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PHASE DIAGRAMS FOR PNEUMATIC AND HYDRAULIC CONVEYING

Haim Kalman[1,2], Naveen M. Tripathi, Ofek G. Gabrieli[2], Dmitri Portnikov[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 hkalman@bgu.ac.il*

Pneumatic conveying (PC) and hydraulic conveying (HC) have significant applications in various industries. These two ways of conveying differ only by the type of the carrier fluid, one is compressible and the other is not. Even so, these two ways of conveying considered very different attracting different research groups rarely having a dialog. Therefore, one of the main objectives of our ongoing research is to compare both systems and bridge the gap to found common analysis for both PC and HC. In this paper we present a new design for an HC system using the feeding technology of PC. Thus, the particles are fed into a pure liquid stream by controlling the particle mass flow rate. A few preliminary results are presented and will act as the foundation for future analysis.

KEY WORDS: Pneumatic conveying, hydraulic conveying, phase diagram.

1. INTRODUCTION

In order to be able to design a pneumatic conveying line for dilute phase flow, the air flow rate and the total pressure drop should be calculated. They are calculated by using a number of valuable parameters, which are listed bellow.

1. Saltation or Pick-up velocity define the border limit between dilute and dense phase flows. In order to have dilute phase flow the fluid velocity should be higher than the saltation velocity. Using, instead, the pick-up velocity, gives higher velocities and an additional factor of safety. A number of correlations can be found in the literature describing both threshold velocities, Kalman et al. (2005), Rabinovich & Kalman (2007, 2008). Knowing the relevant threshold velocity enables to define the required fluid flow rate.

2. The acceleration length, which is the length of the pipe, after feeding particles or after a bend, that particles are accelerating until reaching the steady state velocity. It is a common practice in PC to provide the full acceleration length before any variation in flow (bend, valve, etc.). Santo et al. (2017b)
3. Particle final velocity is used to calculate both the acceleration length and pressure drop. Santo et al. (2017a)
4. Steady state pressure drop in a horizontal pipe is complex to calculate, but essential to predict the total pressure drop over a conveying pipe line. Naveh et al. (2017)
5. If the pipe line include also a vertical section, the pressure drop over the vertical pipe should also be calculated.
6. At the acceleration zone the pressure drop is higher then the steady-state pressure drop. Therefore, the additional pressure drop due to acceleration should be calculated. Tripathi et al. (2017)
7. Bend pressure drop is a significant parameter since the pressure drop along a bend could be much higher then along an equivalent length of a steady state flow.
8. Particle attrition and size reduction is a parameter to be considered while designing a conveying line. The conveying is aimed to move particles from one point to another, but the cost might be a significant breakage of particles which change the particle properties. Portnikov et al. (2017)

All the above are basically defined for PC conveying. However, physically they should also be applied to HC. In an ongoing research we are investigating each one of the above parameters for PC, trying to define general correlations and then check the application to HC and correct the correlations accordingly. Here a number of parameters analysis will be presented.

2. COMPARING PHASE DIAGRAMS

Pneumatic conveying is basically analysed by showing a measured phase diagram or state diagram (Zenz diagram), as is shown in Fig. 1, Klinzing et al. (1997). This diagram is specific to a conveyed material and conveying gas, it is also specific to a pipe material and diameter, and finally, it is specific to the pipe orientation (horizontal, vertical or bend). Figure 1 presents such a general diagram for a horizontal pipe. 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, while the bottom line is for zero mass flow rate, namely, gas only. For each particle mass flow rate a velocity for minimum pressure drop can be found. This velocity is usually called the saltation velocity and distinguishes between dilute phase flow (to the right) and dense phase flow (to the left).

Hydraulic conveying is basically divided to two kinds of slurry flows. For fine powders, in sizes smaller than 40-70 microns (depending on the particle density), the flow is homogeneous. This is called homogeneous flow or non-settling flow. In this case the analysis is conducted for as single flow (probably non-Newtonian) with mixture properties.

This kind of flow is not discussed nor mentioned in pneumatic conveying. This kind of flow should exist for sufficiently small enough particles that will not settle down. If Archimedes number is assumed to define the border between settling and non-settling flows, than sand particles of 40 μm in HC are equivalent (same Ar number) to particles of

20 μm in PC. These very small particles might not be relevant for pneumatic conveying, and if yes, PC faced many difficulties. Indeed, Klinzing et al. (1997) stated that "It has been shown that empirical and theoretical solutions to pneumatic conveying problems involving coarse particle flow cannot readily be applied to fine particle flow." They also stated that particle size of 350 μm is used as the cut-off point in determining the distinction between fine particle and coarse particle suspension. This is an excellent example how knowledge of one area can be reflected in the other.

For larger particles of HC the flow is called heterogeneous flow or settling flows where the flow is treated as two-phase flow as for PC. In such a case it is common to analyze the flow by a similar phase diagram as shown in Fig. 2 (Abulnaga, 2002). Although the figures (12 & 13) look similar there are a number of differences:

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

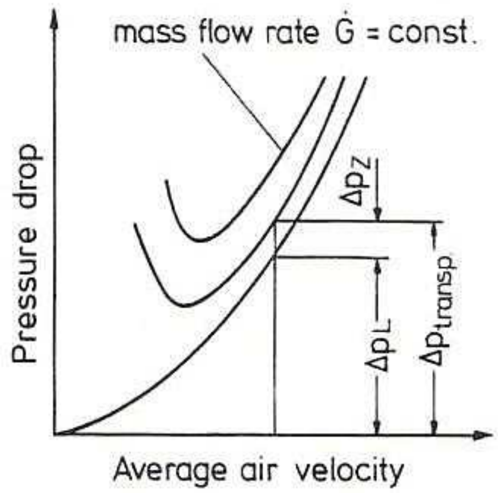

Fig. 1 Phase diagram for PC, Klinzing et al. (1997).

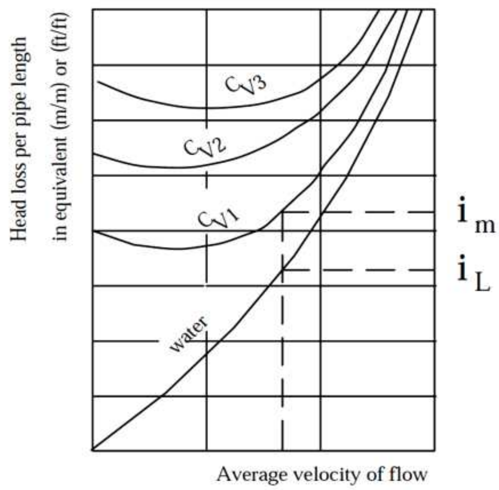

Fig. 2 Phase diagram for HC, Abulnaga (2002).

The differences probably originated from tradition and other kind of constraints.

1. For liquids it was easier to measure the pressure drop with manometers which gave the mix head loss.
2. In PC usually 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 give the superficial velocity. However, in HC they use a mixing tank in which the particles and the liquid are mixed and then they are pumped as a mix to the line. This is why it is impossible in such installations to measure the liquid flow rate.
3. Since in PC the solid is fed into the pipe line directly to the air flow, it is easy to control the solid mass flow rate in the feeder. However, by using a mixing tank in HC it is easier to control the solid concentration.

Obviously, one set of data may be transformed to the other. However, in order to better compare the two systems, a new feeder for HC is designed. The new feeder controls the mass flow rate in a similar way as in PC, and feed the particles into a liquid stream.

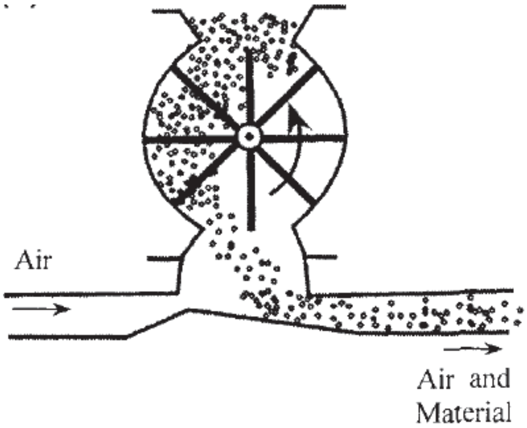

Fig. 3 Rotary valve feeder typical for PC.

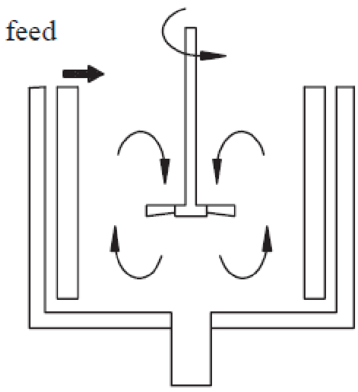

Fig. 4 Mixing tank typical to feed HC.

3. EXPERIMENTAL

The experimental test rig is presented in Fig. 5. Tests have conducted to evaluate phase diagram and pressure drop trend on this experimental setup connected with 32.85-meter long steel pipeline and 56 mm inside pipe diameter. This test rig consists of a rotary feeder connected with mixing chamber on its bottom. In the mixing chamber, a venturi tube has been mounted following a liquid flow regulator to reduce the pressure. Pipeline layout has contained three elbows (R/D=2), one Blind-T (L/D=1), four horizontal and one vertical section. A filter house separator at the end of the pipeline has installed to achieve the separation of the particles from the liquid. Solid mass flow rate and volumetric concentration is being measured by using sampling tank. This tank is connected with main pipeline using pneumatic valve for off line measurement.

The experimental facility for our study is positive pressure type. Pressure drop along the pipe have measured by using high accuracy flush diaphragm absolute and differential pressure transducers. Those have mounted on riders as per instruction of user manual to ensure accuracy of readings of the pressure values and for avoiding additional problems common to pressure tapping in hydraulic conveying. Absolute transducers have range of (0-1) bar and accuracy level ±0.1%, whereas differential transducers have range of (0-500) mbar and accuracy level ±0.075%. Differential transducers have been used to find the pressure drop of specific section of pipe in acceleration and steady state zone as well.

In our experiments centrifugal pump with delivery capacity of 30-81 m^3/hr., has been used. Electromagnetic liquid flowmeters of range 0-40 m^3/hr., with an accuracy of ±0.5% of full scale have been used to measure flow rate. Data received from flowmeters and pressure transducers has processed by a software LabVIEW 2014 manufactured by National Instruments (NI).

Figure 6 shows in more details a scheme of the feeding area, and Figs. 7 & 8 show a photo of the feeding area and the flow in the pipe. As can be seen in Fig. 6, two flow rates are mounted along the pipeline. One is measuring the pure liquid flow rate and the other the mix flow rate. By such an arrangement it will be possible to measure on-line the solid concentration or mass flow rate (when the problem of back-flow is solved). It is also important to me3ntion that since in such an arrangement the pump is pumping pure liquid, a simple centrifugal pump can be used without any concern regarding the particle attrition.

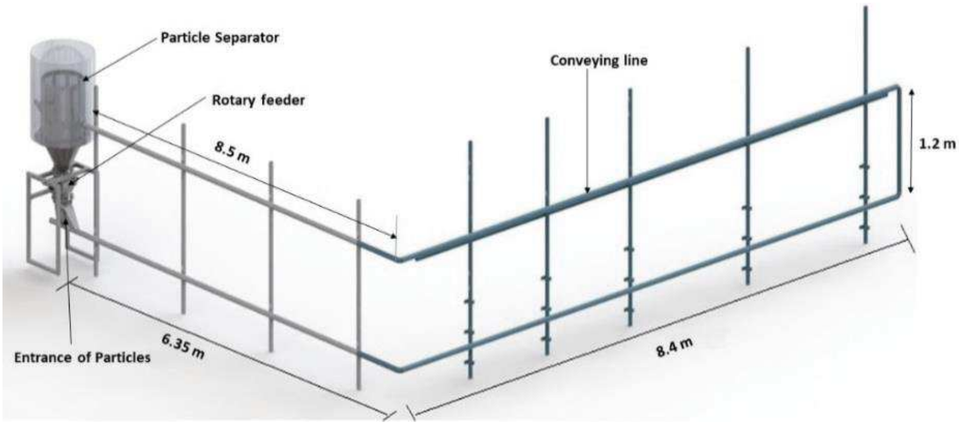

Fig. 5 Layout of the 56 mm I.D. x 32.85 m length experimental setup.

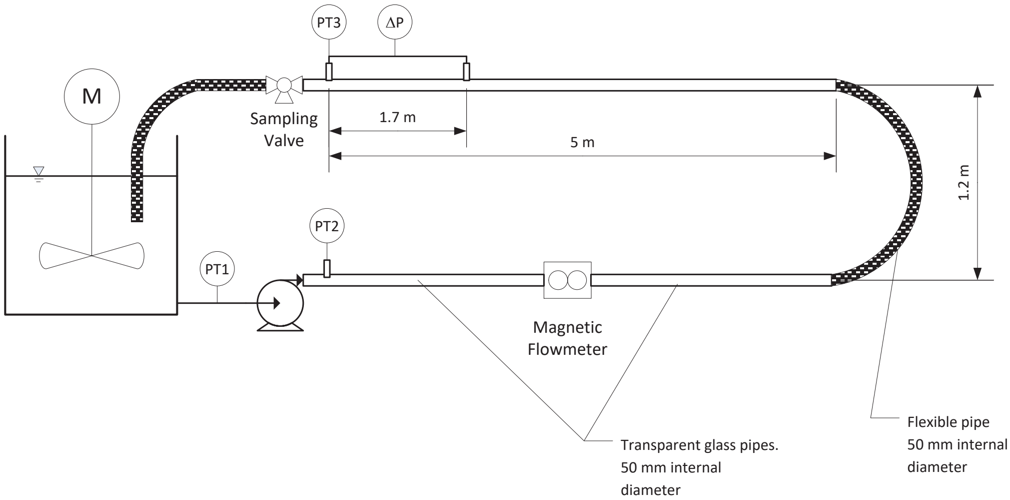

Fig. 6 Layout of the feeding zone for the new HC system.

4. RESULTS AND DISCUSSION

We tested a number of materials both in air and in liquid. The results are presented here in two ways. Figures 9 and 10 show the gage pressure distribution before and after a blinded-

T bend as a function of the location. For the PC the air only and a number of solid mass flow rates for the same superficial air velocity are presented. For the HC the water only and one solid mass flow rate and superficial water velocity is presented. From such figures a number of data can be defined. The pressure distri8bution before the bend presents a linear line which defines the steady-state pressure drop as will be presented later in the phase diagrams. After the bend the pressure difference decrease again to the steady-state condition. Right after the bend the pressure drop is higher due to the reacceleration of particles. According to the results, the acceleration length for PC is about 3 m while for HC is about 1.5 m. By extrapolating the pressure lines the bend pressure drop can be found. It is much higher for HC. This is a topic for further research.

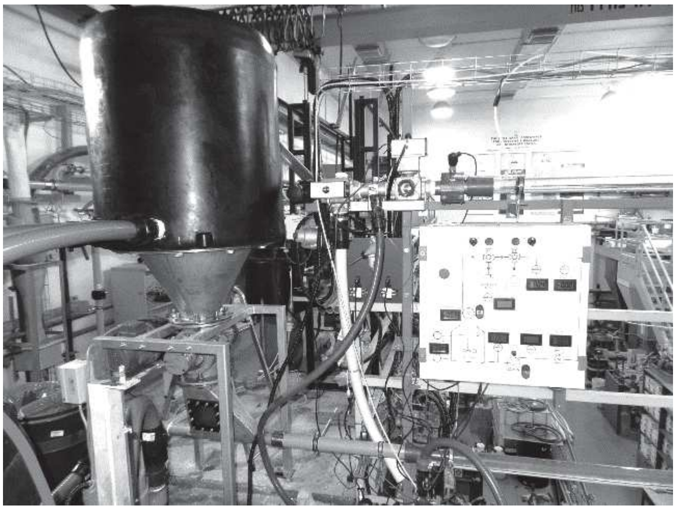

Fig. 7 Photo of the feeding zone for the new HC system.

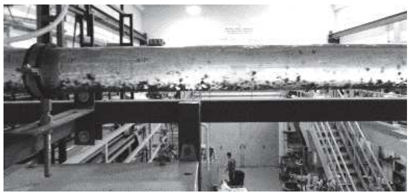

Fig. 8 Example of flow in HC.

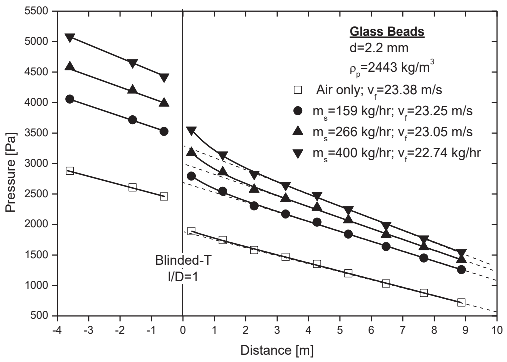

Fig. 9 Pressure distribution before and after a blinded-T bend for PC.

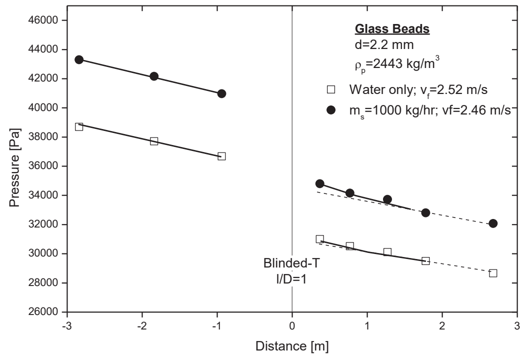

Fig. 10 Pressure distribution before and after a blinded-T bend for HC.

Based on the steady-state pressure drop per unit length of a horizontal section of the pipe, as shown in Figs. 9&10, the phase diagram can be plotted. Figures 11&12 show the phase diagrams for the glass beads for PC and HC, respectively. The comparison presents clearly that although the solid mass flow rate is much higher (twice) for HC, but the pressure drop is about 5 times higher. However, for energy calculations the superficial velocity plays a major role, which is about 10 times lower for HC. The minimum pressure point was not reached in PC because the blockage conditions were approached. It was easy in HC to reach the minimum pressure point which presents conveying with stationary layer at the bottom of the pipe. By such experiments, PC and HC might be compared and the comparisons should be further investigated.

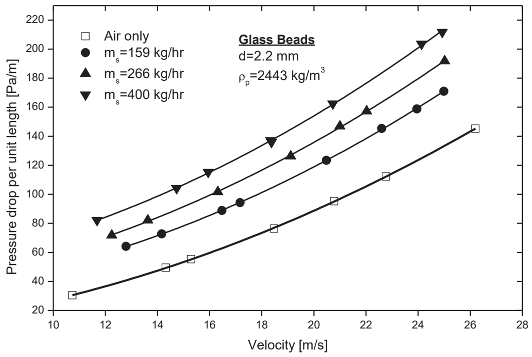

Fig. 11 Pressure distribution before and after a blinded-T bend for PC.

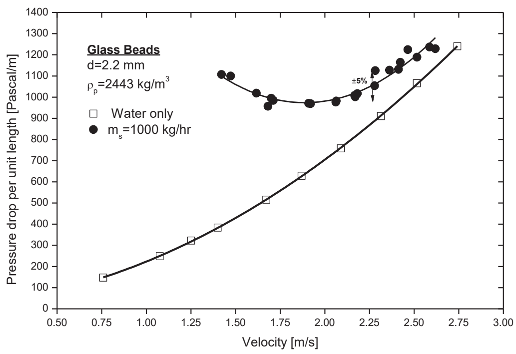

Fig. 12 Pressure distribution before and after a blinded-T bend for PC.

5. CONCLUSIONS

Pneumatic conveying and hydraulic conveying are treated differently, present different phase diagrams and have different ways of analysis and calculations. One reason is that due to a number of reasons, the basic phase diagram is different. Therefore, in order to compare performances of PC and HC a new feeding device, based on PC technology was designed and operated with HC. In this way information and details might be transferred from one field to the other. In any case, using such a rotary valve feeder for HC has a number of advantageous over the classical mixing tank:

1. Attrition of particles related to the feeding is negligible.
2. A simple centrifugal pump can be used without erosion since it pumps clear water.
3. The mass flow rate can be measured at two locations along the pipe for clear water and for the mix. By comparing these measurements the solid mass flow rate or the volumetric concentration can be calculated on-line.

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