Computers and Electronics in Agriculture 118 (2015) 159–166

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

Optical flow profiling method for visualization and evaluation of flow disturbances in agricultural pneumatic conveyance systems

Tyrone Keep, Scott D. Noble *

Department of Mechanical Engineering, University of Saskatchewan, Saskatoon, Saskatchewan S7N 5A9, Canada

ARTICLE INFO

Article history:
Received 7 April 2015
Received in revised form 8 August 2015
Accepted 25 August 2015
Available online 15 September 2015

Keywords:
Air seeder
Pneumatic conveying
Imaging
Laser illumination
Seed transport
Dilute phase flow

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 particles. A flow visualization method was developed to aid in understanding physical design changes made to agricultural pneumatic conveying systems. This optical flow profiling method is demonstrated by providing qualitative flow images and quantitative values to describe the behaviour of the particle flow, both upstream and downstream of a 25 mm spherical obstruction. The sphere was attached to the bottom of an acrylic conveying line that was conveying wheat particles [equivalent diameter: 3.66 mm] at an air speed of 20 m/s and a mass flow rate of approximately 5 kg/min. Probability density maps of particle occurrence were developed to describe the chance of a wheat particle being present in a particular location of the conveying line. The data contained in these maps were 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.

1. Introduction

Pneumatic conveying is an important and widely used method of handling agricultural materials. Specifically, air seeders employ dilute-phase pneumatic conveying for transporting seed and granular materials from the air cart (a mobile storage tank that dispenses seed and granular fertilizer) to the seeding implement (air hoe-drill or disc-drill). This method of seeding is popular for planting wheat and other small and medium grains in large fields in western Canada, the U.S. Midwest, Australia, Ukraine and Russia. As these implements have increased in size (the largest have planting widths in excess of 30 m wide) more attention is being paid to the nature of particle flow in the conveying line.

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 and Seleghim, 2003) and can cause pipe wear and product damage due to higher conveying velocities (Klinzing et al., 2010).

If the particle location through flow obstructions (elevation changes or bends) is better understood, conveying power can be potentially reduced while minimizing damage to the particles conveyed. This is of great interest in air seeder design and development, among other applications. Therefore the objective of this study was to develop and test an optical system to image cross-sections of a laboratory-based conveying line to aid in understanding particle behaviour, and the cross-sectional location in particular. 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.

The concept of using a laser to illuminate a thin sheet of a fluid flow is not new (Adrian and Yao, 1985; Maas et al., 1993; Westerweel, 1997; Yan and Rinoshika, 2011). Laser light sheet flow visualization has been around in many forms since the 1980s and has been used to visualize the behaviour of fluid flows seeded with small particles that are assumed to mimic the fluid's behaviour (Adrian, 1991). Other methods such as Particle Imaging Velocimetry (PIV), Stereo PIV, and Particle Tracking Velocimetry (PTV) use and have expanded on many of the same principles of visualizing a flow using laser light and tracer particles (Adrian and Westerweel, 2011).

While these are all well understood techniques in experimental fluid mechanics for flows seeded with very small particles, they are not as widespread in pneumatic conveying systems that are

* Corresponding author.
E-mail addresses: tyrone.keep@usask.ca (T. Keep), scott.noble@usask.ca (S.D. Noble).

http://dx.doi.org/10.1016/j.compag.2015.08.029
0168-1699/

Nomenclature

List of symbols

PDM	particle occurrence probability density map
I	test image
R	reference image
N	number of test images
m	image width (pixels)
n	image height (pixels)
i	horizontal pixel location
j	vertical pixel location
CP	coordinates of the centre pixel of the image
x_{max}	maximum x coordinate of conveying line in the image
x_{min}	minimum x coordinate of conveying line in the image
y_{max}	maximum y coordinate of conveying line in the image
y_{min}	minimum y coordinate of conveying line in the image

designed to convey larger particles. Giddings et al. (2011) used PIV to image the fluid behaviour in a venturi section of a coal conveying system. This study also included a brief description of laser sheet illuminated cross-sectional distributions of coal particles with a size range up to 140 μm. These images were used to visually describe the system but were minimally processed and were not the focus of the research. Yan and Rinoshika (2013) undertook a similar study using high-speed PIV to image large scale particles (≈2 mm). The main focus of these studies and others like them was to determine the velocity of the particles, not the probability of occurrence in a cross-sectional location.

2. Methods and materials

The optical flow profiling method that was developed to explore the location of product flow has two main subsystems: imaging and mechanical. The imaging portion of the apparatus was developed in order to quantify the flow behaviour of large agricultural particles being conveyed, while the mechanical system is used to position, align, and allow for movement along the conveying line.

2.1. Optical system

Selective illumination of a thin cross-section of the conveying line is achieved through the use of a red laser and a line generating optic. This creates a thin sheet of laser light perpendicular to the conveying line and the nominal direction of flow. As particles travel through the sheet of light they are illuminated. An image of this laser sheet and any particles that happen to be passing through it is captured with a machine vision camera and mirror. Subsequent images are taken and together they are used to develop a probability density map (PDM). The intensity of each pixel in the map indicates the probability of a particle travelling through that pixel location within the conveying line.

Fig. 1 shows a schematic version of the optical system with the major components labeled. These include a 5 mW–635 nm laser and a Prosilica GC 1290 machine vision camera (Allied Vision Technologies GmbH, Stadtroda, Germany). The camera has a resolution of 1280 by 960 pixels and was operated at 15 frames per second with an exposure time of 0.05 s. This relatively long exposure was chosen as a compromise between available light, particle blur, and frame rate. The images of the cross section are captured through the use of a mirror and a band-pass interference filter that allows only light with the same wavelength as the laser to reach the camera sensor. This helps to remove noise due to extraneous lab lighting and enables future work with different laser wavelengths in the same enclosure. The laser sheet is created by a 635 nm red laser that is shaped using a cylindrical line generating lens, with a 30° spread with a Gaussian intensity profile. The optical system is mounted on an optics bread board attached to linear bearings and bearing rails. This and the rest of the mechanical system will be discussed in greater detail in the following section.

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 (63.5 mm outer diameter, 57.3 mm inner diameter). 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 with properties as shown in Table 1 was metered at an approximate rate of 5 kg/min into a 20 m/s airflow [$Re_{air\ only}$ - $\approx 7.1 \times 10_4$, $Re_{particle} \leqslant 4.8 \times 10^3$ depending on superficial air velocity]. The wheat was dispensed from a lab-scale air cart using a metre roller controlled by a stepper motor. Conveying air was supplied by an electrically-controlled centrifugal fan with feedback loop to maintain a stable velocity.

Cross-sectional probability density maps for particles were obtained by acquiring and processing successive images of the laser sheet and particles passing through it. An example of a single frame (captured with a different camera) taken at the mid-plane of the sphere (position 12.5 mm in Fig. 1) is shown in Fig. 2.

In addition to particles reflecting light, the tube wall also intercepts and scatters part of the laser sheet to the camera. This artifact needed to be removed from the images as the intense ring of light would oversaturate the compiled image and wash out the much fainter reflections from the particles. The first step in this process was to develop an average reference frame without product flow. The average reference frame was then subtracted from the test images to minimize the artifacts caused due to the scattering of the laser sheet by the acrylic tubing. It was assumed that this tube wall interference was relatively consistent throughout the test. The proof of concept test was completed using Eq. (1) with 50 reference frames collected, averaged and then subtracted from each of 1000 test frames with product flowing. A generalized schematic of this process is found in Fig. 3.

$$\mathrm{PDM}(i,j) = \sum_{k=1}^{N} \left(\frac{I_k(i,j) - R(i,j)}{\sum_{i=1}^{m} \sum_{j=1}^{n} (I_k(i,j) - R(i,j))} \right) \left(\frac{1}{N} \right) \quad (1)$$

Artifact removal was completed on-the-fly as each image was collected using National Instruments LabVIEW data acquisition software with the NI Vision module (National Instruments, Austin, TX.). After artifact removal an average of the images was calculated, as shown in Fig. 4, to obtain a raw probability density map of the particle location within the conveying line.

The normalized cross-section of each location was post-processed using ENVI + IDL image analysis software (Exelis Visual Information Solutions, Boulder, CO.) to develop the probability density maps and to determine the location of the centroid of these maps. An example of an unprocessed image is shown in Fig. 5. The top of the conveying line is to the right of the image.

The cross-sections were manually evaluated to determine the centre coordinates of the image, as minor variations were observed between imaging locations. The x and y coordinates of the pipe