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WHAT DO PNEUMATIC CONVEYING AND HYDRAULIC CONVEYING HAVE IN COMMON?

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Pneumatic conveying (PC) and hydraulic conveying (HC) differ only by the type of carrier fluid: One is compressible and the other is not. Nevertheless, they are considered very different, attracting different research groups that rarely have a dialog. Therefore, the main objective of this research is to compare both systems, bridge the gap, and establish common analysis principles for both PC and HC. In order to bring both these conveying methods into a common ground, a new feeder based on PC technology is designed and used in HC. Hence, similar phase diagrams are obtained. Additional windows are opened to define future research efforts to conduct PC and HC research with the same tools. In order to do this, the significance of the Archimedes number is introduced in this paper. Furthermore, non-settling flows, more common in HC, are analysed, and detailed explanations are presented to show that they should also exist in PC, for which they have never been mentioned.

KEY WORDS: pneumatic conveying; hydraulic conveying; phase diagram; Archimedes number; non-settling flow

1. INTRODUCTION

Pneumatic conveying (PC) is basically analysed in many papers and textbooks by showing a measured phase diagram or state diagram (Zenz diagram), Klinzing et al., (1997). The diagram presents the steady-state pressure drop per length of pipe versus the superficial gas velocity. Each line presents a constant particle mass flow rate, whereas the bottom line is for zero mass flow rate, i.e., air only. For each solid mass flow rate, a velocity for minimum pressure drop can be found. This velocity is generally called the saltation velocity and distinguishes the dilute phase flow (to the right) from the dense phase flow (to the left).

For HC of large particles, the flow is called heterogeneous flow or settling flow, where the flow is treated as a two-phase flow similar to that for PC. In such a case, it is common in many papers as well as textbooks or handbooks to analyse the flow using a phase diagram similar to that of PC: Abulnaga, (2002), Wilson et al., (2006). Although the figures look similar, there are a number of differences:

1. Instead of pressure drop (PC), head loss is presented (HC).
2. Instead of superficial gas velocity (PC), mix velocity is presented (HC).
3. Instead of lines of constant solid mass flow rates (PC), lines of constant volumetric concentrations are presented (HC).

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The differences between the two ways of presenting the phase diagrams probably originated due to convention and other kinds of constraints.

- For liquids, it is easier to measure the pressure drop with manometers, which give the mix head loss.
- In PC, typically, the solid is fed into the air stream. Therefore, there is a part of the pipe in which only air flows and it is possible and easy to measure the air flow rate to determine the superficial velocity. However, in HC, a mixing tank, in which the particles and the liquid are mixed, is used. After mixing, the mix is pumped into the pipeline. This is why it is impossible in such installations to measure the liquid flow rate; the mix velocity is presented instead.
- Since, in PC, the solid is fed into the air flow in the pipeline directly, it is easy to control the solid mass flow rate in the feeder. However, using a mixing tank in HC, it is easier to control the solid concentration.

Each single point in the phase diagrams can be converted from one set of parameters to the other. However, in order to compare the two systems better, a new feeder for HC was designed, and is presented in this paper. The new feeder controls the mass flow rate in a similar way to that in PC, and feeds the particles into a liquid stream. This design presents a number of additional advantages, as discussed later. In this paper, we also try to transfer knowledge from one field to another.

2. EXPERIMENTAL

The PC system used in this work is described in detail in other papers: Naveh et al., (2017), Tripathi et al., (2018a,b), Santo et al., (2018a,b), and is not elaborated on herein. The system comprises a 52.5 mm ID galvanized steel pipe, 54 m in length. The particles are fed using a screw feeder.

The HC experimental test rig comprises a 33 m long galvanised steel pipeline with a 56 mm inside pipe diameter. The pipeline layout contains three elbows (R/D=2), one blinded T, four horizontal sections, and one vertical section. The solid mass flow rate and volumetric concentration are measured using a sampling tank.

The main innovative parts are the feeding and separation units, which are presented in Figure 1. The liquid feeding line contains a liquid tank, a pump, a magnetic flow meter, and the particle feeding unit. The particle feeding unit contains a particle hopper, rotary valve (manufactured for PC) and mixing chamber (drop-through chamber). The separation device includes the particle hopper, on which a steel container is held. Inside the steel container, another envelope made of a predefined sieve is mounted (Figure 1b). As a consequence, water is pumped from the liquid tank to the conveying line through the magnetic flow meter and feeder. Thus, the magnetic flow meter can measure the liquid-only flow rate. As the rotary valve is active, it transfers particles from the particle hopper to the mixing chamber. The rotary valve speed controls the particle mass flow rate. The mixture in the mixing chamber is sucked via the venture tube into the conveying line.

The system described can also operate in the conventional way with slight changes. In such a case, the liquid tank becomes the mixing tank, with an appropriate mixer added from the top. The pump injects the mixture directly into the conveying line, bypassing the rotary valve feeder.

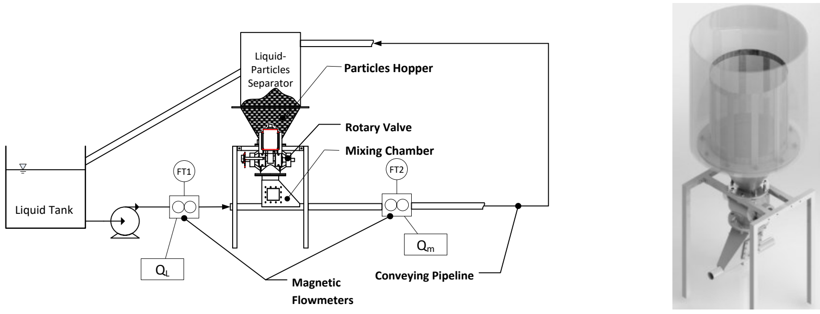


Figure 1. Layout of the feeding zone for the new HC system: a. All feeding devices; b. Separator.

3. RESULTS AND DISCUSSION

In this section, the opportunities available, based on a comparison of PC and HC (which requires further investigation), are presented and discussed. Some specific use cases are available owing to the application of the new feeder with HC. In any case, the following sections present some answers; however, many questions remain unanswered.

3.1 PHASE DIAGRAMS

Plotting the pressure drop per unit length for a constant solid mass flow rate against various fluid velocities gives a line in the classical (for PC) phase diagram (Zenz diagram). Such lines for both air and water are presented in Figures 2a and 2b, respectively. The phase diagram for HC shows a clear minimum pressure point distinguishing the dilute phase flow from the dense phase flow. Figures 2c and 2d present some visualization of the flow in HC, at the two velocities marked in Figure. 2b. The minimum pressure point is not seen in PC (Figure. 2a), although it exists, because of the concern for blockage. The minimum pressure drop exhibits a slightly different behaviour for PC and HC. The minimum pressure velocity is commonly attributed to the saltation velocity in PC, where particles start to create a layer at the pipe bottom, whether it moves or not. In the case of HC, at the minimum pressure point, the layer is already established, as shown in Figure. 2c, although it is still moving slowly, and the rest of the particles are moving above, as in dilute phase flow. At lower velocities, the layer at the pipe bottom is stationary (Figure 2d) and the particles are moving above it.

There are a number of significant differences between PC and HC. The air velocities for PC are in the range of 10-30 m/s, whereas for HC, the water velocities are much lower, in the range of 1-3 m/s. This will certainly lead to lower particle attrition in HC. Although the mass flow rates for PC are in the range of very dilute, their values (150-400 kg/h) are about three times lower than those for HC (1000-1500 kg/h). Owing to these reasons, the pressure ranges in PC (60-200 Pa/m) are about five times lower than those in HC (200-1800 Pa/m).

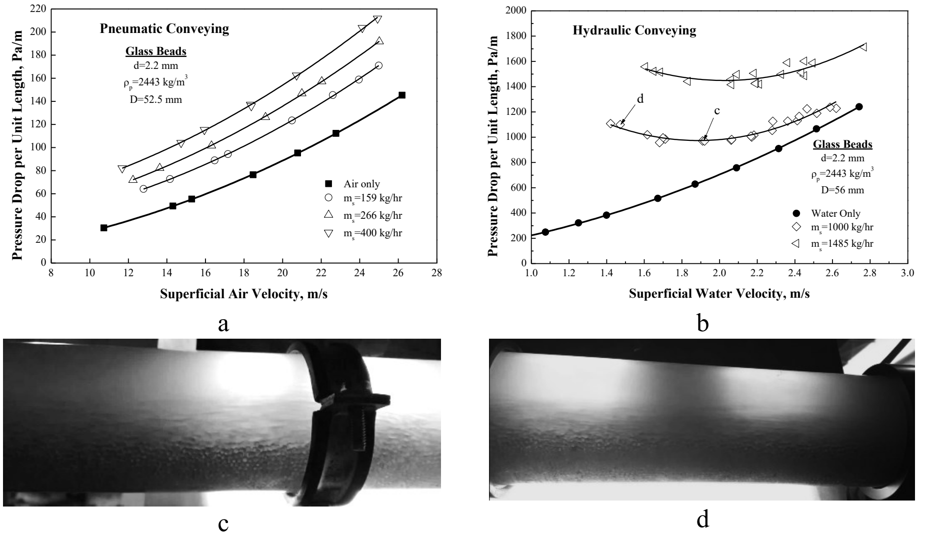


Figure 2. Phase diagrams for glass beads having median size of 2.2 mm in a. PC; and b. HC. Visualizations for flows marked in Figure 2b at c. minimum pressure velocity with sliding bed; and d. the dense phase zone with stationary bed.

3.2 EFFECT OF BUOYANCY FORCE AND ARCHIMEDES NUMBER

When particles are conveyed in a horizontal pipe, they are moving both horizontally (axially) and vertically (radially). The horizontal flow is dominated by the inertia of the fluid and the drag force (opposing movement). Therefore, in most models for two-phase flow, the Reynolds number obviously plays a major role.

$$Re = \frac{Inertial\ Force}{Viscous\ Force} = \frac{\rho U d}{\mu} \tag{1}$$

where ρ is the fluid density, μ is the fluid dynamic viscosity, U is the particle relative velocity, and d is the particle diameter.

The vertical movement of the particles is basically affected by the particle weight, buoyancy force, and drag or viscous force. Some recent works on various threshold velocities (mainly for PC, but in some cases, also including HC) showed that the Archimedes number (Ar) is appropriate (Kalman and co. workers). The Ar is defined in the same way as the Re (encouraging force divided by the resisting force) but for the vertical movement, i.e., as the ratio between the sinking force (weight minus buoyancy) and the viscous force.

$$Ar = \left(\frac{Sinking\ Force}{Viscous\ Force}\right)^2 = \frac{\rho_f(\rho_p - \rho_f) g\, d^3}{\mu^2} \tag{2}$$

For instance, it was shown that the pick-up velocity from a layer of particles can be described as the Re as a power function of the Ar. The function is common to both fluids, air and water, for large particles, Kalman et al., (2005). For small particles, Van der Waals force affects dry fine particles behaviour. Hence, the pick-up velocity of large particles for both PC and HC is:

$$Re^* = 5.0Ar^{*3/7} \quad for \quad Ar^* > 16.5 \tag{3}$$

where Re* is the Reynolds number modified by the effect of the pipe diameter and Ar* is the Archimedes number modified by the particle shape, Kalman et al., (2005).

In another paper, Rabinovich and Kalman (2008a) used a similar expression to describe the minimum pressure velocity for PC. This model describes hundreds of experiments found in the literature and is presented in Figure 3a and Equation (4).

$$Re^* = 1.1Ar^{*3/7} \quad for \quad Ar^* > 2{,}450 \tag{4}$$

The minimum pressure velocities for a number of cases of HC (for example, from Figure 2b, and other measurements not shown here) are presented in Figure 3a. Figure 3a shows that the new HC experiments exhibit a line having the same slope as that for PC, but with a larger coefficient (1.8) as compared with that for PC (1.1). Obviously, this is an excellent topic for further investigation. However, the coefficient of restitution (CoR) looks to be the best candidate for explaining this difference.

Please note that HC may present uncommon cases. The particle density may be higher, equal to, or lower than the fluid density. In the first case, the particles will sink. In the second case, the particles will neither sink nor float (neutrally buoyant), resulting in a non-settling flow. In the third case, the particles will float. Figure 3b shows a phase diagram for the third case. Because the volumetric concentrations in the tests were low, the particles almost did not affect the water-only pressure drop, and an increase in the pressure drop was only noticeable at very low velocities. Figure 3c shows the particle layer created at the pipe top. It should be emphasised that when particles have lower densities than those of the carrier fluid, the Ar becomes negative. Since the friction or behaviour should be the same whether the layer is created at the pipe bottom or top, the Ar should be defined by the absolute value. Hence, the plastic pellets are represented in Figure 3a by their absolute value.

3.3 CONVEYING OF NON-SETTLING PARTICLES

For most cases of PC and HC, the particles experience significant lifting or sinking forces. These vertical forces are strengthened by vertical flows of eddies in turbulent flows. Hence, in parallel to their axial movement, they also move vertically and collide with the pipe walls. Due to these collisions, the particles lose energy and velocity. The energy is recovered by the drag force applied by the fluid, which requires a relative velocity. Since the particles are moving at a different velocity than that of the fluid, each phase should be analysed separately, as for two-phase flows. However, there could be some cases in which the particles are neither moving down nor up, and they follow the fluid stream exactly and at the same velocity. This is actually one-phase flow but with mix properties (density and viscosity); this can be called non-settling particle flow. These kinds of flows are noticed in HC and are commonly reported for high concentrations and fine particle sizes, typically less than 75 μm, Curtis, (2008), for particles smaller than 40-70 μm, depending on the density of the solids, Abulnaga, (2002), for a settling velocity less than about 1.5 mm/s, or for a size less than 40 μm (Wilson et al., 2006). The particles in non-settling flows will move at the fluid velocity since there is no loss of energy due to collisions with the walls.

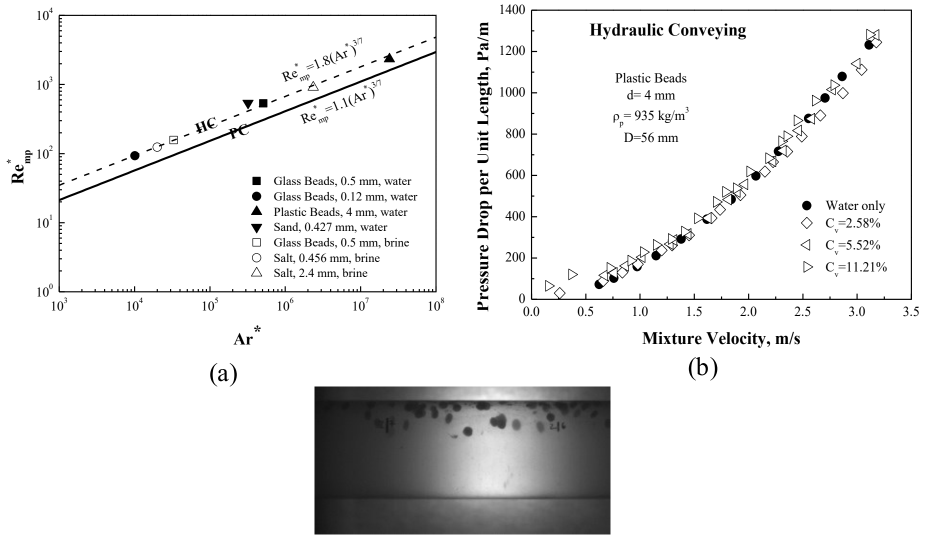


Figure 3. (a) Models for minimum pressure velocity in PC and HC; (b) Phase diagram for plastic beads in HC; and (c) flow visualization.

This can be realised in a number of cases:

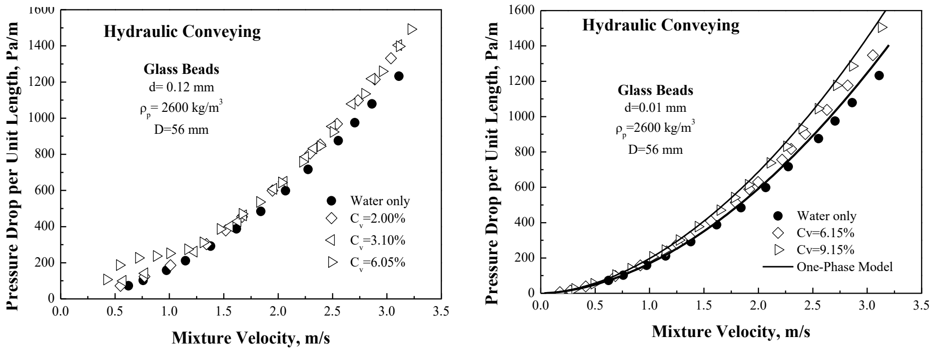
1. Particles are so small that their weight is negligible.
2. Particle density is similar to the fluid density.
3. The conveying is conducted at zero gravity.
4. Particle-to-wall collisions are fully elastic.

The first three cases present non-settling velocity. It should be emphasised that all the above conditions present cases for ideal non-settling flows. It should also be emphasised that the first three cases are well represented by the Ar number; the Ar number is zero in an ideal non-settling case. Obviously, for non-zero Ar, the flow may be practically considered as non-settling for a reasonable pipe length.

Recently, Santo et al. (2018a) tested tens of materials and measured the ratio between the average particle velocity (in a cross-section at the steady-state zone) and the superficial air velocity in PC, for very low particle concentrations.

$$\frac{U_p}{U_f} = 1 - 0.02\left[Ar * \left(\frac{\rho_p-\rho_f}{\rho_f}\right) * \left(D/D_{50}\right)^{-2}\right]^{0.14} \qquad (5)$$

It is clear from the equation that the velocity ratio approaches one when the Ar approaches zero. As the particle size increases (Ar is larger), the velocity ratio decreases. Some preliminary experiments with HC showed that Equation (5) is probably valid for HC as well. The velocity ratio was calculated for a number of cases, but the most important one is that of sand of 40 μm size, giving a velocity ratio of 0.976. Additionally, a few materials tested in HC, for various particles in either water or brine, and in PC, are presented. The phase diagrams of some of the materials show a minimum pressure point, which implies that the particles are settling. In Figure 4, two more phase diagrams are presented, both for glass beads, one for 0.12 mm (Figure 4a) and the other for 0.01 mm (Figure 4b), which present to the right and left of the 40 μm sand point. Figure 4a presents a slight but still existing minimum pressure point; hence, the flow was defined as a settling flow. However, Figure 4b presents no evidence for a minimum pressure point; hence, the flow was defined as non-settling. Indeed, the pressure drop line is similar to the water-only line, but slightly elevated.



(a) (b)

Figure 4. HC of glass beads of (a) 0.12 mm size showing settling behaviour; and (b) 0.01 mm size showing non-settling behaviour.

Using the above analysis, it is possible to define initially that non-settling flow might be expected for a 2-inch pipe for materials having:

$$Ar\frac{\rho_p-\rho_f}{\rho_f} < 10 \quad (6)$$

which gives a velocity ratio higher than about 0.97.

As reported in the literature, a case of non-settling flow can be solved as a one-phase-flow, but with the mixture properties. This was checked for water-only flow and for a flow of glass beads of 0.01 mm size and 9.15% volumetric concentration (Figure 4b). The pressure drop was calculated using the friction factor defined by Moody, as:

$$f = 0.0055\left[1+\left(2\cdot 10^4\cdot\frac{\epsilon}{D}+\frac{10^6}{Re}\right)^{\frac{1}{3}}\right] \quad (7)$$

The mixture density was calculated with the volumetric concentration and mix viscosity, using the Toda and Furuse (2006) equation, which is valid for concentrations up to 50%:

$$\frac{\mu_m}{\mu_l}=\frac{1-0.5C_v}{(1-C_v)^3} \quad (8)$$

The calculation closely follows the experiments, as shown in Figure 4b.

4. CONCLUSIONS

This paper describes an effort to analyse both PC and HC using the same tools. As a first step, a new feeder based on a rotary valve was designed and used for HC. Hence, the phase diagrams plotted for both PC and HC were similar, and analysis was conducted. Although this paper points out topics that require further investigation, some conclusions were drawn.

- It is possible to use a rotary valve (or a similar valve) for HC, to control the solid mass flow rate rather than the particle concentration.
- The Ar and Re numbers are the governing parameters for both PC and HC. Their use is shown for the minimum pressure velocity of HC measured in this work compared to a correlation developed in the past for PC. Both behaviours showed the same power function, but with a slightly different coefficient. This difference is probably related to the CoR for wet systems.
- The Ar number should be defined by its absolute value to cover cases for floating particles (in HC) as well that create a moving layer at the top of the pipe.
- An analysis of Santo et al.'s (2018a) results for the velocity ratio, and the phase diagrams from this research, predict an estimated border between non-settling and settling flows for low concentrations. This is valid for HC and is expected to be valid also for PC.

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