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Liquid suspensions of single and binary component solid particles—An overview

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Abstract

In this paper theoretical approaches and experimental findings relative to the hydrodynamics of liquid suspensions of solid particles by liquids are reported and discussed. For the single particle specie systems, advantages and possible faults of well known empirical correlations are discussed. For binary-solid mixture suspensions, experimental evidence are reviewed and approaches capable of successfully describing observed behaviour are reported.

Keywords: Sedimentation; Fluidization; Voidage function; Binary-mixture

1. Introduction

Fluidisation and sedimentation, and more generally solid–liquid suspensions, are unit operations where a solid phase is contacted with a fluid phase. They have in common the fact that the solid particles are completely supported by the fluid with the particle–particle direct contacts playing what is thought a minor, if not totally negligible, effect on the overall force balance. Therefore we have:

$$\text{particle weight}\,(W) = \text{total fluid–particle interaction force}\,(F_\mathrm{T}), \quad (1)$$

which is the basic equation for the fluidising and sedimenting systems. The total fluid–particle interaction force can then be split, if necessary, into two contributions as is done, for example, in the case of single particle falling in an infinite expanse of fluid (Bird, Stewart, & Lightfoot, 1960):

$$\text{total fluid–particle interaction force} = \text{buoyancy force}\,(F_\mathrm{B}) + \text{drag force}\,(F_\mathrm{D}). \quad (2)$$

The zero net force on the solid phase makes it behave very much like a fluid (hence the name fluidisation) with obvious advantages for the process industry: movimentation, mixing or density-driven segregation all of which are much easier when the solid is suspended rather than loosely packed. Although sedimentation and fluidisation can be carried out with any fluid, we will consider here only Newtonian liquid systems. In recent years, gas–solid systems have been by far the most studied, as a result of their greater industrial relevance, in spite of the fact that a practical application of solids suspended in liquid was reported (Agricola, 1950) to be used some 450 years ago as a means of separating solids of different sizes and densities. Since then the utilisation of liquid–solid suspensions in the mining industry has been reconfirmed in a paper more than 100 years ago (Munroe, 1888) and at the beginning of Second World War (Richards & Locke, 1940). However, only recently solid–liquid systems have become the centre of attention again thanks to their applications in new industrial fields such as biochemical processing, water and wastewater treatments and food technology. A typical example is the purification of proteins by absorption techniques which was presented by Draeger and Chase (1991). If this process is carried out in fixed beds of solid absorbent the particulates present in the liquid quickly clog the apparatus. In contrast, the use of expanded solid–liquid suspensions facilitates the passage of suspended matter through the absorbent particle-increased interstices eliminating the need of any preliminary filtration.

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Nomenclature

Ar	Archimedes number, $d^3(\rho_p - \rho)\rho g/\mu^2$
C_D	drag coefficient
d	particle diameter (m)
D	column diameter (m)
F_B	buoyancy force (N)
F_D	drag force (N)
F_T	fluid–particle interaction force (N)
g	acceleration due to gravity (m/s^2)
k	numerical parameter
n	numerical parameter
p	pressure (N/m^2)
P	piezometric pressure (N/m^2)
Re	Reynolds number, $d\rho u/\mu$
Re_t	Reynolds number, $d\rho u_t/\mu$
t	time (s)
u	velocity (m/s)
u_t	terminal settling velocity (m/s)
V	particle volume (m^3)
W	particle weight (N)
z	elevation (m)

Greek letters

ε	voidage
μ	fluid viscosity (kg/m s)
ρ	fluid density (kg/m^3)
ρ_b	bed bulk density (kg/m^3)
ρ_p	solid density (kg/m^3)
Φ	particle volume concentration

Subscripts

L	larger particle
S	smaller particle

Fluidisation, sedimentation and transport systems are identical from a fluid dynamic point of view, since fluidisation can be transformed into sedimentation (or vice versa) by simply changing the reference system. It is important to recognise that in this sense liquid superficial velocity and particle settling velocity are interchangeable.

2. Fluidisation and sedimentation of single species solids

2.1. Solid–fluid interaction forces

Wallis (1969) presented the general one-dimensional momentum equation for the particle phase in a solid–fluid suspension as follow:

$$\rho_p\left(\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial z}\right)=b+f-\frac{\partial p}{\partial z}, \tag{3}$$

where, on the right-hand side, b represents all the body forces, $-\partial p/\partial z$ is the pressure gradient force which, in general, should include contributions from both the fluid and particle pressure, and f accounts for all the surface forces acting on the solid phase that are not included in the pressure gradient term. Under uniform, steady-state conditions the left-hand side of the above equation vanishes, and for most practical purposes b reduces to the gravitational forces, p represents the fluid pressure and f consists of the sum of the hydrodynamic drag and any direct contact forces (which are absent for the problem in hand in which the particles are not touching each other).

The terms in Eq. (3) represent forces per unit volume of the particle phase. Multiplying by the volume, V, of a single particle and employing the above considerations yields the steady-state force balance for a single particle:

$$-V\rho_p g + F_D - V\frac{dp}{dz} = 0. \tag{4}$$

The pressure gradient for a solid–fluid suspension where the solid phase is completely supported by the fluid is given by:

$$\frac{dp}{dz} = -[(1-\varepsilon)\rho_p + \varepsilon\rho]g. \tag{5}$$

Incorporation of Eq. (5) into Eq. (4) leads to:

$$V\rho_p g = F_D + V\frac{dP}{dz} + V\rho g, \tag{6}$$

where P is the piezometric pressure defined by:

$$P = p - \rho g z. \tag{7}$$

P is thus the contribution to the total pressure that arises as a result of the solid particles being suspended by the fluid. In Eq. (6) the left-hand side represents the particle weight and the right-hand side the overall fluid particle interaction force. We can, as suggested in the introduction, split the overall interaction force into a buoyant and a drag contribution. There is little doubt that the first term in it can be classified as drag and the last as buoyancy. A point of contention is the second term on the right-hand side of Eq. (6). Some consider that it makes more sense to include it with the third term to give the overall buoyancy force as it possesses the same physical origin (Gibilaro, Di Felice, Waldram, & Foscolo, 1987; Gibilaro, 2001). Others argue that, as it owes its origin to energy dissipation, it cannot be considered as a buoyant effect (a conservative force by definition) and, therefore, should be added to the first term to give the overall drag force (Clift, Seville, Moore, & Chavarie, 1987). The argument is not simply a semantic one. Unfortunately, direct measurements cannot help us in this case as so far only total fluid–particle interaction forces have been measured (Bicknell & Whitmore, 1967) and possible ways of quantifying the buoyant and the drag contributions independently are no more than thought experiments (Fan, Han, & Brodkey, 1987). In deciding which of the alternative formulations is better suited for analysis of suspensions, the comments of Buyevich (1995) are textually reported: "*... no matter how the particles have been suspended, the very presence of suspended neighbours apparently helps to maintain any particle in the suspended state by providing for a supplementary force which has nothing in common with drag. ... any particle feels the presence of a pressure gradient but is entirely insensitive to what is the cause of the gradient occurrence*".