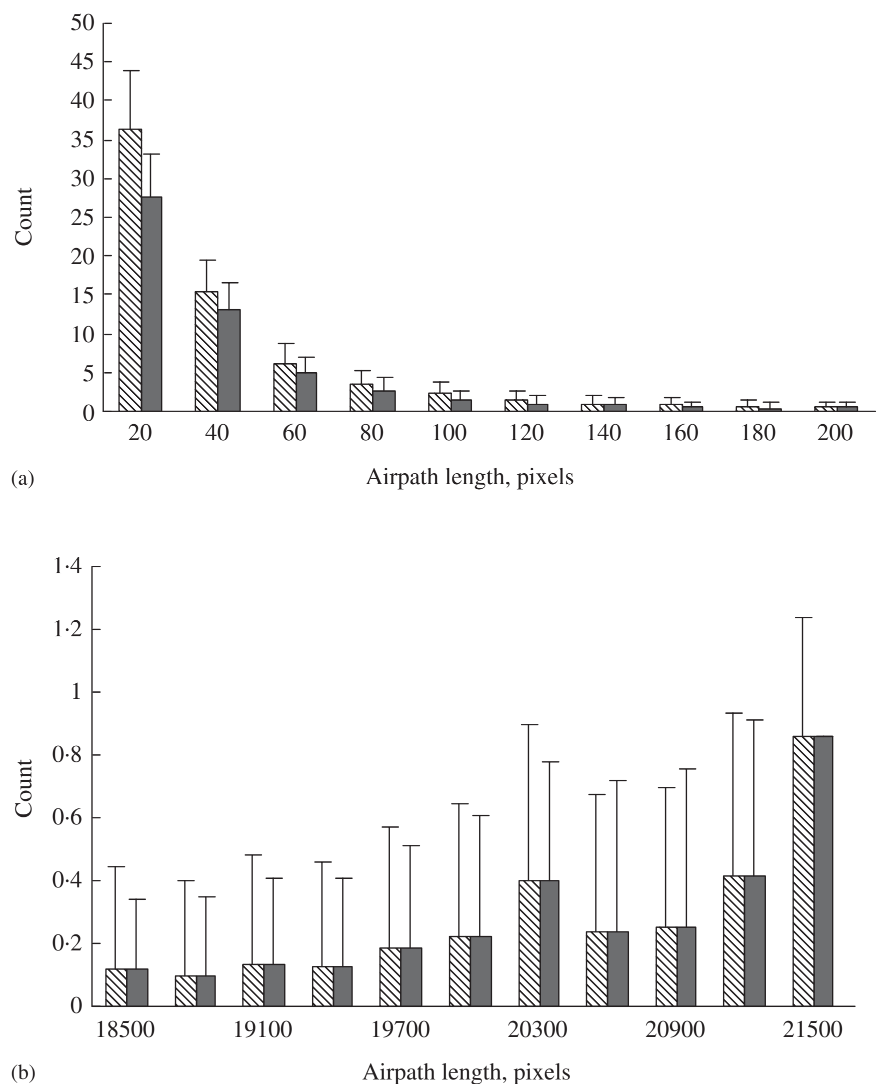

Fig. 13. Frequency distribution on the length of airpaths in horizontal direction (◪) and vertical direction (■) of a pea bulk image: (a) smaller airpath lengths and (b) larger airpath lengths

The ratio of vertical airspace area to the horizontal airspace area is similar for all seed types. This ratio does not explain the difference in reported airflow resistance for wheat and pea bulks. The numbers of airpaths along the horizontal directions are 92%, 145% and 187% more for wheat, barley and flax, respectively, than in the vertical directions, but for pea and mustard bulks, the increase was only 28% and 17%. The number of airpaths seems to explain the airflow resistance difference along the horizontal and vertical direction in the grain bulks (Table 4).

The airpaths are distributed non-uniformly in the vertical direction than in the horizontal direction for the oblong kernels such as wheat, barley and flax seed. For the spherical kernels such as peas and mustard, the airpaths are distributed uniformly in both the horizontal and vertical directions. Non-uniform distribution of airpaths inside the grain bulks is a reason for the airflow resistance difference along horizontal and vertical directions of grain bulks.

The ratio of total airspace area to the total number of airpaths in the grain bulk also explains the reason for the airflow resistance difference along both directions in the grain bulks (Table 5). This ratio is equivalent to the reported airflow resistance ratio.

4. Conclusions

There is significantly more compaction of grains at the bottom than at the top for grain bulks of oblong-shaped kernels. Airspace area is uniformly distributed in both the horizontal and the vertical directions for grain bulks of spherical shaped kernels unlike oblong kernels. Airpath area and airpath lengths along the horizontal direction are 100% higher than in the vertical direction for wheat, barley and flax seed bulk and only 30% higher for pea and mustard bulks. This explains the higher airflow resistance for oblong kernels in the vertical direction of the grain bulk. The number of airpath lengths and airpath areas are higher for oblong kernels than for the spherical kernels. Non-uniform distribution of airpaths and the number of airpaths inside the grain bulks are the reasons for the airflow resistance difference along horizontal and vertical directions in many grain bulks. The ratio of total airspace area to the total number of airpaths in the grain

Table 4
Comparison of airflow resistance ratio with ratio of the number of airpaths

Grain type	*Reported airflow resistance ratio (horizontal to vertical direction)*	*Number of airpaths (vertical direction/horizontal direction)*	*Reference*
Wheat	0·63	0·52	Kumar and Muir (1986)
Barley	0·47	0·40	Kumar and Muir (1986)
Flax seed	0·38	0·34	Irvine *et al.* (1992)
Peas	1	0·82	Alagusundaram *et al.* (1992)
Mustard	0·72	0·85	Velasco *et al.* (1998)

Table 5
Comparison of airflow resistance ratio with the ratio of total airspace area to the number of airpaths

Grain type	*Airspace area to airpath number ratio, voxel*		*HD/VD*	*Airflow resistance ratio horizontal/vertical (Reported values)*	*Reference*
	Horizontal direction (HD)	*Vertical direction (VD)*			
Wheat	333	654	0·51	0·63	Kumar and Muir (1986)
Barley	323	829	0·39	0·47	Kumar and Muir (1986)
Flax seed	214	727	0·30	0·38	Irvine *et al.* (1992)
Peas	2150	2839	0·76	1	Alagusundaram *et al.* (1992)
Mustard	282	332	0·85	0·72	Velasco *et al.* (1998)

bulk explains the reason for the airflow resistance difference along both directions in the grain bulks.

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References

Alagusundaram K; Jayas D S; Chotard F; White N D G (1992). Airflow pressure drop relationships of some specialty seeds. Sciences des Aliments, **12,** 101–116

Brooker D B; Bakker-Arkema F W; Hall C W (1974). Drying Cereal Grains. AVI Pub. Co. Inc., Westport, CT

Irvine D A; Jayas D S; White N D G; Britton M G (1992). Physical properties of flax seed, lentils, and fababeans. Canadian Agricultural Engineering, **34,** 075–081

Jayas D S; Sokhansanj S; Moysey E B; Barber E M (1987). The effect of airflow direction on the resistance of canola (rapeseed) to airflow. Canadian Agricultural Engineering, **29,** 189–192

Jayas D S; Sokhansanj S; Moysey E B; Barber E M (1990). Predicting pressure patterns in canola bins. Canadian Agricultural Engineering, **32,** 249–254

Jayas D S; Alagusundaram K; Irvine D A (1991). Resistance to airflow through bulk flax seed as affected by the moisture content, direction of airflow and foreign material. Canadian Agricultural Engineering, **33,** 279–285

Kumar A; Muir W E (1986). Airflow resistance of wheat and barley affected by airflow direction, filling method and dockage. Transactions of the ASAE, **29,** 1423–1426

Matthies H J; Peterson H (1974). New data for calculating the resistance to airflow of stored granular material. Transactions of the ASAE, **17,** 1114–1149

Tollner E W (1993). X-ray technology for detecting physical quality attributes in agricultural produce. Postharvest News and Information, **4**(6), 149–155

Velasco L; Martinez Jose M; Haro A (1998). Application of near-infrared reflectance spectroscopy to estimate the bulk density of Ethiopian mustard seeds. Journal of the Science of Food and the Agriculture, **77,** 312–318

Yang C; Chung P; Chang C (1996). Hierarchial fast two-dimensional entropy thresholding algorithm using a histogram pyramid. Optical Engineering, **35**(11), 3227–3241