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Prediction of thickener performance with aggregate densification

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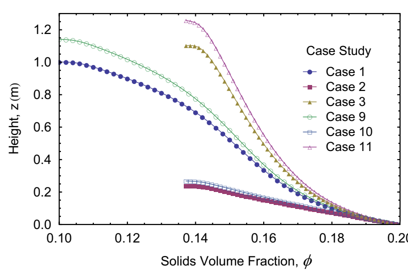
HIGHLIGHTS

- Aggregate densification in thickeners is considered via theory of Usher et al. (2009).
- Access to much larger solids fluxes in a densified thickener is demonstrated.
- Solids fraction profiles near the top of thickener are sensitive to suspension rheology.
- Thickening enhanced if underflow solids fraction is less than that in aggregates.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper aims at investigating the effects of densification of aggregates within a suspension on thickener dewatering performance. The comparisons of the maximum permitted underflow solids flux calculated from both an initial undensified thickener and a densified thickener were achieved. Large underflow solids fluxes were attained in densified thickeners. The effects of densification on the bed heights and on the solids residence times required to achieve a given underflow solids flux and a given underflow solids volume fraction were also computed and compared. Substantial reductions in the bed heights and the solids residence times are possible in densified cases. Previous studies have assumed the functional form of the compressive yield stress in the suspension so as to give an exceedingly weak gel in the neighbourhood of the solids volume fraction at the top of the bed. The implications of considering a different gel rheology with a rather stronger gel were considered. The effects of this new rheology lead to a slightly less sharp spatial gradient in the solids volume fraction near the top of the bed. In addition, the effect of varying the underflow solids volume fraction was considered. The observations of substantial increases in underflow solids fluxes and substantial reductions in bed heights and solids residence times were only achieved when the underflow solids volume fraction was less than or comparable with the solids volume fraction within the aggregates. However, if the underflow solids volume fraction was considerably larger, aggregates were considered to be overlapping and interpenetrating. As a result, the improvements in thickener performance due to densification were insignificant.

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1. Introduction

A large amount of waste in the form of liquid with suspended solids is produced by the minerals industries and wastewater plants each year (Boger, 2009). Water needs to be removed from these suspensions by using dewatering devices (Bustos et al., 1999; Bürger and Wendland, 2001). In particular, thickeners are devices commonly used in the minerals industries and wastewater plants, due to low operating costs (Stickland et al., 2008). However, robust design and operation of a device such as a thickener rely on understanding the rheological behaviour of the suspension that it is used to process.

Detailed understanding of suspension rheology entails detailed models for the microstructure and micromechanics of that suspension,

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which have been studied by Brady and Bossis (1985, 1988), Phillips et al. (1988), and Marchioro and Acrivos (2001). Models at this level of microstructural detail tend however to be computationally intensive. Buscall and White (1987) have developed a suspension dewatering theory based on phenomenological sludge rheological properties: a so-called 'hindered settling function' and a so-called 'compressive yield stress' (both quantities to be defined shortly). This theory operates on a *continuum* rather than on a microstructural level.

The above-mentioned sludge rheological properties have been commonly used to design a thickener and predict the thickener performance[1] via this phenomenological theory over the last several years (Landman et al., 1988; Martin, 2004; Usher and Scales, 2005). Experiments and mathematical simulation models for extracting the relevant sludge rheological properties have also been developed by many authors (Kynch, 1952; Buscall and White, 1987; Landman and White, 1994; Green et al., 1998; Bürger and Concha, 1998; Lester et al., 2005; Diehl, 2007). Indeed it could be argued that the Buscall and White (1987) theory for predicting the behaviour of dewatering equipment has enjoyed wide take up owing in large part to the development of reliable and inexpensive bench-scale experimental techniques (using small suspension samples), that determine the material properties (Stickland et al., 2008; de Kretser et al., 2001; Usher et al., 2001; Landman et al., 1999; Green et al., 1998) subsequently needed for engineering design of thickeners (and/or other dewatering equipment) on a phenomenological level.

The above-mentioned theoretical and mathematical models used for the predictions of thickener performance did not however account for shear stress which could be important in thickeners due to the presence of rakes which shear the suspensions in order to improve the thickener performance. Thus, discrepancies still exist between theoretical models and industrial thickener operations (Usher et al., 2009; van Deventer et al., 2011).

A complete understanding of how suspensions might dewater in the presence of shear again involves detailed descriptions of suspension microstructure, and how such microstructure is influenced by changes in solids volume fraction as well as by shear (Brady and Bossis, 1985, 1988; Phillips et al., 1988; Marchioro and Acrivos, 2001; Bossis and Brady, 1984; Graham and Bird, 1984). What has become apparent is that, in the presence of shear, there is not only a Buscall and White (1987) type 'compressive yield stress' term (driving suspended solids from high to low concentrations, Landman et al., 1999; Fang et al., 2002), but also a 'shear-induced diffusion' effect, driving solids from zones of high to low shear (Leighton and Acrivos, 1987a, 1987b; Acrivos, 1995). The phenomenon of shear-induced diffusion is considered to arise as a result of solids in the suspension acquiring a random component to their velocity due to hydrodynamic interactions with other (randomly positioned) solids (Acrivos, 1995). There have been numerous studies quantifying these effects (Breedveld et al., 1998; Wang et al., 1996, 1998; Husband et al., 1994; Graham et al., 1991; Abbott et al., 1991; Foss and Brady, 1999; Brady and Morris, 1997). Shear-induced diffusion has also been introduced into continuum level models of suspension mechanics (Phillips et al., 1992; Subia et al., 1998; Fang et al., 2002; Kapoor and Acrivos, 1995). Such continuum models can be considered to be informed by processes occurring at the microscale, but certainly do not require detailed microstructural information to be employed. In the works cited above, the models have been used to good effect in various geometries (e.g. pipe flows, rotating cylinder flows, inclined-settler flows, etc.).

The work of Usher et al. (2009) however chose to incorporate shear in a somewhat more empirical fashion which can nonetheless be adapted conveniently and readily onto the framework of the dewatering calculations from the Buscall and White (1987) theory. Usher et al. (2009) focussed on suspensions containing bound aggregates of solids known as flocs, and in particular considered systems that are flocculated using polymers, the role of the polymers being to bridge solid particles and thereby to bind solids together into the aforementioned aggregates. Given that binding by polymer bridges may be considered irreversible (on time scales of interest), Usher et al. (2009) speculated that shear stress produced by rakes or rotors might change the microstructure of a suspension by leading to further binding and thereby aggregate densification[2]; individual aggregates may become more tightly bound and simultaneously wider channels open up between aggregates (a process which could potentially be considered as being very loosely analogous to shear-induced diffusion driving solids away from the neighbourhood of the rake, and opening up channels near it). This aggregate densification then affects the suspension settling process and thereby the thickener performance (Usher et al., 2009; Gladman et al., 2010; van Deventer et al., 2011).

The aggregate densification theory developed by Usher et al. (2009) quantified the extent to which the shear-induced change of aggregate diameters during the settling process affected the sludge rheological properties. The ability of the suspension to form a weight bearing gel relies on maintaining contacts between adjacent aggregates. However, these contacts become fewer as the individual aggregates densify, which can lead (as noted above) to wider channels between aggregates. Viscous drag between the solids and adjacent fluid tends also to be reduced, owing to these wider channels.

As a development of the aggregate densification theory, the performance of a densified thickener must be predicted. Usher et al. (2009) presented the significant improvement possible for the performance of a densified thickener based on the predictions of the solids flux and the solids settling rate in a thickener with a given bed height. In the case of a thickener that processes material beyond the solids fraction at which the suspension forms a weight bearing gel, it was not made explicit by Usher et al. (2009) how closely the solids flux in these fixed bed height cases approached the maximum possible solids flux (which is only realised for an arbitrarily tall bed). Thus, the possibility of accessing an underflow solids flux which is demonstrably much larger than the maximum permitted underflow solids flux in an undensified thickener has not been explicitly investigated in such cases. Moreover, the possibility of dramatic reductions in the solids residence time and the bed height required to achieve a given underflow solids volume fraction in a densified thickener have not been explored.

Whenever studying a densified thickener, an important parameter is the ratio of the solids residence time to the characteristic time scale for densifying aggregates. Residence time is evidently an important parameter used for the prediction of the performance of a densified thickener, since the evolution of the aggregate diameter depends on the residence time (van Deventer et al., 2011): aggregates can potentially densify to attain a final steady state diameter, but the final steady state aggregate diameter is

[1] More generally the theory can be used to design and predict the performance of other types of dewatering equipment including e.g. batch settlers and pressure filters (Buscall and White, 1987; Howells et al., 1990; Landman and Russel, 1993; Landman and White, 1994; Davis and Russel, 1989; Green et al., 1998; Landman et al., 1999; de Kretser et al., 2001). The overarching theory is the same, although the boundary conditions required depend on the particular type of equipment under consideration.

[2] This is a different physical picture from one where weak aggregates might be formed due to electrostatic and van der Waals forces between particles (Kralchevsky et al., 2008), in the absence of any bridging polymer. The microstructure of an aggregate which involves polymer bridging is arguably more complex than that of one where e.g. spherical particles are subject to electrostatic, van der Waals and possibly also Brownian forces (Brady and Bossis, 1988; Davis and Russel, 1989) (in addition to hydrodynamic forces and gravity which would be present in either case).

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