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# Designing thickeners by matching hindered settling and gelled suspension zones in the presence of aggregate densification

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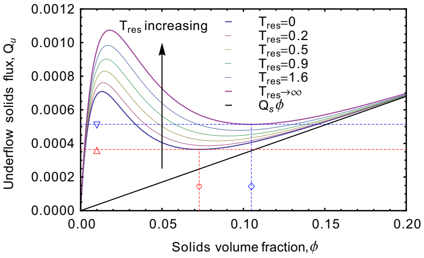
## HIGHLIGHTS

- A continuous thickener for solid–liquid separation is modelled.
- Flocs within the thickener undergo aggregate densification facilitating dewatering.
- Model couples hindered settling zone and gelled suspension zone within thickener.
- Depending on operating regime, thickener height can be dominated by either zone.
- Gelled zone dominates as suspension flux through thickener is reduced.

## GRAPHICAL ABSTRACT



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## ABSTRACT

A model is presented for design of a thickener for solid–liquid separation where the flocs or aggregates within the solid–liquid suspension undergo an aggregate densification process due to the action of rakes. This aggregate densification facilitates suspension dewatering. The novel feature of the model is that it manages to couple together a hindered settling zone (higher up in the thickener, where the flocs are separated from one another, and the suspension cannot bear weight) and a gelled suspension zone (lower down in the thickener, where the flocs are packed together, and the suspension is able to bear weight). The model determines solids fraction profiles throughout the hindered settling zone and the gelled suspension zone, and also gives zone heights and residence times. Parametric investigations using the model are carried out for different suspension fluxes (which influence the solids fluxes and underflow solids fractions attained), and also for different specified amounts of and rates of aggregate densification.

## 1. Introduction

The need to dewater solid–liquid suspensions to reduce volumes of solid–liquid waste and extract clean water is common in many industries (e.g. minerals processing (Boger, 2009; Jones and Boger, 2012), wastewater (Martin, 2004), dairy processing (Matsche et al., 2002), pulp and paper (Pere et al., 1993)). Continuous thickeners are among the devices used for achieving such dewatering (Bustos et al., 1999).

Theories exist in the literature for design of thickeners to achieve a given target solids flux and/or a given target underflow

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solids fraction (Usher and Scales, 2005; Diehl, 2001, 2008, 2012). Traditionally (Talmage and Fitch, 1955; Fitch, 1966) these have been based around the Kynch theory (Kynch, 1952). This theory recognises (i) that solids settle due to buoyancy through being heavier than surrounding liquid, (ii) that buoyancy is balanced by viscous drag, and moreover (iii) that settling becomes hindered as the solids fraction in the suspension increases. While the Kynch theory approach does indeed predict solids fluxes (and hence thickener cross sectional areas for a given volumetric flow rate of incoming suspension (Talmage and Fitch, 1955)), it does not predict the thickener heights.

Moreover one shortcoming of the Kynch theory is that it tends to lose applicability as the solids fraction rises. Usually in dewatering applications one deliberately adds flocculants to the suspension, and these cause solid particles to aggregate together into flocs, with these flocs then settling faster than individual solid particles would (Heath et al., 2006). As the overall solids fraction becomes high enough however, the flocs can themselves network together into a weight bearing gel. Network stresses that oppose settling then develop in the gel (Buscall and White, 1987), meaning that buoyancy and viscous drag are no longer in balance.

Thickener design can then be achieved via the Buscall and White theory (Buscall and White, 1987; Landman et al., 1988; Bürger and Concha, 1998). This theory (unlike the Kynch theory) is able to predict thickener heights (Usher and Scales, 2005), or more specifically it is able to predict the height of a consolidated bed of gelled suspension thereby setting a lower bound for the possible thickener height. The stronger the weight bearing strength of the gelled suspension, the taller the thickener must be.

Yet another complication one encounters during thickening is that the aggregates or flocs can change their structure in real time during the thickening process. This can happen as a result of the flocs being subjected to shear within a thickener, e.g. due to the action of rakes (Spehar et al., 2014; Gladman et al., 2010). Shear leads to the so-called aggregate densification, i.e. individual aggregates bind together more tightly (Farrow et al., 2000; Usher et al., 2009; van Deventer et al., 2011), which is highly beneficial for the dewatering process. Not only are wider channels opened up between flocs facilitating dewatering, but individual flocs also tend to lose contact with their neighbours, decreasing the suspension's weight bearing strength hence promoting consolidation (Usher et al., 2009; van Deventer et al., 2011).

Aggregate densification thereby allows a given thickener to achieve higher solids fluxes and/or higher underflow solids fractions than before, or alternatively allows redesign of a less tall thickener. Given the importance of aggregate densification, a number of studies have been dedicated to determining how to incorporate it into thickener design procedures (Usher et al., 2009; van Deventer et al., 2011; Zhang et al. 2013a,b). By and large these studies focussed on incorporating aggregate densification into the Buscall and White framework. Apart from the fact that aggregate densification is predicted to enhance thickener performance significantly, the approach is conceptually not very different from a conventional Buscall and White theory.

Recently however a study has appeared (Grassia et al., 2014) suggesting how to incorporate aggregate densification into the framework of Kynch theory. This study would apply to situations where the degree of thickening required (measured by a target underflow solids fraction) is relatively modest so that either the underflow does not form a gel (Spehar et al., 2014) or else it is just barely gelled, with very significant amounts of ungelled material elsewhere in the thickener. Alternatively the study of Grassia et al. (2014) could be considered to correspond to a case where a particularly high solids flux is required (since there is known to be a trade-off between solids flux achieved and solids fraction attained during thickening (Usher and Scales, 2005)). In contrast to a conventional Kynch theory (which as mentioned earlier does not predict thickener heights) this recent study (Grassia et al., 2014) combining aggregate densification with the Kynch theory actually managed to make predictions for thickener heights. Specifically it predicted the height of a hindered settling zone, a region throughout which the suspension is not gelled. There still might be a consolidated bed of gelled suspension very close to the underflow, but Grassia et al. (2014) assumed this to be of negligible thickness compared to the hindered zone.

Even though the effects of aggregate densification have been considered upon 'ungelled' hindered settling zone heights (via the Kynch theory (Grassia et al., 2014)) and upon gelled suspension bed heights (via the Buscall and White theory (Usher et al., 2009; Zhang et al. 2013a,b)), to date there has never been a study which combines the two theories together so as to design a thickener subject to aggregate densification incorporating both a hindered settling zone and a consolidated bed each of which makes a significant contribution to the overall height. Indeed it is not even clear that, in the presence of aggregate densification, it is always feasible to combine the two theories together. Establishing under what conditions the theories can be combined and performing design calculations using the combined theories are the topics of the present work.

This study is laid out as follows. Section 2 details the separate theories of thickener design incorporating aggregate densification (Kynch vs Buscall and White), after which Section 3 explains how to match those theories together: matching involves comparing the solids fraction that the Kynch theory determines in the hindered settling zone to the solids fraction at which the suspension starts to form into a weight bearing gel (the top of the gelled suspension zone according to the Buscall and White theory). A number of case studies are set up in Section 4, and results from the case studies are presented in Section 5. Finally conclusions are offered in Section 6.

## 2. Theory

This section is laid out in three parts. The first part (Section 2.1) describes thickener design using the Kynch theory, and in particular how aggregate densification modifies the theory: the reader is referred to Grassia et al. (2014) for details. The second part (Section 2.2) is analogous but focusses on the Buscall and White theory with aggregate densification: the reader can refer to Usher et al. (2009); van Deventer et al. (2011), and Zhang et al. (2013a,b) for full details. The third part (Section 2.3) explains how to cast the system in dimensionless form, indicating which dimensionless scalings are most useful for which zone of the thickener.

### *2.1. Kynch theory in the presence of aggregate densification*

The key element of Kynch theory (Kynch, 1952) (that applies to ungelled suspensions) is a material property of the suspension called the hindered settling function (Usher and Scales, 2005; Lester et al., 2005). This governs how the effective frictional force on settling solids increases as a function of solids fraction. This hindered settling function is denoted by $R(\phi)$ where $\phi$ is the solids volume fraction. Usually $R(\phi)$ is a sharply increasing function of $\phi$ (Grassia et al., 2008).

According to the Kynch theory, the batch settling or 'free settling' flux of solids (denoted $q_{fs}$) is related[1] to $R(\phi)$ via (Lester

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[1] The $(1-\phi)^2$ term in the numerator of Eq. (1) arises from the solids batch settling speed being less than the solid-to-liquid velocity difference, and the pressure field in the liquid providing more upthrust than a purely hydrostatic field would.