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Axial dispersion of suspended sediments in vertical upward pipe flow

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ABSTRACT

The increasing pressure on earth's raw material resources forces the search for alternatives. An alternative source of raw materials is deep sea deposits. The mining of deep sea deposits comes with many challenges, one of them being the vertical transport of excavated material from the seafloor to a floating production platform at the surface. Material can be transported vertically by means of suspending the material in an upward flow of water in a riser. When the riser is fed irregularly by intermittent batches of solids, accumulation of solids can occur that in turn can result in riser blockage. The accumulation process is counteracted by axial dispersion of the batches. In this paper the vertical hydraulic transport of batches is experimentally explored to get insight in the influence of solids on the axial dispersion process. By analysis of the decrease in volume fraction, the axial dispersion coefficient for the vertical transport of batches of sand, gravel and plastic grains relative to the Taylor dispersion coefficient for dissolved matter in turbulent pipe flow is determined. The analysis shows that the presence of solids attenuates axial dispersion such that it plays a minor role in the transport process, particularly for coarse sediments.
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1. Introduction

There has been several decades of research into hydraulic lifting of solids. The work of Newitt et al. (1961), Condolios et al. (1963), Brebner and Wilson (1964), Cloete et al. (1967), Sellgren (1982) and Grbavčić et al. (1992) for instance aims at (economic) optimization of vertical transport systems. In their work, stationary transport situations are investigated, with a focus on transport velocities, hydraulic losses and production capacity.

Interest in vertical transport for deep sea mining applications emerged in the 1960s with the publication of Mero (1965). He suggests the use of vertical hydraulic transport for lifting manganese nodules, an option also mentioned in Pearson (1975). Research of vertical hydraulic lifting of solids for deep sea mining, again aiming at optimization of systems with a stationary flow, is described in Clauss (1971), Engelmann (1978), Xia et al. (2004a,b) and Yang et al. (2011). Pougatch and Salcudean (2008) performed two-dimensional numerical simulations of an air lift system for deep sea mining applications.

Many workers have investigated the stationary transport of solids. This paper however is concerned with the vertical hydraulic transport of individual batches of solids. Vertical transport distances in deep sea mining operations typically are hundreds to thousands of meters. The mining of rock phosphates in New Zealand happens at a few hundreds of meters water depth, see Widespread Energy (2011), the mining of Seafloor Massive Sulphide deposits happens at two thousand meters of waterdepth, see Nautilus Minerals (2010) and mining polymetallic nodules at even five thousand meters of water depth, as described in Mero (1965) and Pearson (1975). With these large transport distances, irregular feeding of the riser can result in the development of batches of solids, that can overtake each other and even result in formation of solid plugs that can block the riser. This problem has been encountered in terrestrial mining sites (Van den Berg and Cooke, 2004), and it has been addressed in Talmon and Van Rhee (2011) in the context of deep sea mining.

The transport of individual batches can result in system failure, therefore the transport phenomena need to be understood very well. Talmon and Van Rhee (2011) use an advection–diffusion equation to model the transport process. The first important aspect is modelling the nonlinear advection term by means of hindered settling theory. This approach is adopted for hydraulic transport by Clauss (1971), Engelmann (1978), Evans and Shook (1991), Van Rhee (2002) and Talmon et al. (2007). The diffusion term represents particle dispersion, which Talmon and Van Rhee

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Nomenclature

A	cross section area (m^2)
C_D	drag coefficient (–)
c_v	volume fraction of solids (–)
$\bar{c}_v$	time averaged volume fraction of solids (–)
$c_{v,0}$	initial volume fraction of solids (–)
d	particle diameter (m)
D	pipe diameter (m)
g	gravitational acceleration (m/s^2)
h_i	initial batch height (m)
k_f	conductivity of the carrier fluid (S/m)
k_m	conductivity of the mixture (S/m)
l	batch length coordinate (m)
L	length (m)
L_{batch}	batch length (m)
m	mass (kg)
n	Richardson and Zaki exponent (–)
ν_f	kinematic fluid viscosity (m^2/s)
Pe	Peclet number (–)
Q	flow rate (m^3/s)
Stk	Stokes number (–)
t	time (s)
t_p	characteristic particle time scale (s)
t_f	characteristic bulk flow time scale (s)
t	time (s)
Δt_{14}	time needed for a batch to propagate through the measurement section (s)
v_f	fluid velocity (m/s)
v_m	mixture velocity (m/s)
v_s	solid fraction velocity (m/s)
v_{slip}	slip velocity (m/s)
w_t	terminal settling velocity (m/s)
z	axial coordinate (m)
δ	relative decrease in peak volume fraction (–)
δ_A	relative decrease in peak volume fraction due to non-linear advection (–)
δ_D	relative decrease in peak volume fraction due to axial dispersion (–)
δ_{Taylor}	relative decrease in peak volume fraction due to Taylor dispersion (–)
$\delta_{Taylor,ref}$	reference value of the relative decrease in peak volume fraction due to Taylor dispersion (–)
ϵ_m	axial dispersion coefficient due to Brownian motions (m^2/s)
ϵ_z	axial dispersion coefficient (m^2/s)
ϵ_{Taylor}	Taylor dispersion coefficient (m^2/s)
λ	Darcy–Weisbach friction coefficient (–)
ρ	density (kg/m^3)
τ	shear stress (Pa)
CCM	conductivity concentration meter

(2011) model as axial dispersion for turbulent pipe flow according to Taylor (1954). Evans and Shook (1991) adopted the same method and they conducted vertical transport experiments with sand ($d_m = 0.175$ mm) and fine gravel ($d_m = 4.1$ mm). They found that the axial dispersion of sand indeed could be modelled well by Taylor dispersion, but for the fine gravel their measurements were inconclusive. Since axial dispersion counteracts the development of steep gradients in the volume fraction of solids this process is beneficial for prohibiting the formation of plugs.

In this study, the authors are concerned with flow assurance of vertical transport systems in general, especially the formation of solid plugs is a topic of interest. Vertical transport systems for deep sea mining typically have $L/D = O(10^4)$. This is a strong argument to apply a one-dimensional continuum model. The authors are developing a dynamic one-dimensional model of the entire vertical transport system that includes conservation of mass and momentum for the mixture, and that includes the nonlinear advection–diffusion equation to model the transport of solids. This macroscopic model is to be used for studying the development of plugs and for optimization of loading strategies for the riser system. In order to find out whether axial dispersion plays a significant role in attenuation of plugs, this paper experimentally explores the axial dispersion of suspended sediment in vertical pipe flow.

2. Theory of axial dispersion

The transport of suspended solids or dense granular flows can be approximated as a continuum (Jop et al., 2006), which enables the use of the advection–diffusion equation. For the axial dimension z of a pipeline or riser, the advection–diffusion equation reads

$$\frac{\partial c_v}{\partial t} + \frac{\partial c_v \cdot v_s(c_v)}{\partial z} = \frac{\partial}{\partial z} \cdot \left(\epsilon_z \cdot \frac{\partial c_v}{\partial z} \right) \tag{1}$$

In Eq. (1), c_v is the volume fraction of solids, $v_s(c_v)$ is the solids transport velocity and ϵ_z is the axial dispersion coefficient. From Eq. (1) it becomes clear immediately that axial dispersion is relevant for the cases with large volume fraction gradients $\partial c_v / \partial z$, i.e. in the case of plug development. Continuous solids input with minor variations will result in $\partial c_v / \partial z \approx 0$, and in these cases axial dispersion is of minor or even no importance.

An important hallmark in the theory of axial dispersion is Taylor (1953), who studied the dispersion of a solvent flowing through a horizontal pipe in the laminar regime. Taylor (1953) used a parabolic velocity profile for the horizontal pipe (i.e. Poiseuille flow), from which he calculated the axial stretching of the solute. The solvent propagates faster along the centerline than at the wall of the pipe. Molecular diffusion causes mixing of the solvent over the pipe diameter. It proved that axial dispersion could be expressed analogous to a diffusion coefficient, like $\epsilon_z = D^2/4 \cdot v_f^2/(48 \cdot \epsilon_m)$, with ϵ_m being the coefficient of molecular diffusion.

In Taylor (1954), this theory was extended to the case of transport by turbulent flow through a horizontal pipe. Again the analogy with a virtual diffusion coefficient was sought, and it showed that for turbulent flow, the molecular diffusion coefficient ϵ_m is negligible compared to the turbulent eddy viscosity. For transport of a solvent in turbulent pipe flow, Taylor (1954) introduces the axial dispersion coefficient being:

$$\epsilon_z = 10.1 \cdot \frac{D}{2} \cdot \sqrt{\frac{\tau_f}{\rho_f}} \tag{2}$$

The wall shear stress for clear fluid τ_f depends on the pipe properties and flow properties. For turbulent pipe flow it is given by

$$\tau_f = \frac{\lambda \cdot \rho_f \cdot v_f^2}{8} \tag{3}$$

By dimensional analysis Eckstein et al. (1977) pointed out that solid particles migrating under shear at very low Reynolds numbers show

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