Chemical Engineering Science 111 (2014) 56–72

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Effects of aggregate densification upon thickening of Kynchian suspensions

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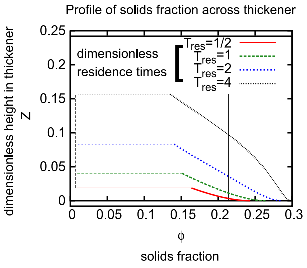
HIGHLIGHTS

- Thickening of ungelled 'Kynchian' suspensions is considered.
- Suspensions are raked causing flocs within them to densify.
- Floc densification is predicted to enhance thickening performance.
- Solids fraction profiles along a thickener can be computed even for Kynchian systems.
- A fully densified state is approached as underflow solids fraction grows.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 25 November 2013
Received in revised form
14 February 2014
Accepted 17 February 2014
Available online 22 February 2014

Keywords:
Suspension
Rheology
Separations
Mathematical modelling
Thickening
Densification

ABSTRACT

A model is presented for the thickening of a raked suspension. The model is based on Kynch theory (Kynch, 1952), i.e. it describes systems with solids fractions sufficiently low that the solids have not gelled into a weight-bearing network. However the model incorporates a modification to describe how raking the suspension causes flocs or aggregates within it to densify. This floc densification opens up channels between the flocs through which liquid escapes, making the suspension easier to dewater. The densification theory presented here predicts profiles of varying solids fraction vs height in the settling zone in a thickener, information which is not normally available when designing thickeners via the conventional Kynch theory. Performance enhancements for thickeners due to raking can be readily determined, either in terms of increased underflow solids fraction or increased solids flux. As underflow solids fraction is increased, thickeners operated at a specified aggregate densification rate (or equivalently at a fixed settling zone height) tend to approach a 'fully densified' suspension state (defined as a point at which the extent of aggregate densification ceases to change with time), with improved thickening performance.

1. Introduction

Dewatering of solid–liquid suspensions is a common engineering operation, with a multitude of applications, in areas including water recycling, waste management and minerals processing (Boger, 2009; Jones and Boger, 2012). There are many different types of engineering equipment available to achieve suspension dewatering, including batch settlers (Concha and Bustos, 1991), filter presses (Landman et al., 1991; Landman and White, 1994; Martin, 2004a), centrifuges (Berres et al., 2005a,b; Stickland et al., 2006), as well as continuous thickeners (Landman et al., 1988; Concha and Bustos, 1992; Bürger and Concha, 1998; Bürger et al., 1999; Martin, 2004b; Usher and Scales, 2005; Doucet and Paradis, 2010).

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http://dx.doi.org/10.1016/j.ces.2014.02.013
0009-2509

Chemical engineers are often faced with the task of designing and operating these types of equipment. However dewatering performance depends not only upon the equipment specifications, but also upon the material properties of the suspension being dewatered (Landman and White, 1994). Accordingly there has been considerable effort in developing dewatering design methodologies that take explicit account of theories of suspension rheology, amongst the best known of them being that of Kynch (1952) and that of Buscall and White (1987).

These design methodologies tend to rely on phenomenological measurements of suspension rheology properties, for which measurement protocols already exist (Berres et al., 2005a,b; Landman and White, 1992; Green et al., 1998; de Kretser et al., 2001; Stickland et al., 2008). However the suspension rheology that is measured is strongly influenced by the suspension physical chemistry. Indeed in engineering practice, suspension dewatering rates are enhanced by addition of chemical flocculants (Usher et al., 2009). These chemical additives usually contain polymers which form bridges (Usher et al., 2009) from one individual solid particle to the next: the particle–polymer binding interactions tend to be sufficiently strong that the bonds can be considered to be irreversible (on time scales of interest). The solid particles joined by polymer bridges then form into a loose aggregate called a *floc*.

These aggregates or flocs tend to settle faster under the action of gravity than the individual solid particles. This is because when more and more individual particles are present in the floc, the downwards net buoyancy force grows more rapidly than its so-called 'friction factor' (defined as the ratio between the frictional drag force on the floc and its speed relative to the surrounding liquid). Indeed, whereas the buoyancy force is directly proportional to the number of individual solid particles in the floc (and hence to the overall floc volume), the friction factor tends to scale as the radius of the floc as a whole (Batchelor, 1967). This latter scaling follows because the surface area of the floc (over which frictional forces act) grows proportionally to the square of the floc radius, whilst the rate of strain (due to the floc moving with a given velocity relative to the surrounding liquid) scales inversely with the radius. It follows that if an aggregate or floc containing a given number of solid particles can be made more compact (such that its overall radius decreases) settling rates can be enhanced yet further.

One mechanism for achieving this is by raking the suspension, which can speed up dewatering rates in some cases by orders of magnitude (Usher et al., 2009; van Deventer et al., 2011; Gladman et al., 2005, 2010; Gladman, 2006). Raking in this fashion introduces shear forces that cause individual particles within an aggregate to displace relative to one another. Except in extreme cases where the imposed shear rates are so high as to tear aggregates apart altogether, these relative displacements produce additional contacts between particles and polymer bridges within the floc, binding the aggregate together rather more tightly (Usher et al., 2009; van Deventer et al., 2011; Mills et al., 1991). Here this process is called *aggregate densification*.

Aggregate densification is expected to affect the suspension material properties and thereby the dewatering performance. Indeed theories describing the effects of aggregate densification upon suspension material properties are already available in the literature (Usher et al., 2009; van Deventer et al., 2011; Zhang et al., 2013a,b). These theories determine material properties not only in terms of the solids fraction within the aggregates themselves, but also in terms of the overall solids fraction of the suspension (which takes account of zones of clear liquid, if any, between the flocs).

One key feature of the theories (Usher et al., 2009; Zhang et al., 2013a,b) is that significant benefits from aggregate densification are expected when overall solids fractions are 'low to moderate', which should be interpreted to mean that solids fraction should be low enough that flocs either remain isolated from one another (interacting with other flocs only hydrodynamically) or else are packed together only very loosely into an exceedingly fragile network. Under these circumstances, aggregate densification then opens up wide channels between flocs, through which liquid can escape. On the other hand, if the solids fraction in the suspension as a whole is comparatively high (e.g. comparable with the solids fraction in an individual floc), it follows that flocs are necessarily tightly packed together and must interpenetrate one another. There are no obvious preferred channels between the flocs for liquid escape, and so attempts to densify flocs may result in less dewatering benefit (Usher et al., 2009).

The aggregate densification theory has been used to model dewatering processes in batch settling (van Deventer et al., 2011) and also in the closely related operation of continuous thickening (Usher et al., 2009; Zhang et al., 2013a,b). Here the focus is specifically on the case of buoyancy-driven thickening, where suspension is fed into and flows through the device, with concentrated suspension being drawn off as underflow at the bottom and with clear liquid being drawn off the top. Such a device combines the conventional chemical engineering benefits of a continuous operation with the mathematical modelling simplicity for a device that (unlike a batch settler) can be made to operate at or near steady state. Indeed steady state operation of thickeners will be the focus in all that follows. Here 'steady state' refers to steady operation in the Eulerian sense. The thickener is of course unsteady in the Lagrangian sense: if one follows the settling solids, their state must be changing as dewatering occurs.

It is noteworthy that the previously mentioned work on modelling thickening with aggregate densification (Usher et al., 2009; Zhang et al., 2013a,b) tended to focus on 'moderate to high' overall solids fractions. Specifically it focussed on cases where flocs were packed together into a network, possibly still with some gaps between flocs (moderate solids fraction) or else with flocs densely packed and interpenetrating (high solids fraction). With the exception of some of the cases considered by Usher et al. (2009), this previous work has not however considered thickening where the level of dewatering demanded is comparatively modest, in other words where a majority of the flocs within the thickener are fairly isolated from one another and so do not experience significant contact interactions with nearby flocs through e.g. being packed together into a network.

It might seem strange a priori that the previous modelling work on densified thickening considered primarily the high overall solids fraction regime (where the benefits of aggregate densification are in certain cases quite limited) and yet has seldom considered the regime of much lower target solids fractions (where the benefits of aggregate densification can be realised). The reason for this concerns the physical differences between low solids fraction suspensions and their moderate-to-high solids fraction counterparts, and how those physical differences consequently impact the resulting mathematical models.

Consider first of all, for simplicity, the nature of the theories in the absence of any aggregate densification. The particular overall solids fraction at which the flocs cease to be isolated, and instead form together into a network, is called the gel point (Landman and White, 1994). Suspensions at overall solids fractions below the gel point are typically modelled using Kynch theory (Kynch, 1952), which balances the buoyancy and viscous drag forces on a floc.

The key material property of the suspension that governs its dewatering behaviour is either a solids settling speed or a solids settling flux (functions of overall solids fraction Kynch, 1952), or a closely related property called the hindered settling factor (a measure of how the friction force grows with solids fraction due