Powder Technology 292 (2016) 158–168

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Experimental flow characterization of sand particles for pneumatic transport in horizontal circular pipes

Tariq S. Khan *, Ying Dai, Mohamed S. Alshehhi, Lyes Khezzar

Department of Mechanical Engineering, Petroleum Institute, United Arab Emirates

ARTICLE INFO

Article history:
Received 30 April 2015
Received in revised form 8 December 2015
Accepted 14 January 2016
Available online 15 January 2016

Keywords:
Air-solid particles flow
Pickup velocity
Blockage ratio
Pipes
Particles pickup rate
Saltation

ABSTRACT

This work presents an experimental study carried out to simulate characteristics of turbulent air-sand particles flow through transparent horizontal pipes with various flow conditions. Experimental analysis focuses on the determination of critical pickup velocity of the solid particles from the horizontal sand layers. Mainly the effects of layer height and pipe diameter on the pickup velocity are investigated. Critical pickup velocity is determined by extrapolating the weight loss curves plotted as a function of corrected velocity above the sand layer. Experimental results show significant effects of layer height and pipe diameter on the pickup velocity. Saltation velocity and dune formation mechanisms are also discussed. Critical pick up velocity of solid particles is found to increase with increasing blockage ratio and pipe diameter. Inclination angle for larger sand bed heights caused leading edge effect on air flow entering the reduced cross sectional area above the layer. Sand particles pickup rate is found to decrease with time as a consequence of decreasing layer height. Experimental results have been correlated and compared with previous studies.

1. Introduction

Multiphase flows occur in variety of industrial processes such as hydrocarbons processing and transportation, cement and pharmaceutical industry, agriculture and food industry. Understanding the mechanism of solids transport in gas transmission flow lines is crucial for their sizing, design and operation. The current study is a contribution towards further understanding of two phase air–solid particles flows in round pipes.

Several studies have been conducted on two phase air–solid or gas–solid particles in various geometries with the perspective of designing or analyzing solids conveying systems [1–8], where it was undesirable to set flow velocity less than the critical conveying velocity as doing so may cause deposition of solid particles ultimately causing clogging of channels or pipelines.

The presence of contaminants in the form of micron sized solid particles, known as black powder may exist in gas transmission and distribution lines with major impacts on flow assurance. It is very likely under certain conditions [9] that these solid contaminants will be sitting in the form of layers in the gas pipelines. Their sudden movement can be very detrimental to filters, compressors and valves, instrumentation and may cause erosion at pipe bends and above all the gas quality is severely compromised. Smart [9] has reported that sitting black powder may cause operational problems, but its movement with gas flow poses even bigger challenge to the industry. Determination of critical pickup velocity concept can be used to predict whether solid contaminants sitting in a gas pipeline network will move with the gas or not. In the current study, pickup velocity has been defined as air superficial velocity above the sand bed that could cause movement of particles regardless of movement pattern. Critical pickup velocity has been defined as minimum pickup velocity that just causes the first movement of particles.

1.1. Previous studies and correlations

Some of the oldest studies on prediction of minimum conveying velocity could be found as early as 1942 [10], followed by some other studies in later years [11–16]. Some pioneer studies on pick up velocity [17–19] and saltation velocity [8,20] are also available.

Several definitions of pick up and saltation velocity are summarized by Cabrejos and Klinzing [2]. For instance, pickup velocity has been defined as gas velocity required to re-suspend a particle initially at rest on the bottom of a pipe [21] or as the fluid velocity required to initiate sliding, rolling and suspension of particles [18]. Cabrejos and Klinzing [2] defined the pickup velocity as the gas velocity required to pick up, entrain, re-suspend, blow away or detach particles at rest on the bottom of pipe. It can be predicted that these phenomena result from a complicated interplay of upward forces like shear lift and buoyancy forces and downward forces such as gravitational and attractive forces between solid particles. Drag force is also worth mentioning here as horizontal movement occurs before vertical lift-off. On the other hand, the saltation velocity is defined as the gas velocity in a horizontal pipeline at which the particles start to drop out of suspension and settle on the

---

* Corresponding author.
E-mail address: tkhan@pi.ac.ae (T.S. Khan).

http://dx.doi.org/10.1016/j.powtec.2016.01.014
0032-5910/

Nomenclature

A	Cross sectional area, m^2
D	Pipe diameter, mm
d	Particle diameter, μm
e	Error
g	Acceleration of gravity, m/s^2
h	Particle layer height, mm
P	Pressure, Pa
Q	Volumetric flow rate, m^3/s
Re	Reynolds Number
T	Temperature, °C
U	Gas velocity, m/s
u	Uncertainty
W	Weight loss, g
Z	Compressibility factor

Greek symbols

α	Angle of inclination
β	Non-dimensional quantity
Δ	Differential/difference
θ	Flare angle of particle layer, rad
μ	Air viscosity, kg/m^3·s
ρ	density of air, kg/m^3

Subscripts

a	Actual
c	Corrected
eq	Equivalent
g	Gas
P	Particle
pu	Pickup
s	Standard
sf	Superficial

bottom of pipe. Another similar definition provided is the minimum velocity in a system containing a horizontal pipeline that will prevent solids deposition at the bottom of pipe [21]. Fig. 1 describes the pickup and saltation velocity mechanisms of solid particles from a horizontal sand bed as defined in the current study.

In the last two decades investigations by teams of Cabrejos and Klinzing [1–3], Kalman et al. [5–7,22–27], and recently Gomes and Mesquita [28,29] are worth mentioning. Cabrejos and Klinzing [1–3] conducted experiments in horizontal pipes. They reported a theoretical model to predict sliding [1] and provided empirical correlation for particles larger than 100 μm [2]. For a given gas flow rate they allowed the layer to erode till a certain layer height is achieved where further erosion stopped. As the layer eroded the cross-sectional area above the layer increased, decreasing the velocity so at a certain stage (minimum layer height) there was no more pickup. They determined the conveying gas velocity (U_{pu}) at this stage using the following equation.

$$U_{pu} = \frac{Q_g}{A_{free}} \tag{1}$$

where Q_g represents the gas volumetric flow rate and A_{free} is the free cross sectional area above the layer. However, they did not report details of layer types and heights.

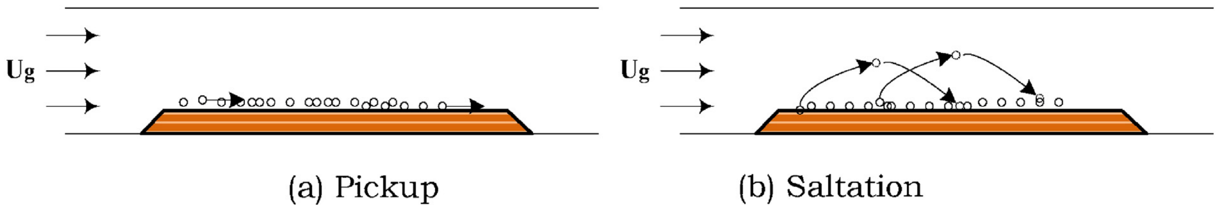
Hayden et al. [4] developed a vertical force balance for a single spherical particle sitting on flat plate to allow particle entrainment for fine particles. They also carried out a set of experiments in 25.4 mm pipe to investigate the relationship between the pickup velocity and particle size. It was reported that the pickup velocity firstly decreases and subsequently increases with particle size within the range of 0–200 μm. Hubert and Kalman [6] used a rectangular wind tunnel to compare pick up and saltation velocities achieved by using layers of particles and heaps. Their layer was in a shallow with its upper surface in line with the wind tunnel wall. Rabinovich and Kalman [25] carried out a similar study to report pickup velocity. Using a number of different materials they showed the pickup velocity to strongly depend on deposit height and shape. They reported the influence of vortex behind particles deposit (heap) to be negligible. Effect of air permeability was reported insignificant for deposit heights lower than 70% of the wind tunnel height, however, this factor affected erosion of deposit. For fine particles, erosion was reported symmetrical while for coarse particles erosion was more significant on the entrance side.

Kalman et al. [7] carried out experimentation on the same rig used by Hubert and Kalman [6]. They determined the critical pickup velocity of air-particles dilute flow by extrapolating the particle weight loss as a function of average air velocity. They proposed a correlation to estimate pick up velocity. The correlation included effects of particle size and density, pipe diameter and fluid density. A three-zone master-curve was defined by establishing a simple relationship between modified Reynolds and Archimedes numbers.

Gomes and Mesquita [28] presented theoretical and experimental analysis of influence of particle size and sphericity on the pickup velocity in horizontal pneumatic conveying. Based on a single particle, they provided a new theoretical relationship for predicting pickup velocity. They showed the pickup velocity to increase with decreasing sphericity. Recently, Gomes and Mesquita [29] carried out a comparative study of previously published empirical correlations on pickup and saltation velocities of solid particles in horizontal pipes and ducts. They reported wide contradictions in previous correlations mainly due to large scatter of data and variety of critical velocity definitions. They also conducted limited experimentation for quantitative evaluation of previous studies.

Select previous empirical correlations along with test conditions are tabulated in Table 1.

The above literature survey reveals that major focus in most of the previous studies had been on the determination of minimum conveying velocity in terms of particles size, density, gas properties and pipe/duct characteristic geometry. To the best of authors' knowledge no previous study has been found in open literature that reports pipe blockage ratio effects on critical pickup velocity determination in a circular pipe. It is also worth mentioning that most of the previous experiments were



(a) Pickup (b) Saltation

Fig. 1. Schematic representation of the movement mechanisms of solid particles in a horizontal pipe.