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Measurement of particle concentration in horizontal, multiphase pipe flow using acoustic methods: Limiting concentration and the effect of attenuation

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HIGHLIGHTS

- Marine model for measuring suspended solid fraction adapted for general use.
- Glass and plastic particles tested at several fractions in horizontal pipe flow.
- Clear differences observed between species and settling and non-settling flows.
- Limiting concentration and penetration depth derived to inform future experiments.
- Method has potential for use in several engineering applications.

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ABSTRACT

An acoustic dual-frequency concentration inversion method, in which the backscattered acoustic signal received by transducers operating in the megahertz range is used to determine the concentration profile in suspensions of solid particles in a carrier fluid and which was originally developed for environmental applications, is applied to arbitrary suspensions of general engineering interest. Two spherical glass and two non-spherical plastic particle types with a range of size distributions and densities are used. Particle concentration profiles in horizontal turbulent pipe flow at Reynolds numbers of 25 000 and 50 000 – below and above the critical deposition velocity, respectively – and nominal concentrations of 0.5%, 1% and 3% by volume are presented for the four particle species, using measured backscattering and attenuation coefficients. In particular, the effects of particle size, density and flow rate on the transport and settling behaviour of suspensions are elucidated. The results demonstrate the potential of this method for measuring the degree of segregation in real suspensions and slurries across a range of challenging application areas, such as the nuclear and minerals processing industries. The limitations of the method are explored in detail through an analysis of the acoustic penetration depth and the application-specific maximum measurable concentration, both of which can be used to determine the most appropriate acoustic frequencies and measurement configuration in a particular case.

1. Introduction

The flow of solid-liquid suspensions in pipes has generally been categorised as follows: Non-settling, in which the solid fraction remains fully suspended in the carrier fluid; unhindered-settling, in which suspended particles can freely settle under gravity; or hindered-settling, in which hindrance to downward-moving particles is provided by upward-moving carrier fluid, through the conservation of mass (Crowe, 2006; Doron and Barnea, 1995; Wasp et al., 1977). Alternatively, five flow regimes for suspensions, and various combinations thereof, are commonly described as follows: homogeneous (or pseudo-homogeneous), in which all particles are suspended and the concentration and velocity is uniform across the diameter of the channel; heterogeneous, in which a concentration gradient exists in the suspension; flow with a moving bed, or sometimes "saltation" flow, in which some fraction of the suspended particles has settled and formed a sediment bed that moves along the channel; flow with a stationary bed, in which at least part of the sediment is stationary

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relative to the channel; or plug flow, in which the solids span the diameter of the channel and move *en masse* (Crowe, 2006).

Most commonly, the five flow regimes described above are delineated by the transition velocities U_{c1} to U_{c4}, respectively (Crowe, 2006). Of these, U_{c1} represents the velocity above which all solids are suspended homogeneously, while U_{c2} (or U_c) is the velocity above which solids begin to settle out of a heterogeneous suspension and form a sediment bed. Some confusion exists because the term "critical velocity" (U_{min}) has also been used to describe the velocity at which the pressure drop reaches a minimum (Doron and Barnea, 1993; Doron et al., 1987). However, such confusion is avoided in this study, with U_c being referred to as the critical deposition velocity (Oroskar and Turian, 1980; Soepyan et al., 2014), although they have been given several other names in the literature ("critical velocity", "minimum transport velocity" or "deposition velocity": Crowe, 2006; Harbottle et al., 2011).

In this study, the influence of particle size and concentration on the flow pattern – specifically the local concentration profile with respect to vertical position – above and below the critical deposition velocity is investigated. There follows a summary of some models and experimental studies of concentration profiles in heterogeneous suspensions in pipes and channels, which are also listed in Table 1, in which ϕ is the particle volume fraction (which is used alongside the mass concentration, M, hereafter), d is the particle diameter, and the Reynolds number, Re, is defined as follows:

$$\mathrm{Re} = \frac{U_b D}{\nu}, \tag{1}$$

where U_b is the bulk (average) axial flow velocity, D is the pipe diameter or channel width, and ν is the kinematic viscosity of the carrier fluid.

Karabelas (1977) derived a model for vertical particle concentration in pipes and channels and found excellent agreement with his own experimental results (plastic spheres in kerosene, oil, and mixtures thereof) and those of Durand and Condolios (1952) (sand in water). The "two-layer" model of Gillies et al. (1991), which was tested against experiments, incorporates a layer of suspended "fines", *i.e.* buoyant particles, and carrier fluid, and a bed with two components, a "contact load" which dissipates energy through friction with the wall, and a "suspended load", the weight of which is held by the carrier fluid. The model has been verified very successfully against experimental concentration profile data for coarse sand suspensions by Gillies and Shook (1994), and has undergone a number of refinements, including extension to higher volume fractions around the deposition velocity ($\phi > 35\%$ or so) (Gillies et al., 2000) and higher velocities (Gillies et al., 2004).

Pugh and Wilson (1999) found the particle concentration varies linearly with height above stationary beds. Admiraal and García (2000) measured the particle concentration above a sand bed in a water channel using a single-frequency acoustic method (at f=2.25 MHz) in which the mean-squared voltage received by the transducer was correlated with the suspended solids concentration. Gillies et al. (2004) presented concentration profiles for sand in pipe flow (with water); it is interesting to note that group's "two-layer" or "SRC" (Saskatchewan Research Council) model (Gillies and Shook, 2000) very accurately predicted the mean delivered solids concentration in high-concentration suspensions (up to several tens of percent by volume).

The simulations and experimental results of Ekambara et al. (2009) closely matched each other and numerical data from the literature in terms of concentration, velocity and pressure drop. In one of several related papers, Matoušek (2009) presented concentration profiles above a partially stationary sand bed and modelled the solid fraction as being composed of three layers – a stationary bed, a shear layer and a fully suspended layer – in contrast to the two-layer model of Gillies et al. (1991, 2004). Using an acoustic power-spectrum measurement method (centred on f=2.25 MHz), Furlan et al. (2012) also found good agreement between experimental and numerical results in horizontal and vertical pipe flow with glass beads in water.

In the fully coupled numerical simulations of Capecelatro and Desjardins (2013), Lagrangian tracking was used to follow the motion of individual solid particles. Excellent agreement was found between the predictions of the simulation and an experimental dataset taken from the literature (Roco and Shook, 1985). Kaushal and Tomita (2013) modified an earlier model (Kaushal and Tomita, 2002a) and found excellent agreement with several earlier experimental studies (Gillies and Shook, 1994; Kaushal et al., 2005; Matoušek, 2009).

There are several objectives in this paper. The first is to investigate flows at lower concentrations, specifically of the order

Table 1
Multiphase and high-concentration pipe and channel flow studies.

Reference	Method	D (mm)	Re (10^3)	Particle properties
Shook et al. (1968)	Gamma rays	24.7 × 101 (channel)	Not applicable	Sand, d=153–510 μm, ϕ=2.5–28%; nickel, d=135 μm, ϕ=2.4–15%
Karabelas (1977)	Sampling, modelling	50.4 and 75.3	≈ 3–55	Resin, d=210 and 290 μm, ρ=1126 kg m^{-3}, $\phi \approx$ 3–6.5%
Zisselmar and Molerus (1979)	LDA	50	≈ 50	Glass, d=53 μm, ρ=2510 kg m^{-3}, $\phi \leq$ 5.6%
Tsuji and Morikawa (1982)	LDV, Pitot probe	30.5	11.7–38.9	Plastic, d=0.2 and 3.4 mm, ρ=1000 kg m^{-3}, $\phi \leq$ 6%; KCl tracers, d=0.62 μm
Gillies and Shook (1994)	Gamma rays	53.2–495	95.8–1,880	Sand, d=0.18–2.4 mm, ρ=2650 kg m^{-3}, ϕ=6–45%
Pugh and Wilson (1999)	Gamma rays	105	87.2–193	Sand, d=1.05 mm, ρ=1530 kg m^{-3}, ϕ=3.6–10.5%; Bakelite, d=0.30 and 0.56 mm, ρ=2650 kg m^{-3}, ϕ=1.2–5.5%
Admiraal and García (2000)	Acoustic probe	300 × 100 (channel)	Not applicable	Sand, d=120 and 580 μm
Kaushal et al. (2002)	Modelling	55, 105	Large range	Zinc, iron and copper tailings (comparison with several studies)
Gillies et al. (2004)	Resistivity probe	103	134–309	Sand, d_{50}=90 and 270 μm, ϕ=10–45%
Ekambara et al. (2009)	Numerical	50–500	Large range	All sand or sand-like, d=90–500 μm, ϕ=8–45%
Matoušek (2009)	Gamma rays	150	66–311	Sand, d=370 μm, ρ=2650 kg m^{-3}, ϕ=3.1–34.9%
Furlan et al. (2012)	Acoustic probe	25.4	50.8–88.9	Glass, d=195 μm, ρ=2500 kg m^{-3}, ϕ=7 and 9%
Capecelatro and Desjardins (2013)	Modelling	51.5	46.7 and 85	Sand-like, d=165 μm, ρ=2650 kg m^{-3}, ϕ=8.4%
Kaushal and Tomita (2013)	Modelling	Several	Several	Glass and sand (comparison with several studies)

d and d_{50} are particle diameter and 50th percentile of size distribution; ϕ is volume fraction occupied by particles; Re is Reynolds number.