19th International Conference on
TRANSPORT AND SEDIMENTATION OF SOLID PARTICLES
24-27 September 2019, Cape Town, South Africa

SIMPLE PICK-UP VELOCITY MEASUREMENTS PROCEDURE AND DEFINING NON-SETTLING PARTICLES USING RHEOMETER

Yeshayahu Levin[1], Amos Ullman[1], Dimitry Portnikov[2] and Haim Kalman[2,3]

[1]Tel-Aviv University, Ramat-Aviv 6997801, Israel. [2]Ben-Gurion University of the Negev, Beer-Sheva, 8410501, Israel. [3]Aaron Fish Chair in Mechanical Engineering – Fracture Mechanics. e-mail: yeshayahu@gmail.com

Pick-up velocity is a threshold value that is taken into account while designing a powder hydraulic or pneumatic conveying system. In this work, a new and simple procedure to measure and predict the pick-up velocity is presented by using a Rheometer. Using a Rheometer, the moment the particles are picked up from a layer is measured by the viscosity change of the upper fluid while the rotation speed increases. By measuring the viscosity change while reducing the rotation speed, it becomes possible to define non-settling particles. Comparing to other works shows, that the new procedure can predict the pick-up velocity and to define non-settling particles well.

KEY WORDS: Pick-up velocity, Hydraulic conveying, Rheometer, Non-settling, Non-saltating.

NOTATION

Ar	Archimedes number, $\frac{g\rho_f(\rho_p-\rho_f)d^3}{\mu_f{}^2}$ (-)
g	Gravity acceleration (m/s^2)
n	Rotational speed (1/s)
Re_p	Reynolds number of particles, $\frac{\rho_f U_{pu} d}{\mu_f}$ (-)
$Re_p{}^*$	Reynolds number based on superficial velocity in pipe (-)
Re_{rh}	Reynolds number based on Rheometer pick-up measurements (-)
T	Torque (N-m)
U_{Pu}	Pick-up velocity (m/s)
μ_f	Fluid viscosity (Pa-s)
μ_w	Water viscosity (Pa-s)
ρ_p	Particle density (kg/m^3)
ρ_f	Fluid density (kg/m^3)

ISSN 0867-7964 ISBN 978-83-7717-323-7 DOI 10.30825/4.12-42.2019

1. INTRODUCTION

Conveying powders using hydraulic or pneumatic carriers is common in various industries. Achieving maximum efficiency of the conveying systems requires to take into account the pick-up velocity of the particles, and to define whether the particles could be considered as settling or non-settling. Pick-up velocity and settling are affected by particles diameter and density, fluid density and viscosity, etc.

Cabrejos and Klinzing (1992, 1994), Hayden et al. (2003) and Kalman et al. (2005), show some correlations between powder, fluid and pipe characteristics, with pick-up velocity. Those correlations are defined based on measurements conducted in complicated systems, including pump, pipes, powder feed system, and measuring system such as camera or pressure gauges.

Viscosity of fluid-particles mixtures are affected by the concentration of the mixtures. According to Einstein (1906) and others (see Pabst, 2003), for a mixture of 20% volume concentration the mixture viscosity is between 50% to 100% higher than carrying fluid viscosity.

In this work we show pick-up velocity measurements using a simple system based on viscosity changes of mixtures measured by a Rheometer. For defining settling or non-settling particles there is less information in the literature. With Rheometer measurements particles-fluid mixture can be classified as settling or non-settling, and can suggest how to predict the behavior of a conveying system.

2. EXPERIMENTAL

2.1 METHOD

Initially, mixtures of fluid and particles were prepared. The ratio between particles and fluid is such that the residue height of particles is up to a half from the general height. This ratio gives a volume concentration of about 20%. The mixture was placed in a cup with 52 mm diameter. The general height is about 90 mm. A rotor with four vertical vanes, based on rotor for powder viscosity measurements (Madariaga et al., 2009), was inserted to the center of the cup. The bottom of rotor is 0 to 2 mm above the residue level (see Figure 1).

The rotor connected to a Rheometer (Anton-Paar Rheolab QC, 0.01-1200 rpm, 0.25-75 mN-m). The Rheometer measures the torque of rotation, while changing rotation speed. Rotation speed increases gradually up to a speed that causes homogenous mixture. Then, the speed decreases gradually up to the initial speed.

2.2 MATERIALS

The materials particles tested were: glass, sand, salt, polypropylene and polystyrene with several different diameters, and fluid materials were water, brine and canola oil. See details in Table 1.

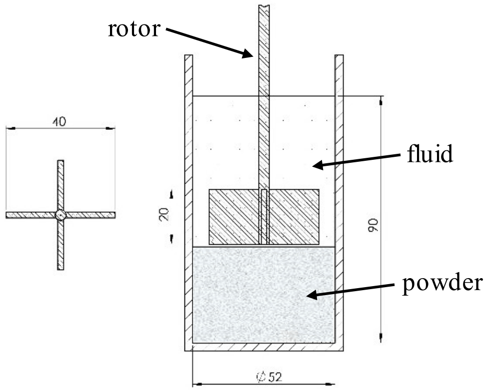


Figure 1. Schematic drawing of the system, initial state.

Table 1

Material properties

No.	Fluid	Particles Material	Particles size (mm)
1	Water	Glass spheres	0-0.002
2			0.04-0.07
3			0.1-0.2
4			0.2-0.3
5		Sand	0.5-0.71
6		Sand powder	0.014
7		Coal Fly ash	0.006
8		Polypropylene	0.4-0.65
9		Polystyrene	2
10	Brine	Salt	0.045-0.106
11			0.106-0.18
12			0.18-0.25
13		Polystyrene	2
14	Canola oil	Polypropylene	0.4-0.65
15		Polystyrene	2
16		Sand	0.5-0.71

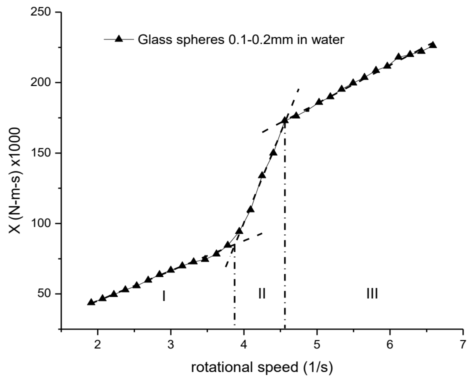
3. PICK-UP VELOCITY

3.1 RESULTS

As a result of the Rheometer measurements, the behavior while the rotation speed increases are analyzed. The measurements are drawn in Figure 2. Since we used a home-made rotor, we didn't have the geometry factor to take into account for viscosity calculations, although it might be calibrated later. However, it was not important because we were interested with the change and not the value. In any case, due to that T/n was increased (linearly) as the rotation speed increased. The vertical axis is defined as the ratio between the measured torque and the rotational speed:

$$X = \frac{T[N \cdot m]}{n[1/s]} \tag{1}$$

On the example graphs of Figure 2, three zones were noticed (for all materials). The 1st zone represents the situation that the particles are not picked-up yet, and it is similar to measuring fluid only. The 3rd zone represents the situation that particle concentration is constant, and rotation causes homogeneous mixture. Both sections are approximately linear, with similar slopes, but not at the same values. Intermediate zone represents the transition phase in which particles are picked up from the bottom to the mixture.



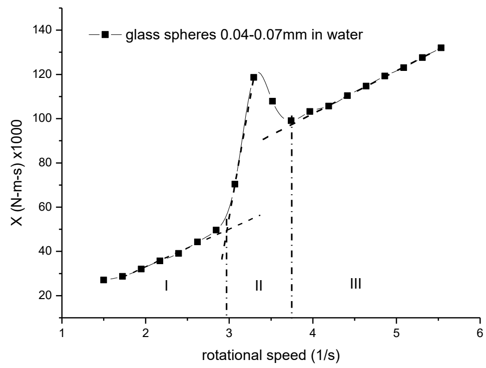


Figure 2. Typical results from a single experiment.

Pick-up velocity is defined by the cross point of the linear lines describing zones I and II. This is the point of the rotation speed where particles started to be picked up. The pick-up velocity is defined as the linear velocity at the outer diameter of the rotor (40 mm) calculated from the rotational speed when transition phase begins.

3.2 ANALYSIS

Following Kalman et al. (2005), all measurements are placed on Reynold vs. Archimedes numbers graph. Reynold number is calculated by linear velocity of rotor's outer diameter at pick-up rotation velocity. Figure 3 shows the pick-up measurements in terms of Reynolds and Archimedes numbers, in logarithmic scales. Three lines, depending on the liquid, are observed. To taking into account the viscosity difference, a modified Reynold number for Rheometer measurements is defined as:

$$Re_{rh} = \left(\frac{\mu_f}{\mu_w}\right)^{0.4} Re_p \tag{2}$$

where both Reynolds numbers are defined on the tested fluid properties. This gives a pick-up correlation for Rheometer measurements, as shown in Figure 4:

$$Re_{rh} = 15.5Ar^{3/8} \tag{3}$$

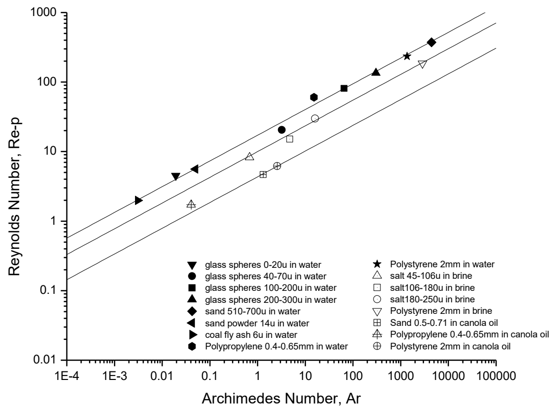


Figure 3. Rheometer measurements: Pick-up Reynolds vs. Archimedes nos.

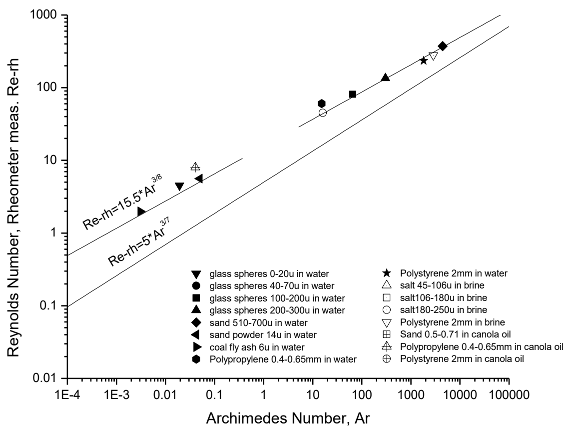


Figure 4. Correlation for Rheometer pick-up measurements compared to Kalman et al. (2005) correlation.

Comparing this graph to the pick-up velocity correlation according to Kalman et al. (2005) (Figure 4), shows that measurements using Rheometer result with higher Reynolds numbers, that is, higher pick-up velocity. It can be explained by the pick-up velocity definition. While according to Kalman et al. (2005), pick-up velocity defines as the velocity of fluid when first particle is picked-up, Rheometer measurements result with higher velocity because viscosity changes are measurable only after some dose of particles are picked-up. To take into account this difference, using Kalman et al. (2005) correlation as reference, a modified Reynolds and Archimedes numbers are defined as:

$$Re_{rh}^{\ *} = 0.323 Re_{rh} \tag{4}$$

$$Ar^{*} = Ar^{0.85} \tag{5}$$

It should be mentioned That Kalman et al. (2005) modified Reynolds number by a function of the pipe diameter to take into account the velocity profile above the stationary layer of particles. Such a modification should be defined also for this case. As seen in Figure 5 modified correlation is similar to Kalman et al. (2005) correlation:

$$Re_{rh}^{\ *} = Re_{p}^{\ *} = 5 Ar^{*3/7} \tag{6}$$

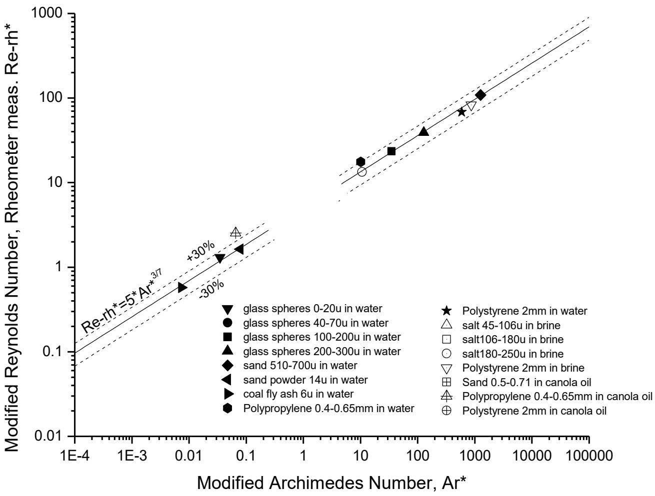


Figure 5. Modified rheometer correlation.

4. SETTLING OR NON-SETTLING

4.1 METHOD

In addition to pick-up velocity measurements, the Rheometer allows to classify if particles of any material and any size in fluid of any kind, will sink while conveying or not. This is achieved by looking at the chart when speed decreases. The tests were conducted by waiting at each rotation velocity 10 seconds before reducing to the other one. It is assumed that this time is sufficient to let particles to sink unless their sinking velocity is quite low. In any case, obviously, the results are subjective and depends on the speed of varying the rotational speed, which is assumed to be slow enough to follow the phenomenon. If the particles are settling, the graph at increasing or decreasing speed will look similar, but in case of non-settling particles the 3rd section will continue downwards (hysteresis), because the mixture stays homogeneous and the particles are not settling. Figure 6 compares settling and non-settling cases. The difference between them is the dashed line, whether it reduces along the increasing line or reduces according to the constant mixture. It shows that while decreasing speed, the mixture stays homogeneous.

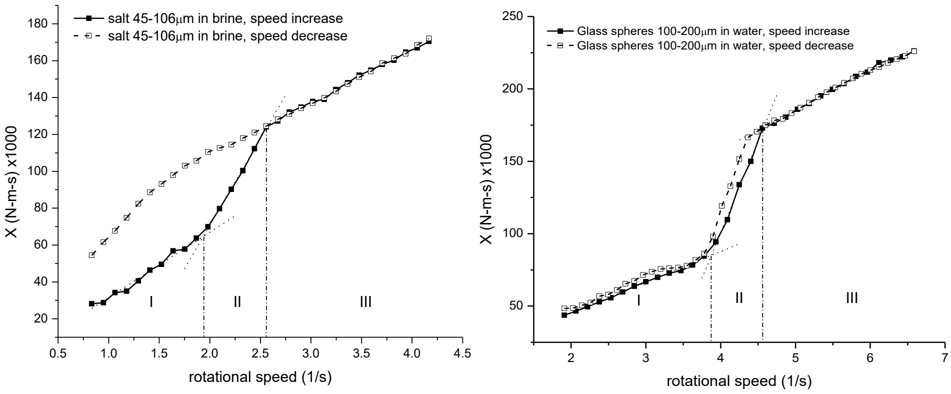


Figure 6. a. Non-settling material graph (left); b. settling material graph (right).

Table 2

List of settling or non-settling measurements

Particles material	Particles size	Fluid material	$\frac{Ar \cdot (\rho_p - \rho_f)}{\rho_f}$	Theoretical velocity ratio (%)	Classify +settling/ -non-settling
Sand	510-700μm	Water	7640	93.0	+
glass spheres	200-300μm	Water	490	95.2	+
glass spheres	100-200μm	Water	106	96.2	+
polystyrene	2mm	Water	35	96.7	+
salt	180-250μm	Brine	12.4	97.2	+
glass spheres	40-70μm	Water	5.21	97.5	?
salt	106-180μm	Brine	3.65	97.6	?
sand	510-700μm	Canola oil	2.57	97.7	+
salt	45-106μm	Brine	0.526	98.2	−
Polystyrene	2mm	Canola oil	0.273	98.3	+
Polypropylene	0.4-0.65mm	Water	0.138	98.5	+
sand powder	14μm	Water	0.0756	98.6	−
glass spheres	0-20μm	Water	0.0313	98.8	−
Polypropylene	0.4-0.65mm	Canola oil	0.00386	99.1	−
coal fly ash	6μm	Water	0.00244	99.1	−

4.2 ANALYSIS

Santo et al. (2018) form a dimensionless correlation for steady state velocity of particles in pneumatic and hydraulic conveying in terms of ratio between particle and superficial fluid velocity as a function of Archimedes number and densities ratio. They assumed that as the velocity ration becomes one the system is certainly non-settling. This assumption can be verified by comparing the results presented in this paper. Table 2 present the measurements for various particulate materials and sizes, fluids, the dimensionless group values, the theoretical relative velocity according to the correlation provided by Santo et al. (2018), and the settling/non-settling observation according to plots as in Figure 6. As a result, for relative velocities over 98.6%, the particles are non-settling, and for under 97.2%, the particles are settling. The domain between these values is not clear yet.

5. CONCLUSIONS

Measurements of powder characteristics using Rheometer is useful and simple. A new method of measurement and analysis enable to measure the pick-up velocity. After some adjustments, these measurements give results likewise as with complicated systems. It was also shown, at the first time that the threshold between settling and non-settling systems can easily be defined by a simple Rheometer measurement. It was shown that non-settling systems are able for $Ar \cdot (\rho_p - \rho_f)/\rho_f < 0.1$.

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