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Turbulent mixing of concentrated viscoelastic polymer solution: Influence of submerged sparge shape and orientation

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ABSTRACT

Aqueous solutions (~0.01–0.2%) of long chain polymers are used during gravity thickening to aggregate particle suspensions. These polymers are often dosed into turbulent flow through submerged pipes (sparges) to maximise their distribution. At high concentrations, these viscoelastic solutions mix poorly with surrounding flows unless highly diluted. If varying the bluff body sparge shape can enhance mixing, such dilution may be avoided.

Turbulent mixing of concentrated (0.2%) polymer solutions sparged into turbulent flows within a transparent channel was captured using high-speed imaging to understand the complex mixing phenomena. Square and round sparges were investigated at 0 or 180° to the channel flow. At 0°, vortex shedding from square sparge edges enhanced mixing, but the 180° orientation produced better overall mixing. Image analysis gave the first quantification of flow past bluff bodies issuing viscoelastic fluid jets at industrial flow regimes, from which more appropriate turbulence model closures for fluid dynamics modelling of the process may be derived.

1. Introduction

Gravity thickeners are large sedimentation vessels (usually in the range 10–130 m in diameter) used to achieve continuous solid-liquid separation of dilute fine particle slurries (Bedell et al., 2015). They find use in a wide range of industries, most notably in almost all mineral processing applications. In such applications the feed slurry will be delivered to an open cylinder (the feedwell, up to 15 m diameter) that is surrounded concentrically by the much larger, deeper tank which forms the main body of the thickener. High molecular weight polymers (flocculants) in aqueous solution are added to the feed slurry, either in or prior to the feedwell to induce the aggregation of fine particles under turbulent mixing conditions. The aggregates are discharged from the feedwell to settle under gravity, forming a concentrated suspension of solids (underflow) at the bottom of the tank. Clarified liquor rises and is collected from the outer edge of the thickener (overflow).

The high molecular weight flocculants used in mineral applications are typically copolymers of acrylamide and sodium acrylate, with the proportion of the anionic functionalities varied in response to pH, ionic strength and the mineral substrate. These polymers will be carefully dissolved in the best available water stream to make-up a "concentrated" stock flocculant solution in the range 0.2–1.0 wt/wt%. The "ageing" of the stock solutions for at least a few hours will maximise the dispersion of the long chain polymers and hence their activity (Owen et al., 2002, 2007); with further dilution immediately prior to dosing into the feed (to as low as 0.005 wt/wt%, but more commonly in the range 0.02–0.1 wt/wt%).

The open literature abounds with papers that examine the flocculation process as applied to mineral phases, from basic performance testing (e.g. settling tests) of new flocculant products through to advanced mathematical modelling of aggregate growth and breakage processes. They are far too numerous to discuss here, but many extensive reviews already exist (Hocking et al., 1999; Hogg, 2013; Fawell et al., 2015). Given the volume of effort in this area, it is surprising that little attention is paid to the impact of flocculant solution concentration on flocculation. This is despite widespread (although not universal) long-term practical understanding within the industry that secondary dilution is almost always beneficial, through improved performance and a reduction in required dosages.

The dosed flocculant solution will always represent a minor volume in relation to the feed slurry. Efficient distribution through the slurry particles is therefore critical, as adsorption for most feeds at practical

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dosages is rapid. Dilution of the applied flocculant solution aids such distribution by increasing the dosed volume (or in the case of a continuously operated thickener, its volumetric flow rate) for a constant dosage, expressed as a mass of polymer per unit mass of the feed substrate (grams/tonne).

The other benefit of high dilution is a reduction in the viscosity of the dosed polymer solution (Rattanakawin and Hogg, 2007), such that it will then mix readily with the feed. The majority of studies make the assumption that such simple mixing is being achieved. In reality, viscous and elastic non-linear behaviour of the long-chain polymers in solution is significant, inhibiting mixing and thereby altering the hydrodynamic requirements for optimal flocculation. Not only does this impact upon flocculation kinetics (Fawell et al., 2009), but this can also potentially affect full-scale thickener underflow density (through the requirement for higher flocculant dosages) and overflow solids losses (with poor flocculant distribution detrimental to efficient fines capture).

Issues with flocculant concentration impact even on basic small-scale performance testing. Mpofu and co-workers (Mpofu et al., 2003, 2004) applied flocculants at 0.1 wt/wt% to clay slurries with fairly mild applied mixing, and the resultant poor distribution of flocculant is likely to have contributed to the high dosages observed. The mixing may have been appropriate at a lower flocculant concentration, possibly reducing the dosage required. There are also numerous examples within the literature where the performance of different flocculant products are compared at a single fixed dosage (Caskey and Primus, 1986; McFarlane et al., 2008), a common approach in many site-based product evaluations. Such comparisons suffer from many issues, not the least being that solutions of products with different molecular weights and functionalities will have different viscosities, which will impact on aggregation performance (as discussed above) unless done at high dilution of reagent solutions.

1.1. Mixing in co-axial jets

The turbulent mixing of confined co-axial jets is a complex fluid dynamics process within a simple geometry which finds applications in devices such as ejectors, industrial burners, jet engine combustion chambers and after-burners. The flow field arising from the interaction of co-axial jets and their mixing behaviour have shown to comprise of three main zones: (i) initial merging zone where the two annular streams enter the mixing duct with their respective axial velocities, (ii) intermediate merging zone where the largest momentum exchange between the jets occurs, (iii) fully merged zone where flow conditions become progressively similar to a single jet (Ahmed and Sharma, 2000). The factors that influence the mixing process of such jets include velocity ratio, temperature ratio, density ratio, compressibility and turbulence levels of the two streams, swirl, pressure gradient, interaction between wall bounded and free shear flows, mixing duct to inner jet nozzle diameter ratio, and the thickness of the inner duct wall (Buresti et al., 1994).

It has been shown that the mixing lengths in pipe flow of dilute polymer solutions can be several times larger than those for Newtonian flows (Ranade and Mashelkar, 1993). These mixing lengths not only affect the flow at the mean velocity level but are known to affect the turbulence level in mixing (Liberzon et al., 2006; Ouellette et al., 2009). Previous attempts by the current authors to quantify the mixing of flocculants were carried out inside a co-axial pipe (pipe I.D.'s of 19 and 4.35 mm) configuration (Mohanarangam et al., 2010). The mixing behaviour of three different flocculant concentrations (0.0075%, 0.05% and 0.2%) injected through the inner pipe were compared against water (0%), using an Ultrasonic Velocity Profile (UVP) unit (UVP-DUO, Metflow SA, Lausanne, Switzerland) to measure the velocities from outside the pipe. Two different velocity ratios between the flocculant and the outer water velocity were also studied, with Particle Image Velocity (PIV) measurements carried out to validate the UVP measurements. This work showed that as the flocculant concentration increased, there was an increasing resistance for it to mix with the bulk water flow. While this study was able to quantify the mixing nature of flocculants under turbulent conditions at close to a pilot-scale, the physical configuration for introducing the flocculant stream (i.e. narrow flocculant pipe positioned coaxially within the larger pipe for the fluid flow) was not representative of how this process is achieved in industrial applications. Flocculant would be far more likely to be dosed through a submerged pipe or "sparge" that represents a bluff body being inserted into the bulk flow. Previous studies have shown that the shape of such bluff bodies can influence jet mixing (Ahmed and Sharma, 2000; Buresti et al., 1994), but have not considered the situation when the jet is a viscoelastic fluid.

1.2. Objectives

In this paper, viscoelastic mixing of a confined co-axial jet is studied using an experimental rig specially designed to be relevant to dosing of a minor (by volume) fluid phase through a submerged solid sparge into turbulent flow of a bulk stream. The viscoelastic fluid in this case is a solution of a polymer flocculant at high concentration (0.2%) relative to concentrations dosed normally within industrial thickener feedwells. This concentrated flocculant is made to mix into the surrounding water stream with the aid of two different submerged sparge shapes (square and round). These two shapes represent simplicity of design and installation that make them quite common in industrial settings. By dosing the flocculant through these sparges, the contribution of their physical shape to aid mixing of the viscoelastic fluid is investigated. Qualitative and quantitative comparisons were made using high-speed imaging and data analysis of the acquired images.

2. Design of experimental rig: Computational study

A dedicated experimental set-up was designed and built, seeking to provide relevant insights into the flocculant mixing processes that occur downstream of a submerged sparge within a full-size thickener. A preliminary computational fluid dynamics (CFD) study was carried out to finalise the scale and dimensions of the rig, which necessitated the following constraints being satisfied:

- The surrounding water flow turbulent length scales based on the sparge diameter must be of adequate Reynolds number to aid mixing of the flocculant.
- The velocity of the injected flocculant relative to the velocity past the sparge must be comparable to the full-scale conditions (Mohanarangam and Stephens, 2009).

The design considered is a simple channel flow (square cross-section), with the sparge inserted at an angle perpendicular to the flow. The analysis presented here focuses on downstream injection (i.e. surrounding and jet flows are both in the same direction), but different flocculant injection directions will be eventually considered. Additional constraints arise from the practical limitations of operating in laboratory conditions:

- The dimension of the sparge must be sufficiently large to allow for proper visualisation.
- The overall channel flow rate is restricted by the available pumping and disposal capacity, the latter important as water mixed with polymer flocculant cannot be re-used.
- The side walls must be sufficiently far away from the sparge, such that they do not significantly alter the flow field.
- The sparge size and flow velocity must be such that no cavitation occurs (which is not a problem for the full-scale sparge, but can be a concern for a scaled-down model).