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Fluid and particle dynamics

3.1 INTRODUCTION
In pneumatic conveying, particles are generally in suspension in a turbulent gas stream. The question of drag on a single particle, and the effects of Reynolds number, particle shape and roughness, voidage, turbulence intensity and scale of turbulence, acceleration, etc. on drag are relevant to pneumatic conveying. These factors will be discussed in this chapter. Equations for calculating important properties such as drag coefficient, terminal velocity, minimum fluidization velocity, and the equation for flow through a packed bed are presented. The characteristics of a powder in terms of its fluidization behaviour are relevant to pneumatic conveying, and will also be discussed.

3.2 LAW OF CONTINUITY
In most cases air is used as the conveying medium. For safety conditions nitrogen or any other gas can be used. In these special cases closed loops (Section 1.6.4) are used in order to circulate these gases and only the losses will be supplemented. One of the major problems in pneumatic conveying is that of gas expansion. This means that gas density and gas velocity change downstream from the product intake until the end of the duct.

For the air alone situation, the air mass flow rate is constant for the total length provided that there is no leakage. The air mass flow rate is given by

\[
\dot{Q} = \dot{V}_\rho = Av_\rho = \text{constant}
\]

where

\[\rho = \frac{p}{RT}\]  \hspace{1cm} (3.2)

and \(p\) stands for the local static pressure. \(R\) is the gas constant and \(T\) the absolute temperature (Section 2.3). The pressure is given by

\[p = p_0 \pm \Delta p_g\]  \hspace{1cm} (3.3)

\(p_0\) is barometric pressure and \(\Delta p_g = \) gauge pressure. Values of the gas constant for air and nitrogen are

\[R = \begin{cases} 287.3 \text{ J/kg K} & \text{air} \\ 296.8 \text{ J/kg K} & \text{N}_2 \end{cases}\]
is the ambient temperature in °C, i.e.

\[
T = (273 + t) \text{ K} \tag{3.4}
\]

## 3.3 Drag on a Particle

### 3.3.1 The standard drag coefficient curve

Studies of the magnitude of drag force on spheres in steady motion in a fluid date back to Newton’s experiments in 1710. In general the drag force \( F \) is expressed by

\[
F = C_D \frac{\rho}{2} w^2 A^* \tag{3.5}
\]

\[
= C_D \frac{\rho}{2} (v_e - c)^2 A^*
\]

where \( w \) is the relative velocity between the gas and the solid, \( A^* \) the projected area normal to flow and \( C_D \) the drag coefficient.

For a spherical particle the cross-sectional area normal to flow, \( A^* \), can be expressed in terms of its diameter \( d \) giving

\[
F = C_D \frac{\rho}{2} w^2 \frac{\pi d^2}{4} \tag{3.6}
\]

A simple dimensional analysis would show that \( C_D \) is a function of the particle Reynolds number \( (Re_p = wd/v) \), where \( v \) is the kinetic viscosity. For a spherical particle moving in an unbounded stationary fluid, the form of the relationship between \( C_D \) and \( Re_p \) is known as ‘the standard drag coefficient curve’ [1]. This is curve A in Fig. 3.1. The drag coefficient for a single particle in an unbounded fluid is denoted here as \( C_{D\infty} \).

Referring to Fig. 3.1, the standard drag curve can be conveniently divided into four regions:

1. Stokes’ law regime (creeping flow regime) with \( Re_p < 2.0 \)

\[
C_{D\infty} \approx 24 Re_p^{-1} \tag{3.7}
\]

2. Intermediate region, with \( 0.5 < Re_p < 500 \), first studied by Allen [2],

\[
C_{D\infty} = 18.5 Re_p^{-0.6} \tag{3.8}
\]

3. Fully developed turbulence regime (Newton’s law region), with \( 500 < Re_p < 2 \times 10^5 \)

\[
C_{D\infty} \approx 0.44 \tag{3.9}
\]