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Dispersion in particle velocity resulting from random motion through a spatially-varying fluid velocity field in a pipe

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ABSTRACT

A macro-scale probabilistic model of dilute phase pneumatic transport is developed to analyse the dispersion in the velocity of conveyed particles and to predict their velocity statistics. Fluid drag force, proportional to the relative velocity between the particle and fluid, is taken to be the agent that causes particle motion in the axial direction. The basic premise of the approach is that dispersion in axial particle velocity is a result of subsidiary random motion in the radial direction through the fluid velocity field. Two causes are investigated for this radial motion; gravity and inter-particle collisions. As the local fluid velocity experienced by a particle thus continuously varies in an unpredictable fashion, then the associated drag force fluctuates as does the resulting particle velocity. The non-deterministic nature of the fluid velocity acting on the particle is captured by treating fluid velocity as a stochastic process whose description comes from combining knowledge of the flow field with the nature of the radial motion of the particle. This novel approach allows analytical expressions to be obtained for the mean and variance of particle velocity. The accuracy of these predictions was checked by numerical simulation and found to be good. The analysis demonstrates that dispersion in particle velocity is a function of the magnitude of dispersion in fluid velocity (a fluid property), on the inertial rate constant of the particle (a combined particle/fluid property) and the autoregressive parameter (a property reflecting the type of radial motion).

1. Introduction

Pneumatic conveying is described by Fraige and Langston [1] as the use of a gas, which is usually air, to transport solid particles through a pipeline. Pneumatic conveying may be divided into two broad categories: dilute phase (also known as lean phase) and dense phase. The former is more widely used in industry and is characterised by low mass flow ratios and high velocities [2]. The use of high velocities can cause significant attrition of the conveyed product which can have many adverse consequences for product quality. Coupled CFD–DEM models have the potential to provide great insights into particle attrition during conveying [3,4]. However, pneumatic conveying of powders involves the transport of very large numbers of particles concurrently which makes such simulations difficult at present, even if the system is modelled by representing real particles with ideal spheres. The overall objective of this work is to present an approach to the prediction of particle breakage in pneumatic conveying where the emphasis is on the integration of particle conveying velocity and particle structural response. Furthermore, rather than adopting either an experimental or CFD–DEM approach, some of the uncertainties and complexities in the system are captured by a novel macro-scale probabilistic approach to predict particle breakage. The task is subdivided into two parts: this paper deals with the prediction of the distribution in particle velocity in the pipe while a second, companion paper is concerned with the determination of the distribution in impact velocity at a bend and the attendant breakage [5].

In principle, there are various reasons why particles at any specific cross-section of a pipeline may be transported at different velocities. The presence of a polydispersed particle size means larger, heavier particles require longer times and pipe lengths than fine particles to reach any attainable velocity. Inter-particle collisions and particle–wall collisions add variability to particle velocity profiles. Temporal fluctuations in fluid velocity resulting from turbulence can also produce dispersion in particle velocity. Finally, the existence of a spatial velocity profile in the gas phase means that those particles which are near the centreline of the pipe are subject to preferentially higher fluid velocities than those close to the pipe wall. The specific aim of this paper is to quantify the dispersion in particle velocity resulting only from the last mentioned phenomenon; the random migration of particles through the carrier gas velocity field. Theoretical predictions will be validated against numerical results and the level of variability in velocity arising from this phenomenon compared to the contributions of the other phenomena. The model pneumatic conveying system under examination consists of a long, straight horizontal pipe section terminated by one 90° bend. The model is predicated on a number of assumptions. The particles considered are monodispersed spheres

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Nomenclature

c_D	Drag coefficient for an individual sphere in an unbounded fluid
F_D	Drag force acting on the conveyed particle
g	Acceleration due to gravity
m	Mass of a particle
n	Parameter in the 1/7th power law velocity profile which is a function of Re
p_e	Effective inertial rate constant of the particle
$P(u_e)$	Probability density function of effective fluid velocity
$P(u_f)$	Probability density function of fluid velocity
r	Radial distance from the pipe centreline
r_p	Radius of a particle
R	Internal radius of the pipeline
R_{ue}	A first-order autoregressive function to describe autocorrelation
r_φ	Characteristic dimension required in the calculation of φ
Re	Pipe Reynolds number
Re_p	Particle Reynolds number
u_e	Effective fluid velocity, i.e., the average spatial fluid velocity acting on the particle projected area
u_f	Fluid velocity at a radial distance r from the pipe centreline
u_m	Maximum fluid velocity at the pipe centreline
u_p	Axial velocity of the conveyed particle
u_φ	Characteristic velocity at which conveyed particles move in the radial direction
z_t	A random term which is sampled from the normal distribution
Δt	The time step used in the algorithm to calculate u_e
μ_{uf}	Mean fluid velocity
μ_{un}	Mean normal impact velocity for collisions with the pipe bend
μ_{up}	Mean particle velocity
ν	Kinematic viscosity of air
ρ	Density of air
ρ_p	Density of the conveyed particle
ρ_{ue}	Autocorrelation coefficient in the algorithm used to calculate u_e from its value at the preceding step
σ^2_{uf}	Variance in fluid velocity
σ^2_{up}	Variance in particle velocity
τ	Separation time
τ_c	Correlation (or decorrelation) time constant
τ_f	Representative fluid time constant
τ_p	Particle response time constant
φ	Autocorrelation parameter in the first-order autoregressive function R_{ue}

with diameters which are small compared to the pipe diameter although not so small as to be in the ultra-fine range (<20 μm). Furthermore, particles are treated as point masses from a kinetic perspective and no rotational effects are included. The system is assumed to be completely dry to avoid complications such as particles clumping together or adhering to the pipe wall.

2. Theory

2.1. Statistics of fluid velocity

Several additional assumptions were made regarding the air velocity in the conveying system. The air velocity has a high magnitude to ensure that particles remain in suspension, the radial and tangential components of air velocity are not modelled explicitly, there is no systematic variation in air velocity in the axial direction in the straight length of pipeline, entry length effects are ignored and the effect of the bend on the air flow pattern in the straight section of piping is not taken into account. Fluid velocity is taken as invariant with respect to time and fluctuations in it over turbulent time scales are not analysed. Any modification to the air flow pattern due to the presence of the particles was also neglected. In reality, the presence of a solid phase may affect the spatial and turbulent structure of the flow field; however for a low mass flow ratio the influence of the particles on the carrier gas characteristics can be neglected [6].

The high air velocity implies that the Reynolds number of the air flow is large and the flow is considered to be turbulent. Such flows may be characterised by the empirical 1/7th power law velocity profile, which relates the fluid velocity, u_f, at a radial distance of r from the centreline to the maximum velocity along the centreline, u_m, in a pipe of internal radius R. This velocity profile is given as Eq. (1) [7], in which n is a function of Reynolds number. Fig. 1 schematically illustrates the velocity profile across a pipeline.

$$u_f = u_m\left(1-\frac{r}{R}\right)^{\frac{1}{n}} \quad n = 1.77\log_{10}(\mathrm{Re})-1.6. \tag{1}$$

As a spatial variation in fluid velocity exists, the distribution in fluid velocity can be represented by its probability density function (PDF) and its statistics quantified by mean and variance. The PDF of fluid velocity, $P(u_f)$, is given as Eq. (2) by considering the fractional cross-sectional area of the pipe in which the fluid velocity lies between any values u_f and $(u_f + du_f)$.

$$P(u_f) = \frac{2n\left(u_f^n - u_m^n\right)}{u_f^{1-n} u_m^{2n}} \quad 0 \le u_f \le u_m. \tag{2}$$

The first moment of $P(u_f)$ about zero gives the mean fluid velocity, μ_{uf}, while the second moment of $P(u_f)$ about its mean value yields the variance in fluid velocity, σ^2_{uf}:

$$\mu_{uf} = \int_0^{u_m} P(u_f)u_f du_f = \frac{2n^2}{(n+1)(2n+1)}u_m. \tag{3}$$

$$\sigma^2_{uf} = \int_0^{u_m} P(u_f)(u_f-\mu_{uf})^2 du_f = \frac{n^2(5n+1)}{(n+1)^2(2n+1)^2(n+2)}u_m^2. \tag{4}$$

Both are defined solely by the fluid velocity parameters u_m and n. Fig. 2 shows the PDFs of fluid velocity for three different values of n. When n has a realistic value of 6, the mean fluid velocity is just under 80% of u_m and the standard deviation in fluid velocity is approximately 13% of u_m. The fluid velocity distribution is left-skewed which is in accord with the experimental data presented by Hamed and Mohamed [8]; it becomes more skewed to the left as the magnitude of n is increased.

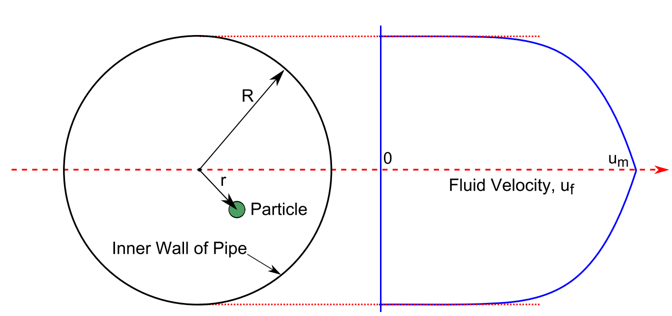

Fig. 1. Illustration showing the turbulent velocity profile in a pipeline.