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Review

Activated sludge rheology: A critical review on data collection and modelling

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ABSTRACT

Rheological behaviour is an important fluid property that severely impacts its flow behaviour and many aspects related to this. In the case of activated sludge, the apparent viscosity has an influence on e.g. pumping, hydrodynamics, mass transfer rates, sludge–water separation (settling and filtration). It therefore is an important property related to process performance, including process economics. To account for this, rheological behaviour is being included in process design, necessitating its measurement. However, measurements and corresponding protocols in literature are quite diverse, leading to varying results and conclusions. In this paper, a vast amount of papers are critically reviewed with respect to this and important flaws are highlighted with respect to rheometer choice, rheometer settings and measurement protocol. The obtained rheograms from experimental efforts have frequently been used to build viscosity models. However, this is not that straightforward and a lot of errors can be detected with respect to good modelling practice, including fair model selection criteria, qualitative parameter estimations and proper model validation. These important steps are however recurrently violated, severely affecting the model reliability and predictive power. This is illustrated with several examples. In conclusion, dedicated research is required to improve the rheological measurements and the models derived from them. At this moment, there is no guidance with respect to proper rheological measurements. Moreover, the rheological models are not very trustworthy and remain very "black box". More insight in the physical background needs to be gained. A model-based approach with dedicated experimental data collection is the key to address this.

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Contents

1. Introduction and incentives to measure and model rheology for activated sludge applications

Rheological measurements are state-of-the-art in a multitude of engineering disciplines. For homogenous, non-dispersive fluids, viscosity represents a fluid property which can be measured and transferred into plant design. Indeed, designs of equipment (pumps, mixers, aeration systems, etc.) applied in conjunction with these liquids are mostly based on their thermo-physical properties. These fluids can either behave as Newtonian liquids, i.e. constant proportionality between shear rate and shear stress, or non-Newtonian if this is not the case. However, in wastewater treatment, the rheological behaviour of activated sludge (AS) is much more complex as it is composed of water and dissolved wastewater constituents as the continuous phase and sludge flocs, particulate wastewater constituents and biological products (i.e. exocellular polymeric substances (EPS)) as the dispersed phase. Despite this complexity, the rheological behaviour of AS is an important property, which is backed up by numerous studies performed on the topic (see further). Indeed, viscosity interferes with (1) sludge pumping (i.e. recycle flows), (2) bioreactor hydrodynamics (i.e. mixing), (3) oxygen transfer, (4) secondary settler hydrodynamics, (5) membrane filtration and (6) sludge dewatering. Sludge rheology is thus crucial for AS management in wastewater treatment plants, especially in transportation for the calculation of pressure losses in pipes and pump selection (Tchobanoglous et al. 2003), and for the design of aeration systems (Cornel et al. 2003; Seyssiecq et al. 2003). Regarding sludge sedimentation, hydrodynamics in secondary settlers, especially in the sludge blanket where high solids concentrations prevail, are crucial for their performance (De Clercq, 2003; Schumacher, 2006; Brannock et al. 2010a). Sludge rheology hence interferes heavily with treatment performance and operational costs as well as with the system design (i.e. dimensioning of pumps and blowers). Besides the sludge management inside the wastewater treatment chain, rheology is also important for further sludge handling like dewatering or biogas production from sewage sludge. To increase biogas production, it is necessary to recycle and recirculate digested sludge in order to mix it with incoming sludge. The flow rate in the recirculation circuits has to be very large and rheology is needed to calculate head losses and pumping power (Slatter, 2001).

Pressure drop of pipe flow for a Newtonian liquid like water is straightforwardly obtained from the pipe diameter and the flow velocity as well as the friction factor depending on the flow regime (laminar or turbulent). Under laminar flow conditions, the friction factor of the Newtonian liquid is inversely proportional to the Reynolds number (Re), and the pressure drop is proportional to the product of the velocity and viscosity. As the Reynolds number increases beyond a critical value (Re $\approx$ 2100), the flow becomes turbulent and results in smaller friction factors (Bird et al. 2001). In contrast, non-Newtonian liquids usually reach turbulent conditions at much higher fluid velocities due to their elasticity. Proff and Lohmann (1997) proposed pipe friction factors and pressure losses of AS that were characterized by sludge thinning properties (power law approach). Tchobanoglous et al. (2003) illustrated the use of Hedstrom number (He) and the Reynolds number to determine the impact on the friction factor and how it affect the pressure drop for AS with Bingham properties (Fig. 1). This presents a critical problem as settleable solids accumulate at the bottom of horizontal pipe sections and eventually lead to pipe blockage (Slatter, 2004). Settling also might pose a problem within the biological reactors, where sufficient mixing is crucial in order to achieve good biological treatment rates. Settling and dead zones due to elevated effective viscosities will lead to a loss of bioreactor performance. Hence, the choice of mixing equipment and propellers during design is important, affecting energy requirements. Optimizing design and operation thus require good knowledge with respect to AS rheology.

Within secondary settlers, on the other hand, where sedimentation is required, hindered and compressive settling will lead to large concentration gradients in the sludge blanket, which might lead to very different rheological behaviour at different locations in the blanket. A good understanding of sludge rheology of high concentration sludge at low shear rates is crucial in this case. This occurs at the bottom of the sludge blanket where the sludge needs to move towards the sludge hopper governed by the bottom slope and/or the scraper. Hence, the design of the sludge removal structures is very dependent on the rheological behaviour of the sludge.