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Enhanced sediment flow in inclined settlers via surface modification or applied vibration for harvesting microalgae

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ABSTRACT

Inclined settlers may be used to improve algal-harvesting economics by enhancing the clarification rate for a fixed sedimentation velocity and areal footprint. For a fixed plate area, smaller inclination angles from horizontal result in increased settling area and clarification rate. To ensure flow of the settled-cell sediment for continuous operation, standard designs utilize a minimum angle of 55° from horizontal. If reliable, shallow-angle flow of sedimented algae is achieved, increased clarification rates may be realized (e.g., 63% enhancement at 20° versus 55° from horizontal). To study the critical sediment-flow angle, we use an angle-of-repose model, which includes an additional normal-force term to account for adhesion. The inclusion of this term is supported by observations that the critical sliding angle decreases with the sediment mass/thickness. To reduce the critical sliding angle, we evaluated the sediment flow of settled, green alga *Chlorella vulgaris* on several low-adhesion surfaces described in the biofouling literature and demonstrated sediment flow at angles as low as 10° using a negatively-charged surface. This surface fouled after immersion for 24 h in spent culture medium, presumably due to the deposition of residual organic matter. Additionally, applied vibration is demonstrated to achieve sediment flow at angles as shallow as 20°.

1. Introduction

1.1. Challenges of cost-efficient harvesting of microalgae

Microalgae may serve as a source of biomass for biofuels due to many desirable qualities, such as high autotrophic productivity [1], accumulation of high-energy-density lipids [2] and growth in brackish water or seawater [3]. However, the microscopic size of individual algal cells (generally 5–20 μm in diameter or length [4–6]) and the low concentrations typical of autotrophic growth in raceway ponds (0.05–0.1% w/w [5]) result in significant harvesting costs, estimated to account for 18.5% of total production costs [7]. The low algal concentrations are particularly problematic, requiring 50–100 fold concentration just to achieve cell concentrations (5% w/w) usually achieved in microbial fermentations [5,8]. Thus, primary harvesting techniques are especially critical for concentrating the large volumes necessary to attain a 1–5% w/w concentration, appropriate for further dewatering techniques. Common primary harvesting techniques include microstraining, flotation and sedimentation [5]. Microstraining tends to be applicable only for large or colonial algae, while flotation may be complicated by floc–bubble capture. Sedimentation is typically performed in conjunction with flocculation to achieve rapid clarification rates, but the cost of flocculants in an algae-to-biofuels process is not insignificant [5–7]. Alternatively, rapid clarification rates may be achieved without flocculation in an inclined settler by increasing the surface area available for sedimentation [9].

1.2. Inclined sedimentation

Inclined sedimentation in parallel-plate, lamellar settlers is a subset of gravitational sedimentation, distinguished by the use of inclined plates to enhance the rate of clarification per areal footprint. Between each of these plates, sedimentation of the suspended algal cells occurs while unclarified suspension flows upward, resulting in the generation of a buoyant clarified fluid and a denser, settled-algae sediment as depicted in Fig. 1. In the case of large Grashof numbers and small Reynolds numbers [10], the generation rate of clarified fluid, Q_c, is proportional to the vertically-projected settling area and the algae's settling velocity as predicted by PNK (Ponder–Nakamura–Kuroda) theory [11,12]:

$$Q_c = NWbv_o\left(\sin\theta + \frac{L}{b}\cos\theta\right), \qquad (1)$$

where N, b and W are the number, spacing, and width of the plates, respectively, while v_o is the particle settling velocity, L is the distance from the bottom of the settler to the clarification interface at the top of the settler and θ is the settler angle relative to horizontal.

Notably, the PNK model predicts large enhancements to the clarification rate for large aspect ratios and shallow inclinations. For example,

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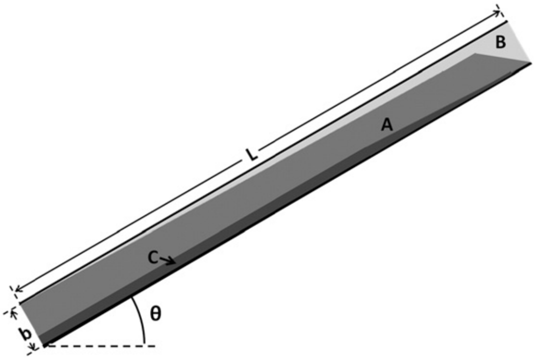

Fig. 1. View of fluids between a pair of inclined plates contained within a continuous lamellar settler. As unclarified suspension (A) is fed from the bottom, the clarified fluid (B) and the settled-cell sediment (C) exit upwards and downwards, respectively, to be collected at the top and bottom of the lamellar settler.

Eq. (1) predicts a 97% increase in the clarification rate for a settler with large aspect ratio ($L/b = 500$) if operated at 8° versus 60°, a result which has been validated experimentally [9]. However, shallow-angle clarification in continuous lamellar settlers typically results in an accumulation of settled sediment due to poor sediment flow, preventing the collection and harvest of sediment from the bottom of the settler. Presumably for this reason, industrial settlers are designed conservatively with minimum angles of either 55° or 60°, as surveyed by Smith and Davis [9].

Depending on the particle or cell type (and presumably the plate surface), prior experimental work has demonstrated sediment flow at slightly shallower angles, e.g., 43° for clay sediments after batch sedimentation [13] and 45° for yeast sediments during continuous sedimentation [14]. On the other hand, a model developed by Kapoor and Acrivos for hard-sphere suspensions with shear-induced diffusion predicts a much shallower minimum angle of 10° from horizontal for a wide range of feed concentrations, but steeper angles of up to 20° may be required for dilute suspensions, e.g., 0.3% v/v typical of algae [15]. An additional limitation has been identified for bottom-fed settlers due to the pressure gradient opposing downward sediment flow [16]; however, this limitation does not further restrict the Kapoor and Acrivos [15] results for dilute biological suspensions. If shallow-angle sediment flow can reliably be achieved, then greater clarification rates may be achieved in lamellar settlers on a per-plate-area or per-settler-volume basis, potentially improving the process economics by minimizing the ratio of capital costs to product-volume/revenue.

1.3. Increased sediment flow using surface modification to reduce adhesion

We hypothesize that sediment flow of the settled algae may be improved by reducing the static friction between the sediment and the inclined plate. If it is assumed that the sediment's cohesive forces are strong compared to the cell-plate adhesion, then the sediment may be modeled as a thin block with infinite width and length. While the magnitude of adhesion in angle-of-repose problems is typically dominated by the sliding object's weight, it is anticipated that cell-plate adhesion forces may be significant for sediments composed of biological cells with specific gravity near unity. For example, a single yeast cell may adhere to glass with a lateral force greater than 20–30 pN [17], yet it is expected to have a buoyant weight of only 0.05 pN ($D \approx 5$ μm, $\rho \approx 1.08$ g/cm^3). Conversely, strong electrostatic repulsion may reduce the normal forces due to gravitational and adhesion forces and, in extreme cases, result in levitation above the surface [18].

Thus, it is anticipated that an angle-of-repose model should include static friction forces that are dependent on the sum of gravitational and adhesion forces [19]. At the critical sliding angle, θ_c, the following equality is expected to hold between the downward gravitational force and the opposing frictional force:

$$F_g \sin\theta_c = \mu\left(F_g \cos\theta_c + F_a\right), \tag{2}$$

where F_g is the sediment's total buoyancy-adjusted gravitational force, μ is the static coefficient of friction for the sediment-wall interface and F_a is the net sediment-wall adhesion force caused by cell-wall interactions. Note that sediment flow and avalanching occur for inclinations θ greater than θ_c, since the gravitational force then exceeds the frictional force. For monodisperse cells with random packing, F_g is proportional to the thickness of the accumulated sediment, assuming negligible compression. Meanwhile, F_a is expected to be independent of the sludge thickness and varies according to the adhesion forces between cells and the inclined plate.

For $F_g \gg F_a$, Eq. (2) reduces to the familiar angle-of-repose expression $\theta_c = \tan^{-1}\mu$. However, more interesting phenomena occur when F_a is comparable to or larger than F_g, as Eq. (2) then predicts that θ_c is not unique to μ and may vary depending on the ratio of adhesion and gravitational forces. Eq. (2) leads to three hypotheses that are tested in this work. First, it predicts that there will be sediment flow for a thick sediment (large F_g) but not for a thin sediment (small F_g) at the same angle. Second, it suggests that the critical sliding angle for a given sediment thickness may be lowered by not only reducing the friction coefficient μ but also by reducing the cell-plate adhesion forces, perhaps even achieving repulsive interactions. Third and lastly, we hypothesize that applied vibration may be used to convey the sediment downward by disrupting the friction force.

1.4. Reduced adhesion via surface modification

Although a wealth of literature exists on biological adhesion, this short review is intended only to cover general theory and simple surfaces, while noting the complexity of the problem [20–39]. One method used to minimize adhesion is the manipulation of substratum surface energy. Studies have suggested that surface energy should be minimized, using close-packed CF_3 surfaces [20] or superhydrophobic surfaces [21,22]. However, the majority of studies investigated an ideal window of substratum surface energies between 20 and 30 mN/m [23–26], with an adhesion minimum occurring at 22 mN/m corresponding to the dispersive component of water's surface tension [23]. This hypothesis is supported by experiments [25,26] that show increased adhesion on surfaces with surface energies both greater than and less than the critical window, such as glass and polytetrafluoroethylene (PTFE) with surface tensions of ~46 and 18 mN/m. Some ideal surfaces within the optimal range are closely-packed CH_3 groups, e.g., alkyl self-assembled molecules (SAMs) at 22 mN, and certain semifluorinated polymers, e.g., polyvinylidene fluoride at 24 mN/m [27].

Despite these predictions, a survey of the literature demonstrates organism-specific variability in adhesion behavior. For example, several studies incorporate the use of SAM surfaces composed of varying ratios of CH_3/OH functionality, and a pure CH_3 SAM surface would be expected to exhibit minimum adhesion based on its ideal surface energy [27]. While some organisms have shown strong adhesion to OH-rich surfaces, e.g., *Enteromorpha* [29], others favor adhesion to CH_3-rich, hydrophobic surfaces, e.g., *Cobetia marina*, *Ulva*, *Amphora* and estuarine bacteria [28–30]. Other research suggests that the subtle changes in the surface tension of the aqueous solution must also be taken into account. Notably, Absolom [31] performed adhesion studies of five different bacteria on five different substrata in five DMSO-modified media, all with different surface tensions. For a given bacterium, adhesion was reduced on surfaces with greater surface energy if the surface tension of the medium was greater than the surface tension of the bacteria, and vice versa.

Alternatively, the adhesion forces may be reduced according to DLVO (Derjaguin–Landau–Verwey–Overbeek) theory [32] by offsetting