EXPERIMENTAL STUDY ON PARTICLE VELOCITY AND ACCELERATION LENGTH IN PNEUMATIC AND HYDRAULIC CONVEYING SYSTEMS

Nir Santo[1], Dimitry Portnikov and Haim Kalman

[1]*Laboratory for Conveying and Handling of Particulate Solids, Department of Mechanical Engineering, Ben-Gurion University of the Negev, P.O. Box 653, Beer Sheva 84105, Israel, santoni@post.bgu.ac.il*

Particle velocity, acceleration length and velocity profile evaluations are essential for the design and modeling in conveying systems. Although the subject was widely researched, the relationship between pneumatic and hydraulic systems has not been addressed and still lacks a correlation that will be consistent over various operating conditions and materials that concludes both conveying medias. The current paper presents a thorough experimental investigation of the above-mentioned characteristics obtained from 2-in dilute phase pneumatic conveying system and a 2-in hydraulic conveying system. Experiments with various operating conditions and conveyed materials in vertical orientations were conducted. The particle's velocities and locations in the pipe were obtained using a high-speed camera combined with image processing. Data was obtained for each particle allowing an investigation of the effect each component has on the phenomena. Correlations are suggested for the characteristic's evaluation in the range of the tested operating conditions.

KEY WORDS: pneumatic conveying, hydraulic conveying, particle velocity, slip velocity, acceleration length

NOTATION

Ar	Archimedes number
d	Particle diameter (mm)
D	Pipe ID (mm)
L_{acc}	Acceleration length
Re	Pipe Reynolds number
u_f	Fluid superficial velocity (m/s)
u_p	Particle velocity (m/s)
$u_{p\text{-}ss\text{-}v}$	Particle steady state velocity in a vertical pipe (m/s)
ρ	Particle density (kg/m^3)

1. INTRODUCTION

A proper design process for pneumatic and hydraulic conveying systems should take into account the most basic pressure drop per unit length evaluation. In order to properly predict the pressure drop, one needs to know the solid friction factor. The latter will be

ISSN 0867-7964 ISBN 978-83-7717-323-7 DOI 10.30825/4.12-24.2019

most properly evaluated by attaining an accurate estimation of the particle velocity. Another important aspect is the acceleration length and velocity profile of the particles within the acceleration zone. For this reason, knowing the particle's velocity in the acceleration region is crucial for a reliable and efficient system design. There are several conventional ways of measuring the particles velocity (Santo et al., 2018). In this study, a positive pressure pneumatic conveying system and a centrifugal pump operated hydraulic conveying system were used to conduct experiments for determining the particle velocity in a vertical pipe with a variety of materials of different size, shape and density as well as various operating conditions. A high-speed camera was used to measure the individual particle's velocity using a Matlab based image processing algorithm written for this purpose. This allowed us to arrive with a common dimensionless correlation for the particle velocity, acceleration length and velocity profile within the acceleration zone for both conveying medias.

2. EXPERIMENTAL

2.1 THE PNEUMATIC EXPERIMANTAL TEST RIG

Experiments were performed to evaluate particles velocity and acceleration length in a vertical pipeline on a pneumatic experimental setup, 11-meter long horizontal and 5-meter vertical section with 2-in (50 mm) ID (Figure 1). Horizontal pipe was made of galvanized steel and vertical section of transparent glass pipe. A bag filter that was clamped at the end of the vertical section achieved separation of particles from the mainstream. A piston forced particle feeder of 20 cm length and 2 cm ID was installed at the beginning of the vertical section, which allowed the particles to feed at zero velocity with very low concentration. A regulator coupled with a knife valve controlled the air-flow. A hot wire flow sensor was installed before the feeder to measure volumetric flow rate. Inlet air temperature and humidity were also monitored. The experimental set-up is shown in Figure 1 and is also described in detail in previous research (Santo et al., 2018).

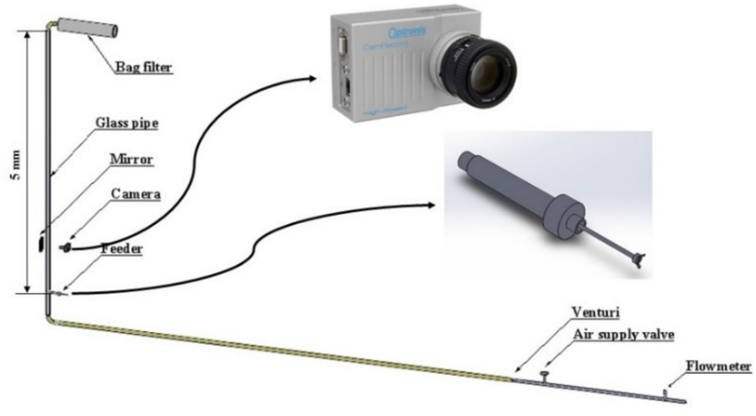

Figure 1. Layout of experimental test rig [D = 50 mm] and high-speed video camera

2.2 THE HYDRAULIC EXPERIMANTAL TEST RIG

The hydraulic test rig (Figure 2) consists of a centrifugal pump that circulates the conveying fluid in a closed loop of 2-in (50 mm) pipes made of galvanized steel with transparent glass sections. A gravitational feeder similar to the one used in the pneumatic test rig was mounted at the beginning of a 4-m transparent pipe section which acts as the primary test section. The particle velocity was measured in several places along the up-stream flow vertical pipe. The particles were collected in a bag filter on the end of the pipe line as shown in the figure.

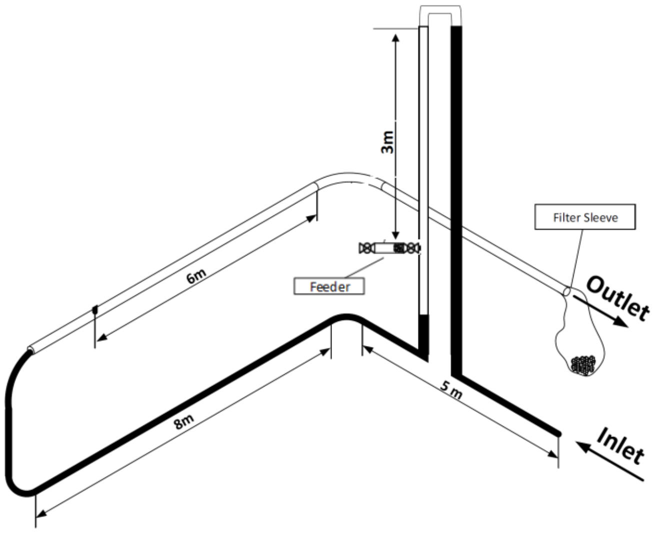

Figure 2. Hydraulic experimental test rig

2.3 PARTICLE VIDEO TRACKING

The particle velocity was measured using a high-speed camera that can capture up to 5000 fps. The videos were investigated using a Matlab image processing code that was written for the purposes of this study. As a part of the image processing, each particle in a frame capture was recognized, and its center of mass coordinates was recorded. The program then identified and followed the particle to the next frame, which allowed us to determine both the distance travelled and the elapsed time and determine the resulting velocity.

2.4 MATERIALS

A verity of materials was tested throughout the research on the pneumatic arrangement as given in Tripathi et al. (2018). The materials differed in size, shape and density. For consolidating the results obtained from pneumatic conveying with the hydraulic conveying, the listed below materials were tested (Table 1).

Table 1

Tested material properties.

Material	**avg size d (mm)**	**Pipe Dia. D(mm)**	**Particle density ρ (kg/m^3)**
Glass beads	2.2	2”	2600
Zeolit beads	2.2	2”	2210
Zirconium beads	2.2	2”	5800
Wheat	3.5	2”	1500

3. RESULTS

3.1 PARTICLE VELOCITY PROFILE

Experiments were conducted at predetermined locations on the vertical transparent pipe starting from feeding point similar to previous research by Tripathi et al. (2018). Each experiment was performed for a specific material flowing through a constant air-flow rate. Similar experiments were repeated for different materials at various operating conditions. Particle average axial velocity has been plotted with respect to axial distance for all tested materials at two different flow velocities: 1.75 and 3.2 m/s. Figure 3 presents the trend of particle velocity of four representative materials (along the axial direction starting from feeding point). It can be seen in the figure that a sharp acceleration is demonstrated at first, becoming moderate further along the pipe. After a certain distance, the velocity seems to stabilize on a constant value suggesting the end of the acceleration zone. Figure 4 presents the trend of particle velocity of zirconium beads with two different flowrates along the axial direction starting from feeding point. It is clear from the graph that with increase of the fluid velocity, particle velocity is also increasing and simultaneously increased requirement of acceleration length to achieve its steady state velocity. These are the common trends for all other materials and is a similar phenomenon to the one observed for pneumatic conveying (Tripathi et al., 2018)

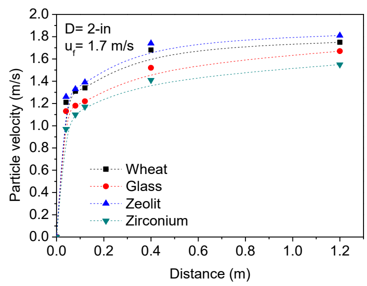

Figure 3. Acceleration trends of four tested materials

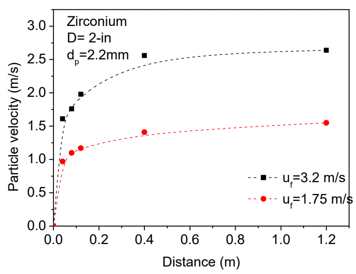

Figure 4. Acceleration trends of zirconium beads at two different flowrates

In prior research by Tripathi et al. (2018), the dependence of the velocity profile on the terminal velocity was described in detail. Based on the above, Figure 5 was plotted. The figure presents the trend of slip velocity between fluid and particles along the axial distance. This graph confirms that as particle velocity increases, slip velocity decreases and subsequently particle attains its terminal velocity. The terminal velocities in the figure were measured separately in a free-fall experimental setup described in Tripathi et al. (2018). Particle velocity at which the slip velocity achieves terminal velocity is called steady state velocity and distance travelled to attain this state is called acceleration length. Particle steady state velocity increases with increase of air velocity resulting in increase of the acceleration length. The phenomenon of Figure 5 confirms that the physical behavior in a vertical pipe is similar for pneumatic and hydraulic conveying in the tested range of experiments.

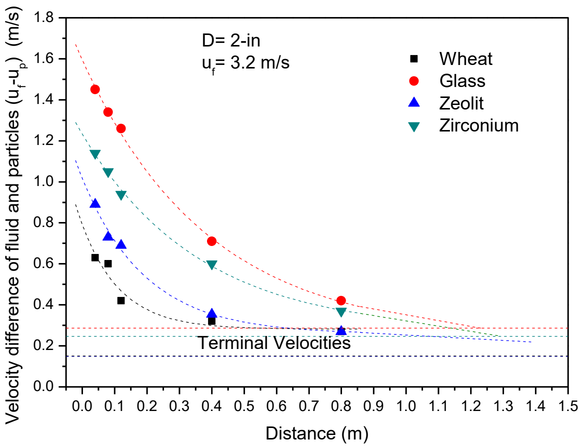

Figure 5. Slip velocity trends of four tested materials

3.2 NORMALIZED PARTICLE VELOCITY PROFILE

Velocity profile in the acceleration region is an important aspect. Each material follows a certain trend at specific operating condition and shows the velocity development in the acceleration region. Velocity profile of a certain material at certain condition assists in the knowledge of actual particle velocity at that location. This helps in getting information regarding particular pressure drop in the acceleration zone for system design. For all materials and operating conditions, local particle velocity has been normalized by the steady state velocity and respective distance has been normalized by acceleration length. Normalized velocity and distance have been plotted on one graph, where it comes on a single trend with ±10% deviation, as shown in Figure 6. Such phenomenon was proposed and analysed in detail in prior research by Tripathi et al. (2018) for pneumatic conveying. Based on the results in this research, the correlation for the velocity profile in a vertical pneumatic conveying pipe given by Tripathi et al. (2018), can now be presented for liquid and gas transportation as follows:

$$\frac{u_p}{u_{p-ss-v}} = \left(1 - e^{-\frac{x/L_{acc}}{A}}\right) - 30 * \left(\frac{x}{L_{acc}}\right)^3 * e^{-\frac{x/L_{acc}}{A}} \quad (1)$$

$$\begin{cases} for\ water: & A = 0.07 \\ for\ air: & A = 0.12 \end{cases}$$

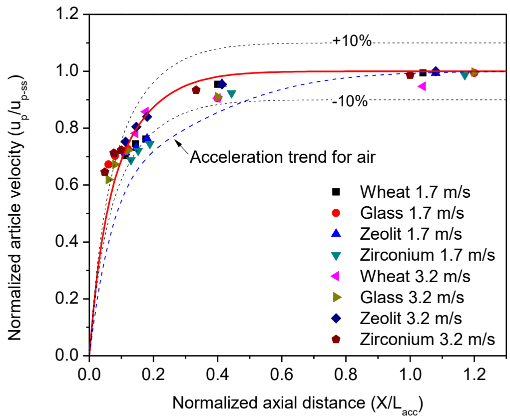

Figure 6. Normalized acceleration trends

3.3 ACCELERATION LENGTH

Acceleration length was measured for conveying velocity and material used as shown in Figure 7. For all materials and conveying conditions, best-fit exponential curve of (u_f-u_p) has been extrapolated up to terminal velocity. Theoretically, the intersection point of (u_f-u_p) curve and terminal velocity line gives the acceleration length. Whereas, practically, it is impossible to get intersection point of (u_f-u_p) curve and terminal velocity point as (u_f-u_p) curves become parallel to the terminal velocity at the stage of fully developed flow. With an approximation of 1%, intersection point of (u_f-u_p) curve and terminal velocity line gives the acceleration length. At the point of intersection, the value of (u_f-u_p) will be 1.01 times of terminal velocity as (u_f-u_p) curve is approaching from higher side. It was also observed that materials of almost same Archimedes numbers had a small deviation in acceleration length; this might be because of difference in Coefficient of Restitution or some other properties. Still, this deviation was within 10% range of derived correlation.

A dimensionless correlation (Equation 2) has been developed to predict acceleration length in a vertical pipe based on the results of Figure 7. It is clear from the correlation that for a particular Archimedes number, the acceleration length increases with increase in air velocity.

$$\frac{L_{acc}}{D} = (B * Re^C - 63.5) * Ar^{0.053} \quad (2)$$

$$\begin{cases} for\ water: & B = 76;\ C = 0.015 \\ for\ air: & B = 2.2 * 10^{-3};\ C = 1 \end{cases}$$

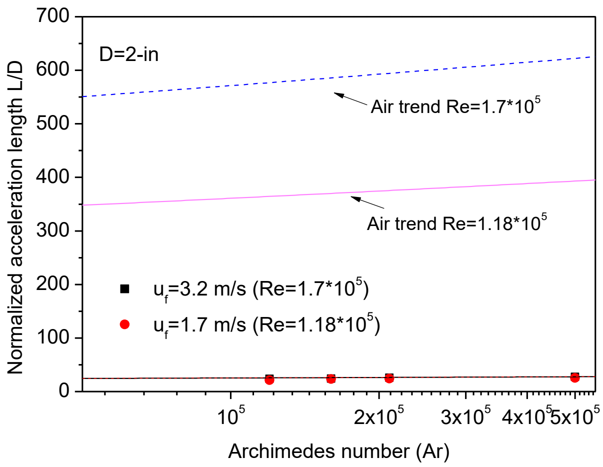

Figure 7. Acceleration length vs. Ar number for air and water conveying

CONCLUSIONS

Accurate solid velocity calculations are crucial for pre-evaluation and design of a conveying system. In this study, the relation between particle and carrying media velocity was examined using a 2-in pneumatic conveying system and a 2-in hydraulic system. A high-speed camera was used in order to measure the velocity of each particle under specific operating conditions. The results show an increase of the particle's velocity with increasing of the conveying media velocity and an increase of the acceleration length with the increase of the conveying velocity and Ar number. Dimensionless correlations from previous study [2] were adapted in order to predict the velocity profile and acceleration lengths in vertical pipes of both pneumatic and hydraulic conveying systems. The correlations are given for the following property ranges:

$$0.06mm < d < 4mm;\ 940\frac{kg}{m^3} < \rho < 5800\frac{kg}{m^3};\quad 3*10^5\frac{m}{s} < Re < 8*10^6\frac{m}{s};$$
$$D = 50mm$$

Future research will focus on the above-mentioned parameters for horizontal conveying.

REFERENCES

1. Santo, N., Portnikov. D., Eshel. I., Taranto. R., Kalman. H., 2018. Expiremental study on particle steady state velocity distribution in horizontal dilute phase pneumatic conveying systems. Chemical Engineer Science, 187, 354-366
2. Tripathi, N.M., Santo, N., Kalman, H., Levy. A., 2018. Experimental analysis of particle velocity and acceleration in vertical dilute phase pneumatic conveying. Powder Technology, 330, 239-251