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Identifying the dominant physical processes for mixing in full-scale raceway tanks

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ABSTRACT

Open racetrack flumes represent the most common reactor for algae cultivation in the biodiesel industry, however, despite numerous experimental and numerical studies into reactor modifications, conditions remain suboptimal for algal growth. In response, a full-scale racetrack flume was constructed at the Ecohydraulics and Ecomorphodynamics Laboratory at the University of Illinois. Experiments on the racetrack flume were conducted for various depth and velocity conditions, using acoustic doppler velocimetry and surface particle velocimetry to characterize mean and turbulent velocity statistics, and dissolved oxygen measurements to investigate the effect of turbulent structures on gas transfer at the water-air interface. Longitudinal bed modifications were introduced to induce secondary flows in the straight portions of the flume. Semicircular and triangular bars of two different sizes were tested in an effort to increase the transfer velocity at the free surface. A range of flow structures were observed including secondary currents of Prandtl's first and second kinds, vortex shedding off of bend vanes, and periodic oscillations in surface lateral currents. Findings indicate that bend dynamics introduce the strongest and most resilient flow structures, and any attempt to induce vertical mixing or accelerate transfer velocities at the free surface will need to utilize or overwhelm these existing structures.

1. Introduction

From the earliest days of the diesel engine, the prospect of using organic material as a renewable fuel source has been remarkably achievable. At the Paris Exposition of 1900, Dr. Rudolf Diesel, himself, ran his new invention on peanut oil and hemp [12]. Since then, however, biodiesels have made only modest intrusions into the transportation fuel sector. Even after the halcyon days of biodiesel in the 1980's and 1990's, biofuels remain only 5% of the transportation fuel market in the United States [48]. In response, there has been an effort since the 1970's to use microalgae, with an oil yield 10–20 times that of competing terrestrial crops [30], as an alternative feedstock for biofuels [52]. Microalgae has a number of benefits over terrestrial crops, including significant reductions in land usage, rapid growth rates, and high oil contents. However, further advancements in cultivation processes are required for algal biodiesel to be cost competitive with petroleum-based products [6,7].

Microalgae is typically cultivated in one of two types of facilities: open raceway tanks/ponds (RWTs) or tubular photobioreactors (PBRs). Currently, RWTs represent the major share (95%) of all algal biomass production [22,28], and it is expected that RWTs will be the cultivation method of choice for their simplicity, ease of cleaning, ability to scale, and low costs [13,18,22,40]. Open RWTs are typically a closed loop consisting of straight stretches with 180° bends. Solution is often guided around bends by use of vanes, and flows are driven by paddlewheel which provides the additional benefit of mixing the solution [6,18].

These facilities can involve a number of hydrodynamic impediments to algal growth, which has made them the subject of numerous studies. First, in the absence of vertical mixing (particularly in the straight portions of the flume) algal cells at the surface can be overexposed to sunlight and undergo photoinhibition, a decrease in specific growth rate from excess sunlight intensity [6,30]. These cells effectively block the surface irradiance, and cells in the lower strata do not receive sufficient sunlight for photosynthetic processes. Ideal conditions for the photochemical and non-photochemical reactions, as observed experimentally by Kok [21] are short bursts of light followed by periods of darkness, which does not naturally occur in straight sections of the pond [5].

A second significant impediment resides in the concentrations of both carbon dioxide and dissolved oxygen in the medium.

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Microalgal biomass consists of approximately 50% carbon on a dry weight basis [29], and efficient methods of introducing carbon into the culture are of paramount importance. This is often performed by introducing carbon dioxide from an external source such as a power plant [6], significantly restricting where these ponds can be located. Alternatively, efficient introduction of carbon from the atmosphere could enhance growth rates [17] without such restrictions. Likewise, photosynthetic reactions produce oxygen as a byproduct which can lead to supersaturation of the culture medium. This has been shown in studies of *Chlorella vulgaris* to lead to a decrease in photosynthetic efficiency of 35% [29]. Therefore, processes are required to catalyze mass transfer both into (CO_2) and out of (O_2) the culture medium.

A third impediment to algal growth is in the formation of recirculation or "dead" zones at the insides of the 180° bend exits. These regions form as a consequence of flow separation at the sharp bend, and result in much lower local velocities. These areas then entrain algal cells, where they are subject to sedimentation and reduced productivity [16].

In light of these and other shortcomings of the open RWT cultivation method, a number of studies, both experimental and numerical, have been performed to try to improve the growth conditions for the algae (Table 1). In particular, several attempts have been made to introduce low-cost modifications to the existing RWT structure in order to produce vertical mixing in the straight sections and enhance gas transfer at the free surface. The Raceway Hydraulics Group of Utah State University [4,14,23,49,51] introduced delta wing vortex generators (DWVGs) to a small-scale laboratory RWT, with success in generating quantifiable vertical mixing. This does, however, come at the expense of energy input. Vaughan [49] found an increase of 1.5 W for a single DWVG, and in reality an array of DWVGs would be required to achieve sufficient mixing. Additionally, it was observed by Godfrey [14] that turbulence levels exceeded critical values for many algal strains, and would actually cause damage to the algae cells by shear from the smallest scales of the turbulence. This leaves open the necessity for less intrusive methods of generating vertical mixing.

Citerone [9] used PVC half-pipe ridges on the bed of a shallow, straight flume to generate cellular, secondary currents with a concomitant increase in the gas transfer velocity at the free surface. It was found that the gas transfer velocity did, in fact, increase 9–15% with the addition of the PVC ridges. This modification, however, requires further understanding concerning optimal geometric parameters (ridge size, spacing, shape) and its interactions with other flow structures in an open RWT.

1.1. Research objectives

The present study seeks to expand on the concept of cellular, secondary currents, by introducing them in a large-scale 0.77 m × 9.57 m open RWT facility (see Fig. 1 for dimension definitions). Secondary currents in open-channel flows are generally categorized into one of two kinds. Secondary currents of Prandtl's first kind are generated by centrifugal forces in curved channels, while those of Prandtl's second kind are driven by turbulence (particularly, gradients in Reynolds stresses) and arise from complex interactions between the channel geometry, boundary roughness, and in environmental flows by sediment transport [32]. In nature, these secondary currents of Prandtl's second kind are observed in regions of elevated sediment concentration and are typically spaced such that a pair of counter-rotating eddies occupy a width approximately two times the flow depth [10,19,20]. These cellular, secondary currents can form in straight, flat conduit [33], however in the current set of experiments they are amplified by introduction of longitudinal bars of various shapes and sizes placed along the bed, to promote vertical mixing to obtain optimal algae growth conditions.

It is anticipated that these secondary flow structures, as in the case of Citerone [9], will promote gas transfer at the free surface. The gas transfer at an air-water interface can be expressed in terms of a transfer velocity, $\overline{k}$, as:

$$\overline{\mathbf{F}}_z = \overline{k}(C_w - \alpha C_a) \tag{1}$$

where $\overline{\mathbf{F}}_z$ is the time-averaged flux across the interface, C_w is the bulk concentration of gas in the water, C_a is the bulk concentration in the air, and α is the gas equilibrium solubility in water. The surface renewal model was first proposed by Danckwertz [11], and it postulates that the aqueous diffusive boundary layer is "renewed" by turbulent action in the water, and therefore the transfer velocity could be modeled as:

Table 1

Recent, existing experimental and numerical studies on open RWT reactors (not comprehensive). Studies vary widely in modifications to conventional RWT design, in parameters of interest, and in methods of quantifying efficiency. Scales are reported based on typical reactor configuration with the width (W) being the width of one leg, and length (L) being the length of straight channel. Xu et al. [53] is an exception given the deviation from standard RWT design, but similar dimensions are reported for sense of scale. For Utah State University Raceway Group, see Voleti [51], Godfrey [14], Lance [23], Vaughan [49], Blakely [4].

Description	Author	Study Type	Scale (W × L)	Efficiency Evaluation
Inserted delta wing vortex generators	USU Raceway Group*	Numerical/Experimental	0.4 m × 5.2 m	Vertical mixing index & power consumption
Varied L/W ratio and bend configurations	Hadiyanto et al. [16]	Numerical	0.7 m × (3.5 m–10.5 m)	Dead zone percentage compared with typical configuration
Varied bend geometries	Liffman et al. [26]	Numerical	5.0 m × 96.0 m	Power Consumption
Full scale with sump baffle, varied bend deflectors, and flow depths	Mendoza et al. [28]	Experimental	0.9 m × 48.0 m	Power consumption, residence times, and dispersion coefficients
Outdoors subject to seasonal variability, with CO_2 supplied, and algal growth	Sutherland et al. [42]	Experimental	1.0 m × 2.2 m	Photosynthetic parameters
Model validated by experimental facility and scaled up to industrial scale	Prussi et al. [35]	Numerical/Experimental	1.0 m × 8.0 m ($500\ m^2$ CFD)	Particle tracking statistics
Varied paddlewheel configurations	Hreiz et al. [18]	Numerical/Experimental	1.9 m × 10.2 m	Mixing time & power consumption
Novel configuration with slope and propeller pump	Xu et al. [53]	Numerical/Experimental	0.7 m × 1.4 m	Conceptual flow pathlines
Comparison of paddlewheel pulsating velocity to flat velocity profile	Ali et al. [2]	Numerical	2.3 m × 23.0 m	Power consumption, vorticity magnitude, and dead zone volumes
Bed modifications in a straight flume	Citerone [9]	Experimental	2.0 m × 15.0 m	Surface divergence & transfer velocity at free surface