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Controlling aerobic biological floc size using Couette-Taylor Bioreactors

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ABSTRACT

Biological floc size is an important reactor microenvironment parameter that is often not experimentally controlled due to a lack of suitable methods. Here, we introduce the Couette-Taylor bioreactor (CTB) as an improved tool for controlling biological floc size, specifically as compared with bubble-column sequencing batch reactors (SBRs). A CTB consists of two concentric walls, either of which may be rotated to induce fluid motion. The induced flow produces hydrodynamic shear which is more uniform than that produced through aeration in SBRs. Because hydrodynamic shear is a major parameter controlling floc size, we hypothesized the ability to better control shear rates within a CTB would enable better-controlled floc sizes. To test this hypothesis, we measured the particle size distributions of activated sludge flocs from CTBs with either inner (iCTB) or outer (oCTB) rotating walls as well as SBRs with varying height to diameter ratios (0.5, 1.1, and 9.4). The rotation speed of the CTBs and aeration rate of the SBRs were varied to produce predicted mean shear rates from 25 to 250 s^{-1}. Further, the shear rate distributions for each experiment were estimated using computational fluid dynamics (CFD). In all SBR experiments, the floc distributions did not significantly vary with shear rate or geometry, likely because shear rates (estimated by CFD) differed much less than originally predicted by theory. In the CTB experiments, the mean particle size decreased proportionally with increased hydrodynamic shear, and iCTBs produced particle size distributions with smaller coefficients of variation than oCTBs (0.3 vs. 0.5–0.7, respectively).

1. Introduction

Activated sludge wastewater treatment systems convert organics and remove nutrients through microbial floc environments. The roles of these floc environments, including the ability to separate from the water effectively, are affected by floc size, a key parameter of the reactor microenvironment (Daigger and Littleton, 2014). Despite its importance, floc size is often left uncontrolled in experiments. When such control is desired, it is often attempted by controlling hydrodynamic shear, which is known to influence floc size (Bobade et al., 2018).

However, precise control of the spatial distribution of hydrodynamic shear is difficult. The most common shear rate control methods (mechanical mixing and aeration flow control) are imprecise and introduce confounding factors. For example, the relationship between a mixing blade and mean shear rate is well established, but large instantaneous shear rates near the blade edge affect floc size (Ducoste and Clark, 1998; Hopkins and Ducoste, 2003). Large instantaneous shear rates can be avoided by altering the superficial gas velocity of the reactor. However, the average shear rate estimated from aeration rates can vary by an order of magnitude depending on which equation relating the two factors is chosen, and may not be appropriate for the actual reactor system used (Chisti and Moo-Young, 1989).

It is therefore desirable to develop other means of controlling the experimental shear rate, particularly if such a method results in predictable, relatively uniform floc sizes. One potential method is to use a Couette-Taylor bioreactor (CTB), which consists of two cylindrical walls enclosing the reactor contents in an annular gap (Taylor, 1936a, 1936b) (Fig. 1 and S12). Rotating either the internal, external, or both walls induces a circular flow within the reactor and directly influences the mean fluid shear rate ($\overline{G}$).

Eq. (1) is frequently used to estimate the average characteristic velocity gradient or $\overline{G}$ for a CTB operated at a target rotational speed (Ω, RPM) and with outer and inner wall radii (R_1 and R_2, respectively) (Taylor, 1936a, 1936b).

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$$\overline{G} = \frac{2\pi}{60}\left(\frac{2R_1R_2}{R_1^2 - R_2^2}\right)\Omega \tag{1}$$

Eq. (1) is most accurate below a threshold rotation speed, determined by which wall is rotating and the scale of the reactor (Eqs. S1-S3)(Andereck et al., 1986), during which flow is laminar and the shear rate is essentially uniform throughout the working fluid. When operated above that threshold, the flow transitions to the Taylor-Couette regime and is characterized by stable, stacked, rotating toroids known as Taylor vortices (Kataoka, 1986). Despite this, shear rates are often estimated using Eq. (1) which does not account for these potential Taylor vortices.

To achieve shear rates of 44 s^{-1}, which are similar to those of wastewater treatment plants (Grady et al., 1999), a bench scale CTB (*i.e.* with a volume on the order of 2–12 L) generally needs to be operated at speeds above the critical threshold, with the critical speeds for our specific reactors listed in Table 3. Further, Eq. (1) provides only a mean shear rate and does not give any information regarding the shear distribution throughout the reactor volume. For example, flow within an oCTB (where the outer wall is rotated) tends to be much more uniform than within an equivalently operated iCTB (where the inner wall is rotated) (Taylor, 1936b). While a CTB should produce more consistent shear, several questions still remain that have not been addressed in the literature. These include the following:

1. Can biological floc aggregation be predicted in real-world CTBs based on theoretical shear distributions?
2. What impact do shear rates produced by the iCTB with Taylor vortices have on the resulting biological flocs compared to an equivalently operated oCTBs?

To answer these questions, we measured the particle size distributions of flocs in CTBs loaded with disaggregated biosolids and operated by rotating either the outer or the inner wall at different speeds. We then estimated the shear rate distributions within the reactors using computational fluid dynamics (CFD). Both the particle size and shear rate distributions were compared to those produced by SBRs with varying height to diameter ratios operated over the same range of predicted average shear rates. Finally, we explored the relationship between the particle size and shear rate distributions, including a comparison with previous efforts (Evans and Liu, 2003) to relate mean floc size with mean shear rate.

We hypothesized that the particle size distributions of biological flocs in a CTB are closely correlated with rotational speed. Previous research has explored a similar hypothesis related to non-biological floc effects in an iCTB (Coufort et al., 2005). However, factors such as a collision efficiency, initial particle size distributions, and aggregate strength all affect reaggregation (Clark, 2009). Those factors are likely different for particles used in non-biological research, such as alum precipitates in water, compared to activated sludge flocs. It is important to determine if the hydrodynamic shear conditions within CTBs do, in fact, provide better control of the size of biological flocs before adopting these bioreactors as improved systems for biological research.

2. Materials and methods

2.1. Experimental plan

To determine the relationship between shear and particle distributions in CTBs, an oCTB and iCTB were loaded with sonicated sludge and operated at mean shear rates controlled by varying the rotational speed as shown in Table 1.

Table 1
Experimental Parameters: Rotating wall speed and associated mean shear rates for Couette-Taylor Bioreactors (CTB) with outer and inner rotating walls (oCTB and iCTB).

Reactor	Rotation (RPM)			Mean shear rate (s^{-1})[a]		
	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3
oCTB	50	100	200	25	50	100
iCTB	45	120	240	45	118	237

[a] Predicted from Eq. (1).

Additionally, three SBRs of equal volume (2.6 L) and varying height to diameter ratios (H/D = 0.5, 1.1, and 9.4) were each operated with aeration rates estimated to produce mean shear rates spanning those experienced by the CTBs (Table 2). The three H/D ratios, which are an experimental factor in SBR studies, were selected to discern if SBR geometry affected floc size and are similar to H/D ratios used in aerobic granulation experiments (Kong et al., 2009; Awang and Shaaban, 2016).

After operating for 2 h at 20 °C, samples were taken from each reactor to determine the particle size distributions of the flocs. The shear distributions within the reactors were then estimated using CFD simulations.

2.2. Reactor construction

The CTBs were constructed with two concentric acrylic cylinders, where the outer cylinders were mounted on flat bases while the inner walls were supported by an internal shaft (Fig. 1) using the configuration-specific dimensions in Table 3.

The iCTB inner wall was rotated using a laboratory mixer attached to the inner wall's shaft. Rotation of the oCTB outer wall was accomplished by mounting it onto a variable speed potter's wheel (*Artista* model, Speedball Art, Statesville, NC). The inner wall of the oCTB was kept stationary by attaching its shaft to a fixed clamp. Rotation speeds were measured using a handheld tachometer.

In both cases, flat polytetrafluoroethylene (PTFE) plates were placed between the inner and outer base plates to reduce friction. Aluminum spacer discs with a central PTFE bushing were fit around the central shaft at the top of the reactors to maintain even spacing between reactor walls. Water was added to the inner cylinder to counteract buoyancy; this water was solely ballast and did not mix with the active reactor volume.

In the CTBs, influent, effluent, and aeration ports were installed on the static wall of each reactor. Aeration was provided by a coiled aquarium style bubble wand (Aquaneat model B01N1KQGBG, CLL Pet Supplies, Madison, WI) which fed air from the output of a vacuum pump at rates of 1.8 L and 0.75 L per min, resulting in superficial upflow gas velocities of 0.25 and 0.39 cm s^{-1} within the oCTB and iCTB, respectively. Other fluids were pumped using peristaltic pumps.

The SBRs were constructed from cast acrylic tubes mounted on flat bases, with an aeration port installed near the bottom wall.

Table 2
Gas flow rates (L/min) used in SBR reactors.

SBR H/D	Desired mean shear rate (s^{-1})[a]				
	25	50	100	200	250
(Squat) 0.5	0.11	0.43	1.7	6.9	10.8
(Med) 1.1	0.07	0.26	1.0	4.1	6.5
(Tall) 9.4	0.02	0.06	0.2	1.0	1.5

[a] Predicted from Eq. (2); see below.