
Tyrone R. Keep†, Scott D. Noble‡

†‡Department of Chemical and Biological Engineering, 57 Campus Drive, University of Saskatchewan, Saskatoon, S7N 5A9, Canada.
*Corresponding author’s Email: tyrone.keep@usask.ca

Abstract

Pneumatic conveying is widely used for transporting granular materials and agricultural products. Traditional flow visualization methods are used extensively in experimental fluid dynamics but have not been commonly used with agricultural products as the flow seeding particle. A flow visualization method that can provide qualitative flow visualization images and quantitative values to describe the flow behavior would be helpful in understanding physical design changes made to agricultural pneumatic conveying systems. The optical flow profiling method developed provides a descriptive visual interpretation of the behavior of the fluid and particles, both upstream and downstream of a 25 mm spherical obstruction. The sphere was attached to the bottom of an acrylic air-line that was conveying wheat particles at an air speed of 20 m/s and a mass flow rate of 5.5 kg/min. Particle occurrence probability density maps were developed to describe the probability of a wheat particle being present in a particular location of the conveying line. The data contained in these maps was used to determine the centroid of the distribution and to plot the change in the cross-sections over the test area of the pneumatic conveying system.

Keywords: pneumatic conveying, flow profiling, product distribution, machine vision, structured illumination

1.0 Introduction

Pneumatic conveying is an important and widely used method of handling agricultural materials. Specifically, the use of dilute-phase pneumatic conveying for transporting seed and granular materials from the air cart (mobile storage tank that dispenses seed and granular fertilizer) to the seeding implement is of interest.

The fluid flow condition most commonly encountered in agricultural pneumatic conveying is dilute two-phase flow. Dilute phase flow is necessary for accurate product splitting and delivery to seeding implements, but it has some disadvantages. It utilizes higher power per unit mass conveyed than other pneumatic systems (Barbosa & Seleghim Jr., 2003) and can cause pipe wear and product damage due to higher conveying velocities (Klinzing et al., 2010). Therefore a flow visualization method needed to be developed that would allow for the evaluation of any improvements to the conveying characteristics developed in future work. The method developed in this paper is closely related to experimental flow visualization methods such as laser light sheet visualization.

The concept of using a laser to illuminate a thin sheet of a fluid flow is not new (Adrian & Yao, 1985; Westerweel, 1997). Laser light sheet flow visualization has been around in many forms since the 1980's and has been used to visualize the behavior of fluid flows seeded with small particles that are assumed to mimic the fluid's behavior (Adrian, 1991). Other methods such as Particle Imaging Velocimetry (PIV), Stereo PIV, and Particle Tracing Velocimetry use and have expanded on many of the same principles of visualizing a flow using laser light and tracer particles (Adrian & Westerweel, 2011).

While these are all well understood techniques in experimental fluid mechanics for seeded flows with very small particles, they are not as widespread in pneumatic conveying systems.
that are designed to convey larger particles. Giddings et al. (2011) undertook a similar study utilizing PIV to image the fluid behavior in a venturi section of a coal conveying system. This study also included a very brief description of the cross-sectional distribution of the particles that were similar in size to coal particles. The main focus of this study and others like it was in the velocity of the particles, not the probability of occurrence in any one location.

If the particle behaviour through flow obstructions (elevation changes or bends) is better understood, conveying power can be potentially reduced while minimizing damage to the seed. Therefore the objective of this study was to develop and test an optical system to image cross-sections of the conveying line to aid in understanding particle behaviour. The system will need to incrementally obtain cross-sectional images upstream, adjacent to, and downstream of the obstruction to visualize the flow behaviour over the region of interest.

2.0 Methods and Materials

An imaging apparatus was developed in order to evaluate the optical flow profiling method that will be used in future work, to explore agricultural product behavior around obstructions in pneumatic conveying systems. The apparatus was used to explore the distribution of transported particles, measured through the use of selective illumination with a red laser. An image of the reflected laser light was recorded and then subsequent images were layered to develop a particle occurrence probability density map (PDM). This image relates the occurrence of particles in any given pixel to intensity of that pixel. The design of the optical flow profiling apparatus and the testing method used in the evaluation of the particle occurrence probability density mapping will be detailed in the following.

2.1 Design and Construction of a Suitable Optical Flow Profiling Apparatus

To enable acquisition of the images needed to construct the probability density maps, an optical flow profiling apparatus was designed and built. A schematic of the apparatus is shown in Fig. 1 with the major components labeled. The optics sled consists of an optical plate, with a 5 mW, 635 nm red laser and a machine vision camera mounted on it. The camera views the cross-section through a mirror and a band-pass filter that allows red light to pass through at the laser’s wavelength. This helps to remove noise due to extraneous lab lighting and enables future side by side testing with lasers of different wavelengths. The laser sheet is created through the use of the 635 nm red laser that is shaped using a cylindrical lens which creates a 30° sheet with a Gaussian intensity profile.

2.2 Implementation and Testing Procedure

The Optical Flow Profiling Apparatus was tested by affixing a 25 mm diameter sphere to the bottom of a clear acrylic section of the pneumatic conveying line, with an outer diameter of 63.5 mm and an inner diameter of 57.15 mm. This disturbance created a very noticeable change in the flow path of the conveyed product that illustrated the applicability of this two-phase flow visualization method. The apparatus was moved along the bearing rails to obtain incremental cross-sections upstream, adjacent to, and downstream of the sphere.

Wheat seed was introduced into a 20 m/s airflow at a mass flow rate of approximately 5.5 kg/min into a single conveying line. The wheat was dispensed from a lab-scale air cart using a stepper motor controlled meter roller. Conveying air was supplied by a three-phase driven centrifugal fan with feedback loop to maintain a stable velocity.
The cross-sections were obtained by acquiring successive images of the flow behavior to develop probability density maps of the location of the particles in the tube. The first step in this process was to develop a reference frame without product flow. The averaged reference frame was then subtracted from the final image to minimize the artifacts caused by the laser’s diffraction through the acrylic tubing. The proof of concept test was completed using Equation (1) with 50 reference frames collected, averaged and then subtracted from each of the 1000 test frames. An example of a single frame (captured with a different camera) taken at the mid-plane of the sphere (12.5 mm) is shown in Fig. 2.

\[ PDM(i, j) = \sum_{k=1}^{N} \left( \frac{I_k(i, j) - R(i, j)}{\sum_{i=1}^{m} \sum_{j=1}^{n} (I_k(i, j) - R(i, j))} \right) \times \frac{1}{N} \]  

Where \( I \) = test image  
\( R \) = reference image  
\( N \) = number of test images  
\( m \) = number of x pixels  
\( n \) = number of y pixels  
\( i \) = x pixel location  
\( j \) = y pixel location
2.3 Analysis and image processing

The averaged cross-sections were post-processed using ENVI+IDL image analysis software to develop the probability density maps and the location of the centroid of these maps. The cross-sections were manually evaluated to determine the center coordinates of the image, as minor variations were observed between imaging locations. The center positions were used to align images prior to resizing and cropping unwanted data. The image was also rotated, masked, and stretched to adjust for perspective distortion. The processed images were then used to calculate the probability density maps and the centroid of each map’s distribution. This was calculated by multiplying the individual pixel intensity by the location of each pixel. This value was then divided by the overall intensity as shown in the following equation.

\[
Vertical\ Centroid\ of\ PDM = \frac{1}{\sum_{i=1}^{m} \sum_{j=1}^{n} PDM(i, j)} \sum_{i=1}^{m} \sum_{j=1}^{n} (PDM(i, j) \times j)
\]  

3.0 Results and Discussions

The probability density maps of the particle occurrence and the resulting centroids were developed upon completion of the testing. From the following results, the particle behavior due to the effect of the obstruction can clearly be determined.

3.1 Particle Occurrence Probability Density Maps

Probability density maps for the occurrence of particles were developed and nine of the most descriptive cross-sections are shown in Fig. 3. These cross-sections are grouped by location: upstream of the sphere’s leading edge, around the sphere, and downstream of the sphere’s leading edge. The location of each cross-section is indicated in the figure with respect to the leading edge of the sphere (the point on the sphere furthest upstream). The striations noticeable in the figure are due to the manufacturing process of the acrylic tube (extrusion marks) which could not be masked from the image as they are caused by reflections off the particles. While they are very noticeable in the final images, they do not affect the conclusions drawn from the data.

The upstream particle occurrence maps indicate a higher probability that a particle would be located in the lower third of the conveying line. 20 mm upstream of the leading edge, a change in the distribution can be seen with a tendency for the product to begin moving to the upper portion of the air line. This trend is reinforced in the cross-sections around the sphere.
The leading edge cross section is slightly different upon first inspection, as it has a much higher probability that a particle would be located at the very bottom of the conveying line. This trend is due to the particles being slowed down by the close proximity of the sphere and influencing the intensity of the laser light reflected.

The downstream cross-sections indicate a very high probability that a particle would be located in the upper third of the acrylic tube with a low probability of particles present in the wake of the sphere. The distribution of particles slowly descends to resemble the upstream distributions as shown in the cross-section taken at 525 mm downstream of the leading edge.

![Figure 3: Particle Occurrence Probability Density Maps. (A) Cross-sections upstream of the sphere’s leading edge; (B) Cross-sections around the sphere; (C) Cross-sections downstream of the sphere’s leading edge](image)

3.2 Centroid of the Particle Occurrence Probability Density Maps

The previously acquired maps provide a qualitative visual interpretation of the flow characteristics. Additionally, the data contained in the maps was used to perform a quantitative analysis of the occurrence of wheat particles. Using the data contained in the pixel intensity, a centroid of the particle occurrence PDM was calculated using Equation (2). The resulting pixel location of the centroid was converted into a distance in millimeters from the bottom of the conveying tube as shown in Fig. 4. The axial profile shows the average distribution of the particles at each test location along the conveying line. It can be seen that the upstream cross-sections have a centroid that is below the center line of the conveying pipe. The sphere’s influence causes a quick drop in the vertical centroid due to stagnant particles being trapped against the sphere. For the rest of the cross-sections, the sphere causes a noticeable vertical increase in the centroid location. This slowly returns to within 3 mm of the starting value 525 mm downstream of the leading edge.
4.0 Conclusions

The optical flow profiling method and apparatus developed for exploring the effect of obstructions or modifiers to the pneumatic conveying behavior were successfully implemented and tested. The flow profiles were qualitatively useful in assessing the flow behavior in addition to being quantitatively used to determine the Centroid of the Particle Occurrence PDM which enabled the visualization of the flow’s axial profile.

It was concluded that the addition of a noticeable flow obstruction could be fully explored and visualized with this method. This visualization method will be used for future pneumatic conveying research in tandem with more conventional pressure and velocity measurements.

5.0 Acknowledgements

The assistance of B. Lozinsky and S. Gregoire in the preliminary design of the optical flow profiling apparatus is gratefully acknowledged by the authors. The staff of the Engineering Machine Shop also deserve thanks for their assistance with design and fabrication of the apparatus.

6.0 References


FIGURE 4: Vertical centroids of particle occurrence PDM at varying cross-section locations

![Graph showing vertical centroids of particle occurrence PDM at varying cross-section locations](image)