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EXPERIMENTAL STUDY ON PARTICLE VELOCITY IN HORIZONTAL PNEUMATIC AND HYDRAULIC CONVEYING SYSTEMS

Nir Santo[2], Dmitry Portnikov[2] and Haim Kalman[1,2]

1. *Aaron Fish Chair in Mechanical Engineering – Fracture Mechanics*
2. *Lab for Conveying and Handling of Particulate Solids, Department of Mechanical Engineering, Ben-Gurion University of the Negev, Beer Sheva 8410501, Israel, santoni@post.bgu.ac.il*

Particle and relative velocity evaluations are essential for the design and modeling in conveying systems. Although the subject was widely researched, The relationship between the particle's slip velocity in pneumatic and hydraulic systems has not been adressed and it still lacks a correlation that will be consistent over various operating conditions and materials for both conveying medias. The current paper presents a thorough experimental investigation of particle velocity obtained from a 1", 2" and 3" dilute phase pneumatic conveying system and a 2" hydraulic conveying system with various operating conditions and conveyed materials. The velocity was 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 equivalent velocity. A correlation is suggested for particle slip velocity evaluation in the range of the tested operating conditions.

KEY WORDS: pneumatic conveying, hydraulic conveying, particle velocity.

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 most properly evaluated by attaining the most accurate estimation of the particle velocity. For this reason, knowing the particle velocity in the steady state region is crucial for a reliable and efficient system design. There are several conventional ways of measuring the particles velocity [1].

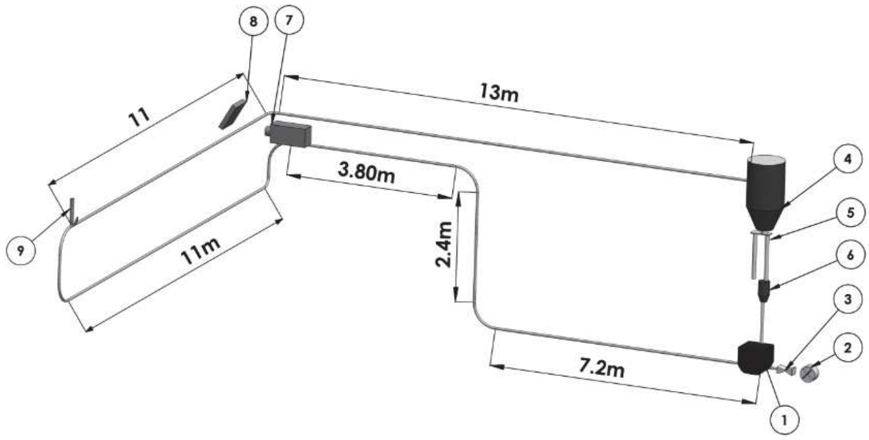
In this study, a positive pressure pneumatic conveying system and a centrifugal pump operated hydraulic conveying system were used to conduct experiments with a variety of materials of different size, shape and density as well as various operating conditions. A high speed camera was used to measure the individual particles' velocity using a Matlab based image processing algorithm written for this purpose. This allowed us to arrive at a dimensionless correlation for the particle velocity.

2. EXPERIMENTAL

2.1. THE PNEUMATIC EXPERIMANTAL TEST RIG

The experimental test rig is shown in Fig 1. It is 55-m in length and made from a 3-in, 2-in and 1-in steel pipe with transparent glass pipe sections.

In order to make sure that the particles were fully suspended and that the measurement area is beyond the acceleration zone, a series of experiments were conducted to identify if any change in velocity occurred within a predetermined distance. It was found that due to the Ventury at the feeder, the initial particle velocity was not zero. This necessitated the use of a new feeder in order to investigate the full range of acceleration. For acceleration experiments a gravitational feeder for very low particle concentrations, was mounted at the beginning of an 11-m straight pipe line, allowing the particles to begin at absolute zero velocity while they are introduced to the pipe line.



Test rig components					
1	Screw feeder	**4**	Bag house separator	**7**	High speed camera
2	Pressure regulator	**5**	Distributor	**8**	Mirror
3	Ventury tube	**6**	Weighing bin	**9**	Gravitational feeder

Fig.1 Pneumatic experimental test rig

2.2. THE HYDRAULIC EXPERIMANTAL TEST RIG

The hydraulic test rig (Fig 2) consists of a centrifugal pump that circulates the conveying fluid in a closed loop of 2-in 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 6-m transparent pipe section which acts as the primary test section. In order to make sure that the particles were fully suspended and that the measurement area is beyond the acceleration zone a series of experiments were conducted to identify if any change in velocity occurred within a predetermined distance.

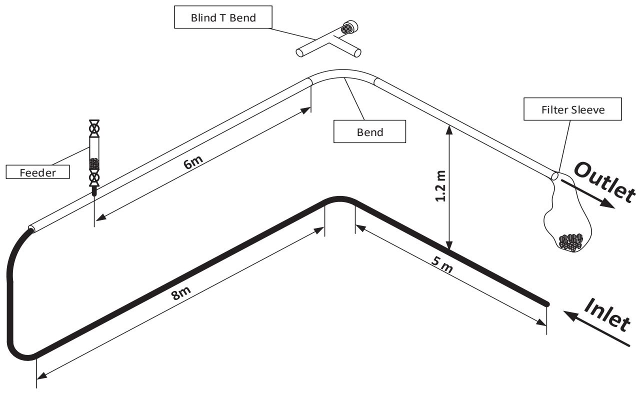


Fig.2 Hydraulic experimental test rig

2.3. PARTICLE VIDEO TRACKING

The particle velocity was measured using a high speed camera that can capture up to 5000 fps. Three dimensional velocity measurements were achieved by using a mirror (8) as shown in figure 1. The video was then 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. In the same manner, the three dimensional velocity was measured, where it was then necessary to correlate between the particles both from the direct image and the mirrored one.

2.4. STEADY STATE DETERMINATION AND BOUNDARY CONDITIONS

Preliminary experiments were conducted on a variety of tested materials in order to make sure that the particles are fully suspended and in the steady state zone. These experiments were done by high speed recording of a transparent section of the pipe in several points along the line starting at the feed point. An analysis of the change in the particles average velocity as the flow develops was defined up to a point where the change of velocity was noted to be lower than a pre determined value. The velocity data was acquired both for the axial direction (the direction of the flow) and for the cross-sectional vertical velocity. For each of the materials, the steady state experiments were conducted after the identified acceleration zone. Figure 4 and 5 shows a representative example of the velocity development in the axial and vertical directions up to the steady state flow for pneumatic and hydraulic conveying respectively. The horizontal axis represents the distance and the vertical axis represents the particle velocity in the horizontal and vertical directions respectively. The values that are given for the vertical component of the velocity are the average absolute values regardless of the direction of the particles (flowing up or down). In pneumatic conveying, it can be seen that while the average axial particle velocity increases along the pipe line and stabilizes at a final steady state value, the velocity in the vertical direction decreases. The decrease in the vertical component of the velocity indicates a more stable axial flow. In hydraulic conveying (figure 5), while the vertical component of the velocity acts similarly to pneumatic conveying, there is a difference in the development of the axial component of the velocity. It was commonly observed, that the axial component begins with a sharp increase of the velocity throughout the first 20-50 cm, and then begins to decrease up to a steady velocity. This is due to the fact that the particles are fed from the top of the pipe and experience an immediate velocity change. Then, the particles do not start to lose energy until they experience the first collision with the bottom pipe wall. It differs from pneumatic conveying, since the travel distance until the first collision (first flight distance) in hydraulic conveying is much higher than the first flight distance in pneumatic conveying [2]. In both cases of hydraulic and pneumatic conveying, It can be seen that the vertical component of the velocity in general, and mostly in the steady state region negligible compared to the axial velocity.

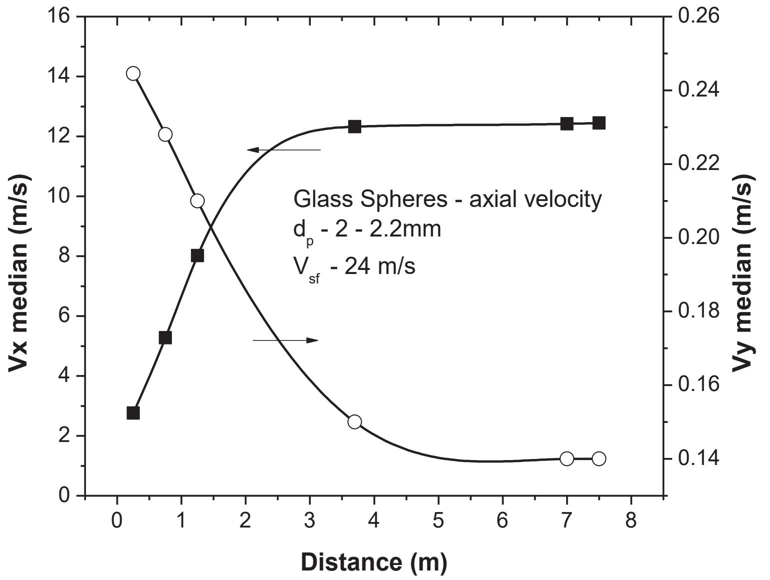


Fig.4 Acceleration graph for glass spheres in the axial and radial directions – Pneumatic

Table 1

Tested material properties.

Material	avg size d (mm)	Pipe Dia. D(mm)	Particle density ρ (kg/m³)	Conveying media
Alumina beads	1.7	1”, 2”, 3”	1120	pneumatic
Alumina tabulated	0.10	2”	1520	pneumatic
Glass beads	0.85	2”	2600	pneumatic
Glass beads	2.2	2”	2600	Pneumatic / hydraulic
Glass beads	0.25	2”	2600	Pneumatic
Zeolit beads	2.2	2”, 3”	2210	Pneumatic / hydraulic
Salt	2.4	2”	2500	Pneumatic
Polysterene cylinders	2	2”	2500	Pneumatic
Zirconium beads	2.2	1”, 2”, 3”	5800	Pneumatic / hydraulic
Polycarbonate cylinder	0.9	2”, 3”	1200	Pneumatic
Styrofoam	4	3”	8.4	Pneumatic
Wheat	3.5	2”	1500	Pneumatic
Rice	2.1	2”	3300	Pneumatic / hydraulic

Plastic beads	0.4	1", 2"	940	Pneumatic
Hard Plastic beads	4	2"	940	Pneumatic
Sand	1.2	2"	2700	hydraulic
Moderate plastic beads	4	2"	940	Pneumatic
Soft plastic beads	4	2"	910	Pneumatic
Pasta flour	0.37	1", 2", 3"	1550	Pneumatic
Methylparaben	0.125	1", 2"	1300	Pneumatic
Polysterene String 0.5X4	0.7	2"	1200	Pneumatic
Polysterene String 0.7X3	0.71	2"	1200	Pneumatic
Polysterene String 1X4	1.44	2"	1200	Pneumatic

2.5. MATERIALS

A verity of materials were tested throughout the research. The materials were differing in size, shape and density. The properties of the particles are given in table 1.

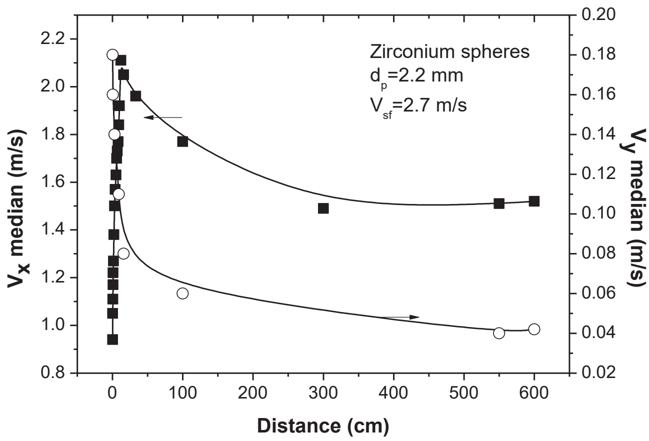


Fig.5 Acceleration graph for zirconium spheres in the axial and radial directions – Hydraulic

3. RESULTS AND DISCUSSION

3.1. SENSITIVITY ANALYSIS

Figures 6 and 7 are representitive example of the particle velocity as a function of the superficial fluid velocity in the axial direction with various particle mass flow rates for pneuamtic and hydraulic conveying respectively. All experiments show a common linear trend that indicates an increase in particle velocity along with an increase of the carrying media velocity. The direct meaning of this resault is that the ratio of gas to solid velocity remains constant over the range of experiments, therefore the ratio of u_p/u_f can be used as a representitive value for each material in the analysis.

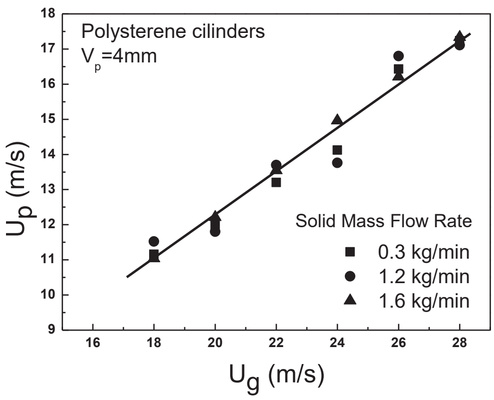


Fig.6 Median axial velocity vs. superficial air velocity for polystyrene with various flow rates.

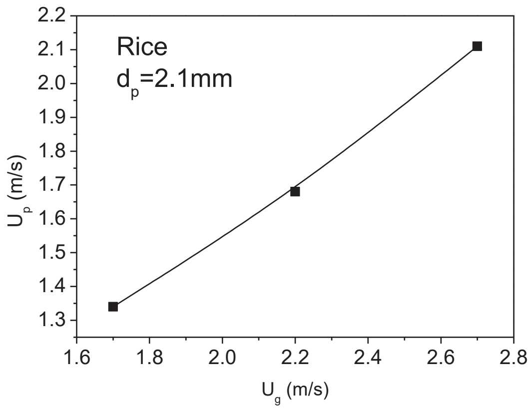


Fig.7 Median axial velocity vs. superficial water velocity for rice with various flow rates.

3.2. PARTICLE VELOCITY ANALYSIS

While Particles are suspended, they continuously encounter collisions with other particles and with the pipe walls. These latter collisions are the main cause for the energy loss of the particles. The particle motion in a pipe can be described mainly by axial motion, but with a small angle either upward or downward. Neglecting the collisions between the particles by assuming very dilute flow, a single particle will collide with the wall, after some distance, and the velocity will be reduced according to the coefficient of restitution. After the collision, the particle will accelerate until the next collision. This mechanism is the reason that at any cross section of the pipe a velocity distribution is measured. Some particles move at higher velocity just before a collision and others move at lower velocity just after a collision. The average particle velocity should therefore be affected by (1) the particle and fluid properties (Ar number) which dictate the falling intensity, (2) the coefficient of restitution which dictates the velocity decrease at each collision and (3) the pipe diameter which dictates together with the Ar number the collisions frequency. However, particle velocity might approach fluid velocity for a number of cases:

1. Elastic particles (coefficient of restitution equals one) will experience elastic collisions that will result in zero energy loss and thus in no velocity reduction due to impacts. The collision will be best characterized by the coefficient of restitution that takes into account both the particle's and the pipe wall's properties.
2. Infinite pipe diameter will also affect the average and overall velocity distribution. This is due to the fact that for infinite pipe diameter particles will not experience collisions and they will continuously accelerate until the velocity ratio becomes 1.
3. Non saltating particles (Ar number approaching zero) that are not affected from gravitational forces and stay suspended and will also not lose energy due to the absence of wall collisions. This phenomenon is much more relevant in hydraulic conveying, where particle density can be similar to the carrying media density or for pneumatic conveying at reduced gravitational forces. It has been previously noted [3] that hydraulically conveyed particles with mean diameter lower than 40μm will behave in

a homogeneous fashion and will be distributed throughout the flow with little change of solid concentration with height.

In this analysis, we employed the commonly used Archimedes number which defines the ratio of the buoyancy forces to the viscous forces and takes into account the relevant parameters that affect the particle to wall collisions. When combining all of the measurements, dependence between the particle to fluid velocity and the Archimedes number, combined with the density and pipe diameter was noticed. Figure 8 shows the dependence of the velocities ratio with other variables for all of the tested materials. The figure also indicates that the results are slightly influenced by the coefficient of restitution and particle shape. It can be seen that three types of plastic beads with the same Archimedes number are differing in the final velocity they achieve. This is due to the fact that their elasticity is different. It can be theoretically expected that particles that experience fully elastic collisions will not lose any energy during the impact and have high steady state median velocity in contrast to a fully plastic impact. However, since all data points fall within an error zone of 10%, we can conclude that Ar, pipe diameter and density have a major effect on velocity while the coefficient of restitution and particle shape has only a minor effect, although its effect for fine tuning should be further investigated. It should also be mentioned that the loading ratio effect was not taken into account since high speed video method for particle velocity will not allow proper picture analyses when the particles are not distinguished at a specific frame. In the figure, the point on the far left side is theoretically representing sand with 40μm diameter that should result with a velocity ratio of 1, according to previous research [3] as mentioned above.

3.3. CORRELATIONS BASED ON THE CURRENT STUDY

None of the previous studies provided a single correlation for prediction of the experimental particle velocity as a function of various conditions that is unite for pneumatic and hydraulic conveying. Moreover, based on the fact that experimental conditions vary, a need for a dimensionless correlation is essential. Based on the experiments in this study, a dimensionless correlation was developed for the median particle velocity. The correlation is given by:

$$\frac{u_p}{u_f} = 1.05 - 0.078\left[Ar * \left(\frac{\rho_p-\rho_f}{\rho_f}\right) * \left(D/_{D_{50}}\right)^{-2}\right]^{0.089} \qquad (1)$$

where D_{50} has been chosen to be a reference pipe diameter of 50 mm (2-in pipe).

4. 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 1, 2 and 3-in pneumatic conveying system and a 2” hydraulic system. A high speed camera was used in order to measure both the three dimensional velocity of each particle and the velocities distribution of the particles under specific operating conditions. The results show a linear increase of the particle's velocity with increasing of the conveying media velocity. The mass flow rate showed to have a minor effect on the particles median velocity (for very dilute flows). A new dimensionless correlation is offered for the median particle velocity estimation that has shown a good agreement of ± 10% with the experimental results and other data from previous studies.The correlation was given for the following property ranges:

$0.06mm < d_p < 4mm; \quad 940\frac{kg}{m^3} < \rho_p < 5800\frac{kg}{m^3}; \quad 14\frac{m}{s} < u_g < 28\frac{m}{s}; \quad 26mm < D < 76mm\ ; \ 0.3 < \eta < 3.$

Future research will focus on the determination of the acceleration length and velocity profile during the primary and secondary accelerations.

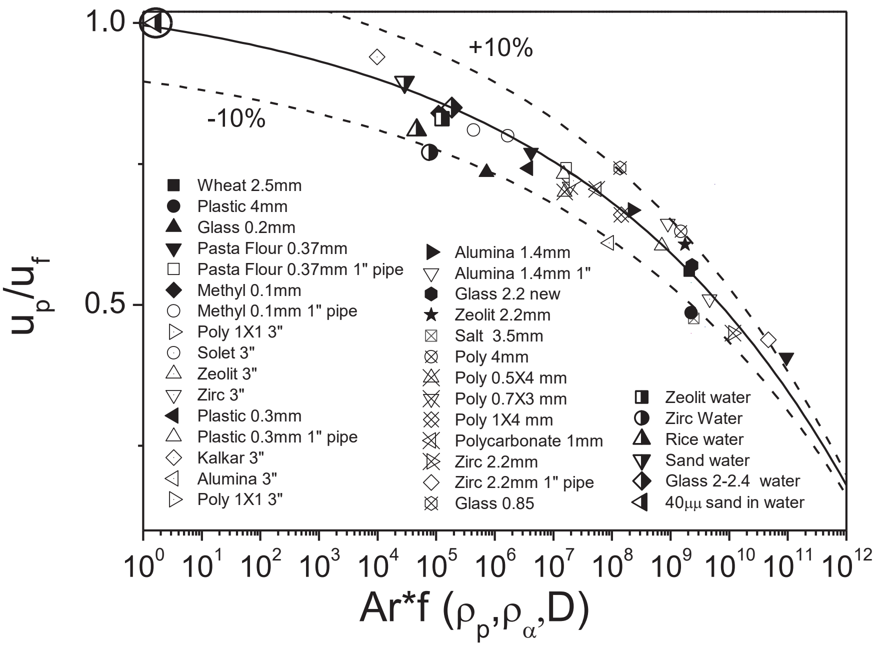


Fig.8 velocity ratio (particle to air superficial) as a function of the Archimedes number density and pipe diameter

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