SAND2020-10160C

Turbulence characterization of algae and viscous cyanobacterial polycultures in open-channel raceways: Implications in the design of cultivation systems

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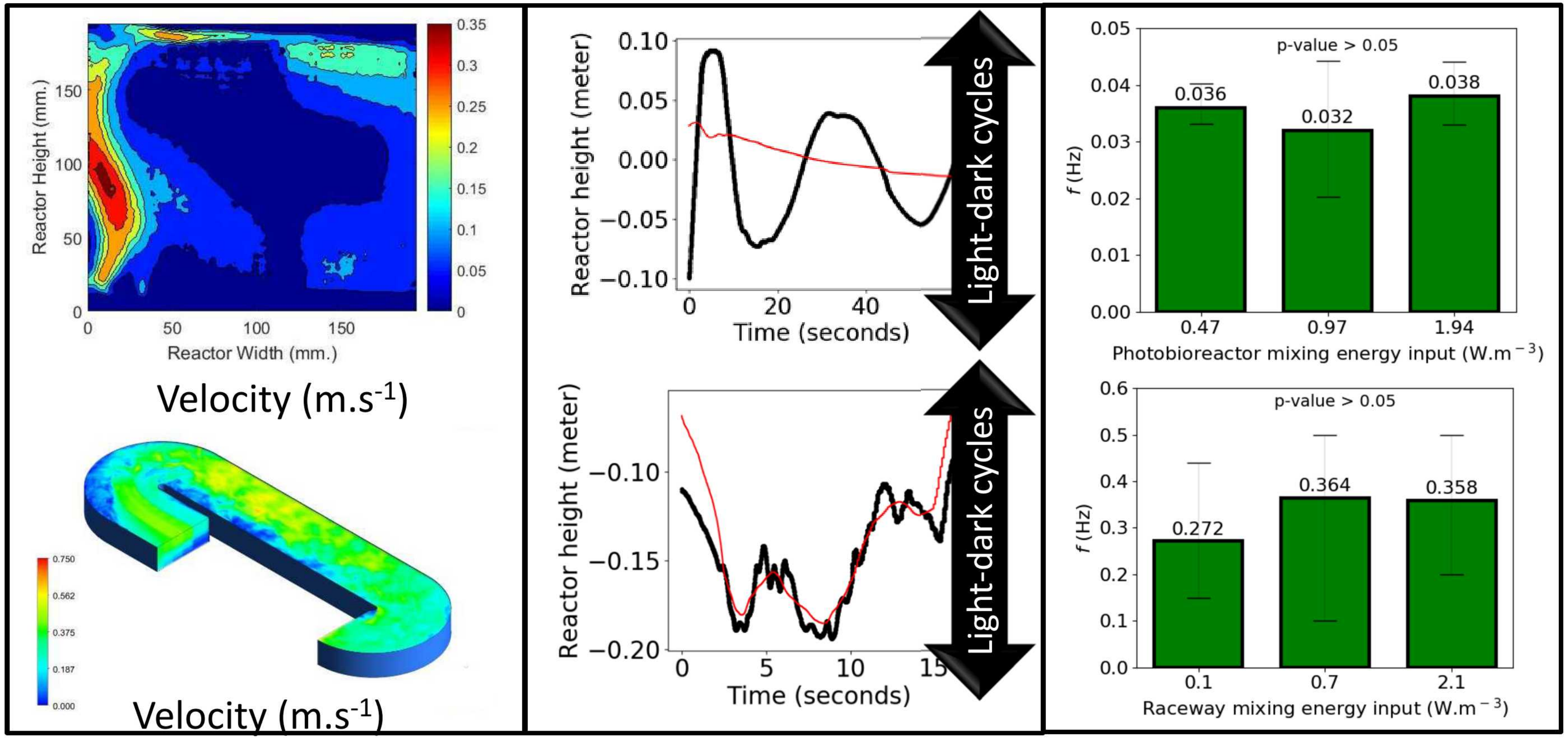
Background: Pilot-scale open-channel raceways and flat-panel photobioreactors maintain well-mixed conditions under a wide range of mixing energy inputs



Differences in mixing energy input do not significantly impact:

- Structure of turbulence
- Frequency of cells motion
- Light/dark cycling frequencies

Quiroz-Arita, Carlos, Myra L. Blaylock, Patricia E. Gharagozloo, David Bark, Lakshmi Prasad Dasi, and Thomas H. Bradley. Biotechnology and Bioengineering 117, no. 4 (2020): 959-969.

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$$\boldsymbol{Terminal\ velocity} = \frac{\mathbf{1}}{\mathbf{18}} * \boldsymbol{g} * \boldsymbol{d}^{\mathbf{2}} \left(\frac{\rho_{Water} - \rho_{Air\ Bubble}}{\mu}\right)$$

Where;

$\boldsymbol{g}$: $Gravitational\ acceleration$

$\boldsymbol{\rho}$: $Density\ (Air\ Bubble/Water)$

μ: Dynamic viscosity

$\boldsymbol{d}$: Diameter of air bubble

→ **Variables are held constant regardless of mixing energy input**

$$\boldsymbol{L} = \frac{\mathbf{4} * \boldsymbol{H} * \boldsymbol{W}}{\mathbf{2} * \boldsymbol{H} + \boldsymbol{W}}$$

$$Convective\ Time\ Scales = \frac{L}{U}$$

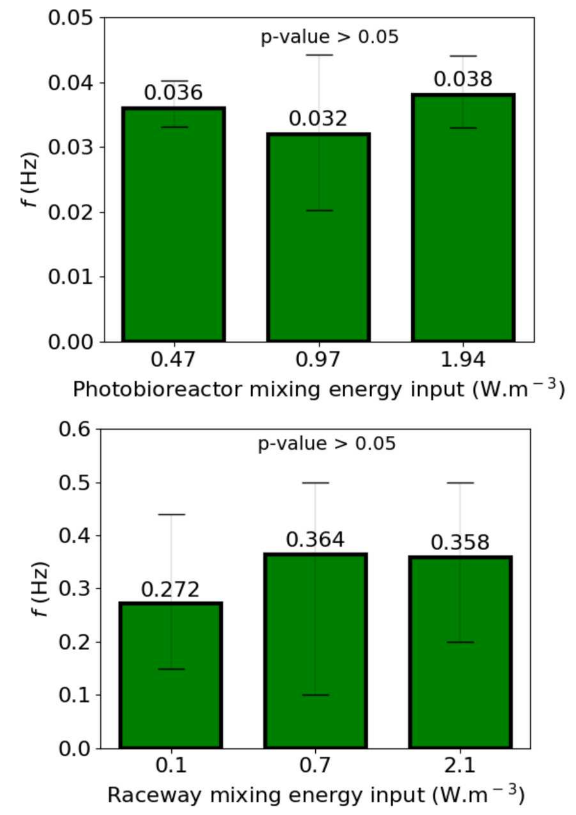
Where;

$\boldsymbol{L}$: $Characteristic\ Length$

$\boldsymbol{W}$: $Channel\ Width$ *(Constant)*

$\boldsymbol{H}$: $Channel\ Height$ *(Constant)*

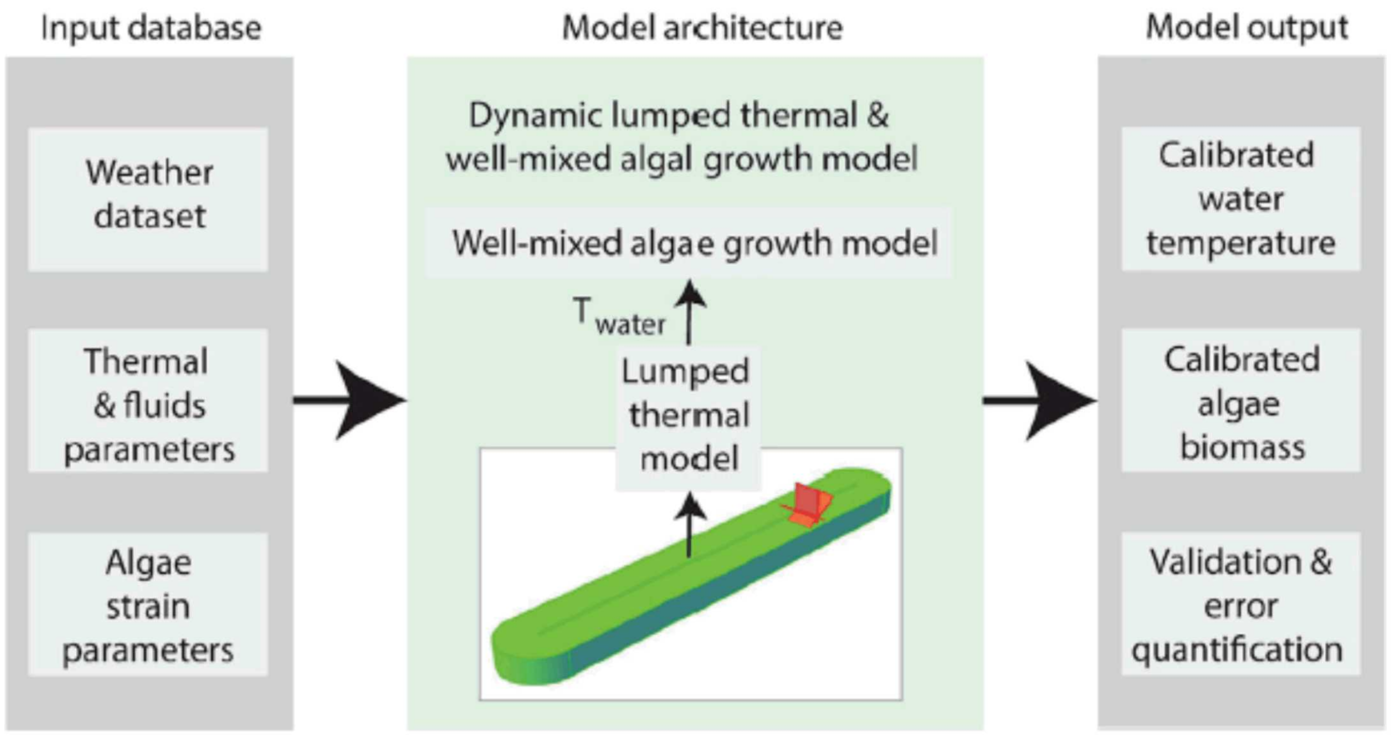
$\boldsymbol{U}$: $Velocity\ Profile$ *(Initial Conditions for Motion)*



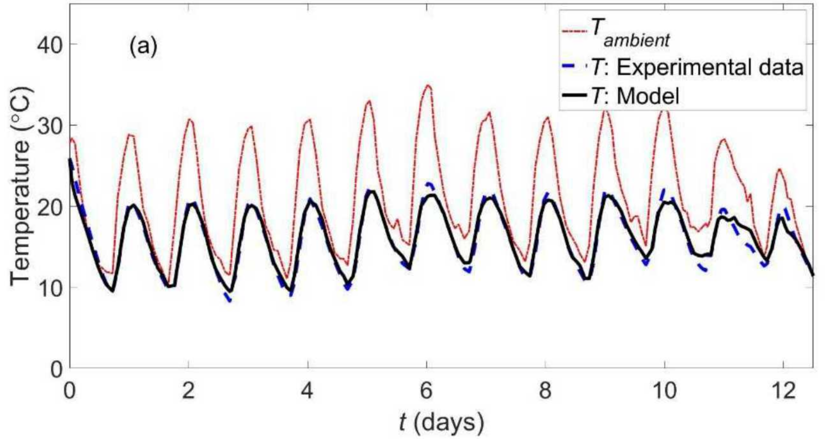
- Air bubbles buoyancy drives flow circulation in flat-panel photobioreactors
- The period of cells motion is the same order of magnitude of large-scale eddies (time scales)

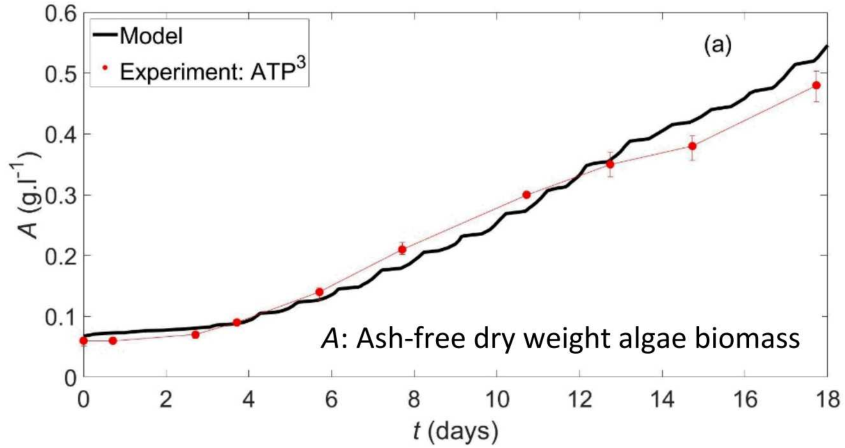
Quiroz-Arita, Carlos, Myra L. Blaylock, Patricia E. Gharagozloo, David Bark, Lakshmi Prasad Dasi, and Thomas H. Bradley. Biotechnology and Bioengineering 117, no. 4 (2020): 959-969.

Background: The thermal system, algae growth rate limitations, and photoinhibition can be represented in a well-mixed raceway or photobioreactor dynamical formulation

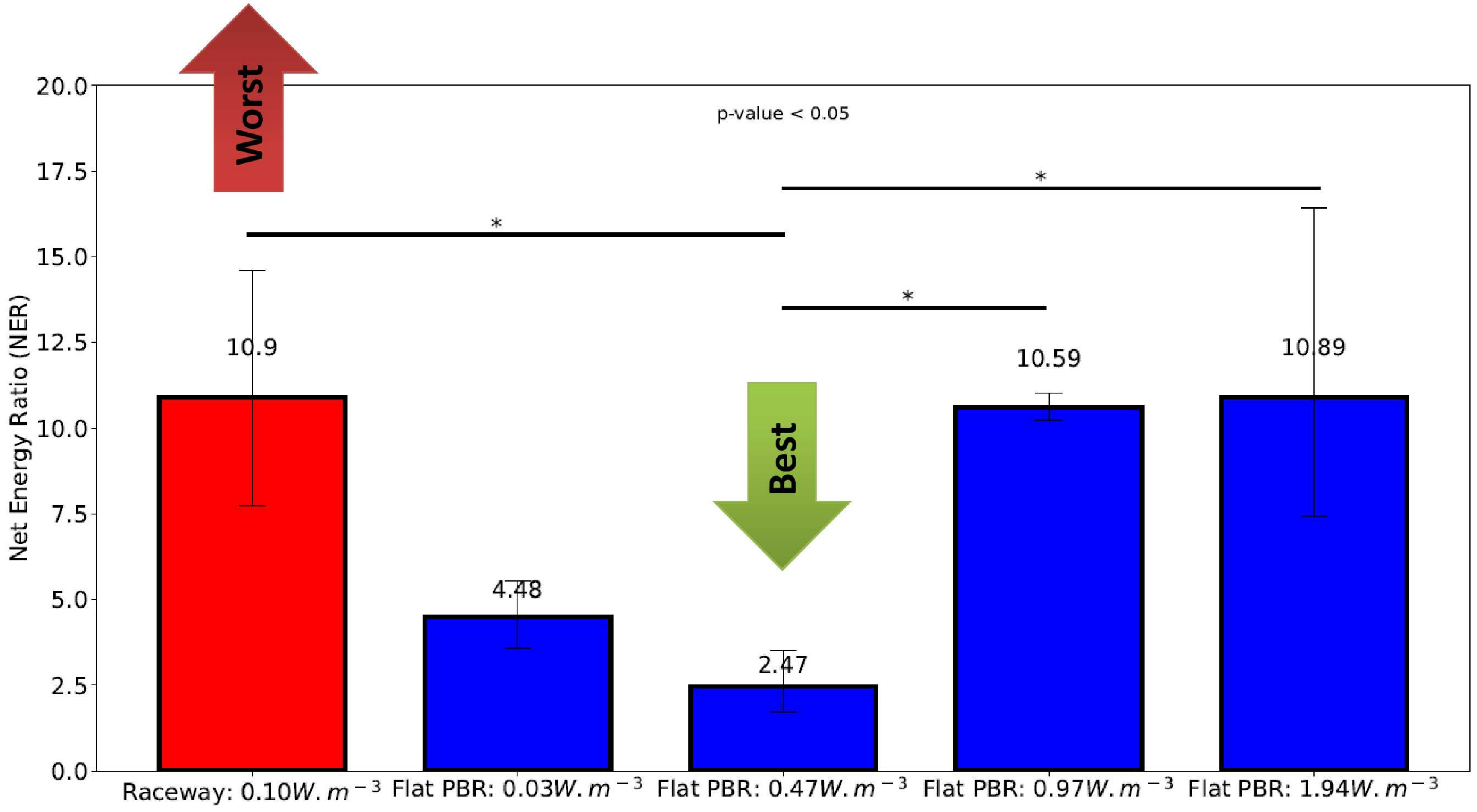


Quiroz-Arita, Carlos, Myra L. Blaylock, Patricia E. Gharagozloo, Thomas H. Bradley, Thomas Dempster, John McGowen, and Ryan Davis. Bioresource Technology Reports (2020): 100405.





Background: Best metrics of sustainability can be accomplished at lowest energy inputs



$$\mathbf{NER} = \frac{\mathbf{Energy_{consumed}}}{\mathbf{Energy_{produced}}}$$

Propagation of uncertainty in the LCA model:

- Experimental error in the maximum growth rates of *Synechocystis* sp. PCC 6803
- Error in cyanobacterial biomass productivities
- Error in biomass to ethanol conversion

(0.108 to 0.280 $MJ_{Energy\ Consumed} \cdot MJ_{biofuel}^{-1}$)

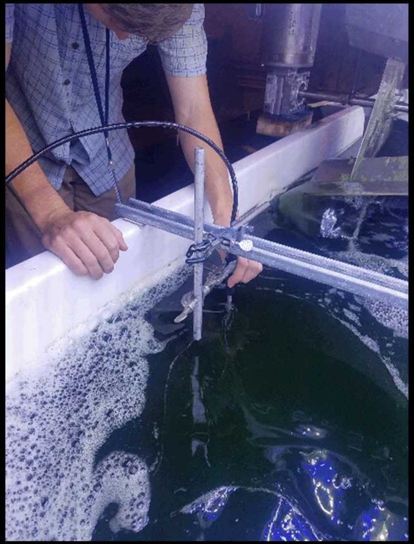
High NER values are in part due to photoinhibition of growth at the high light intensities used in this study

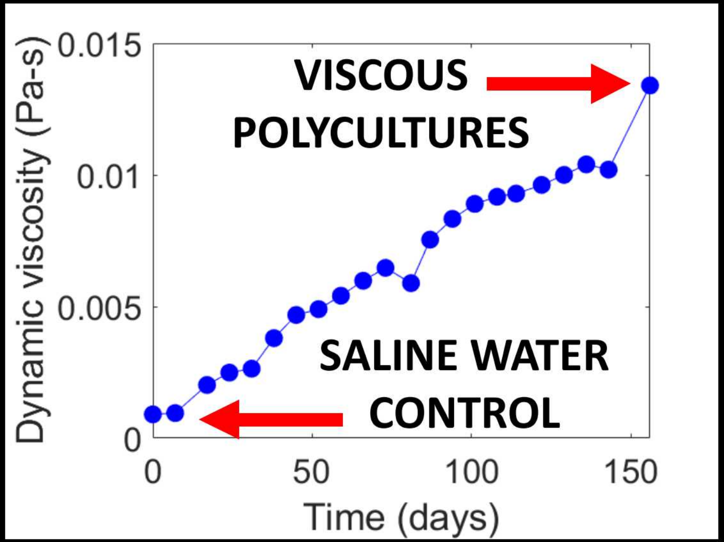
Quiroz-Arita, Carlos, *et al*. (2020) In prep.

State of the field

Previous experimental and computational fluid mechanics studies:

- ***Neglected*** viscosity effects in turbulent mixing, under the assumption that most algae and cyanobacteria cultivation systems present similar viscosities than water
- ***Viscous*** cyanobacterial polycultures are ***ten times more viscous than water*** at stationary phase



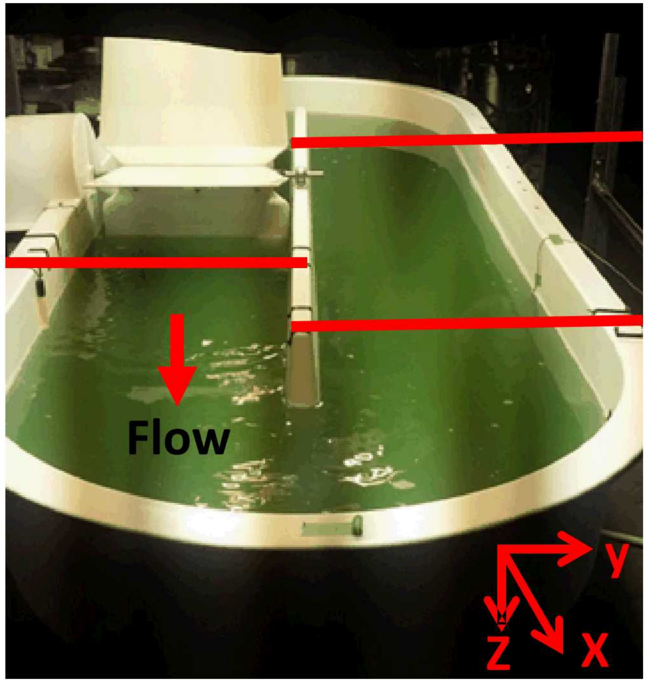


Viscous cyanobacterial polycultures,
Sandia National Laboratories Algae Raceway Testbed

We seek to understand the implications that viscous cyanobacterial polycultures exert in the turbulent mixing characteristics relative to saline water or low viscosity cultures in pilot-scale open-channel raceways as part of a collaboration of Sandia national laboratories and HelioBioSys

Experimental fluid mechanics approach: Velocity measurements were made with Acoustic Doppler Velocimetry at three planes in the raceway

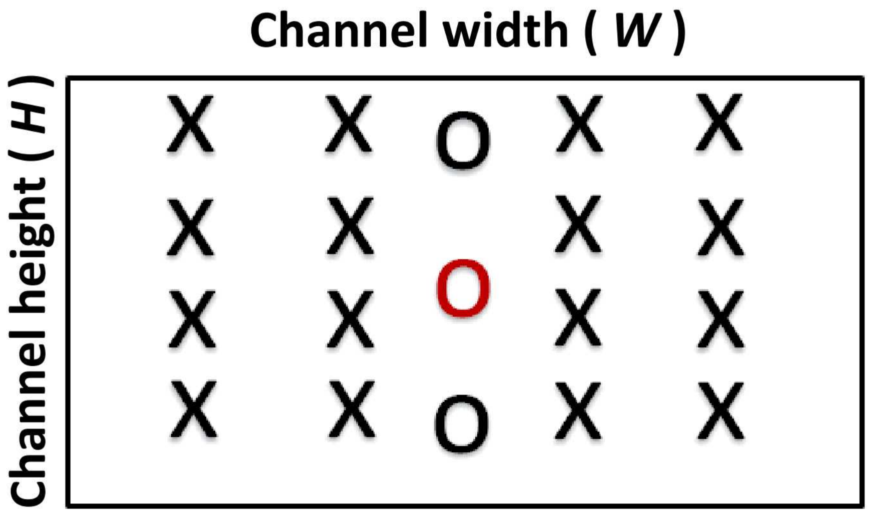
Plane 1:
After paddlewheel



Plane 3:
Before second turn

Plane 2:
After first turn

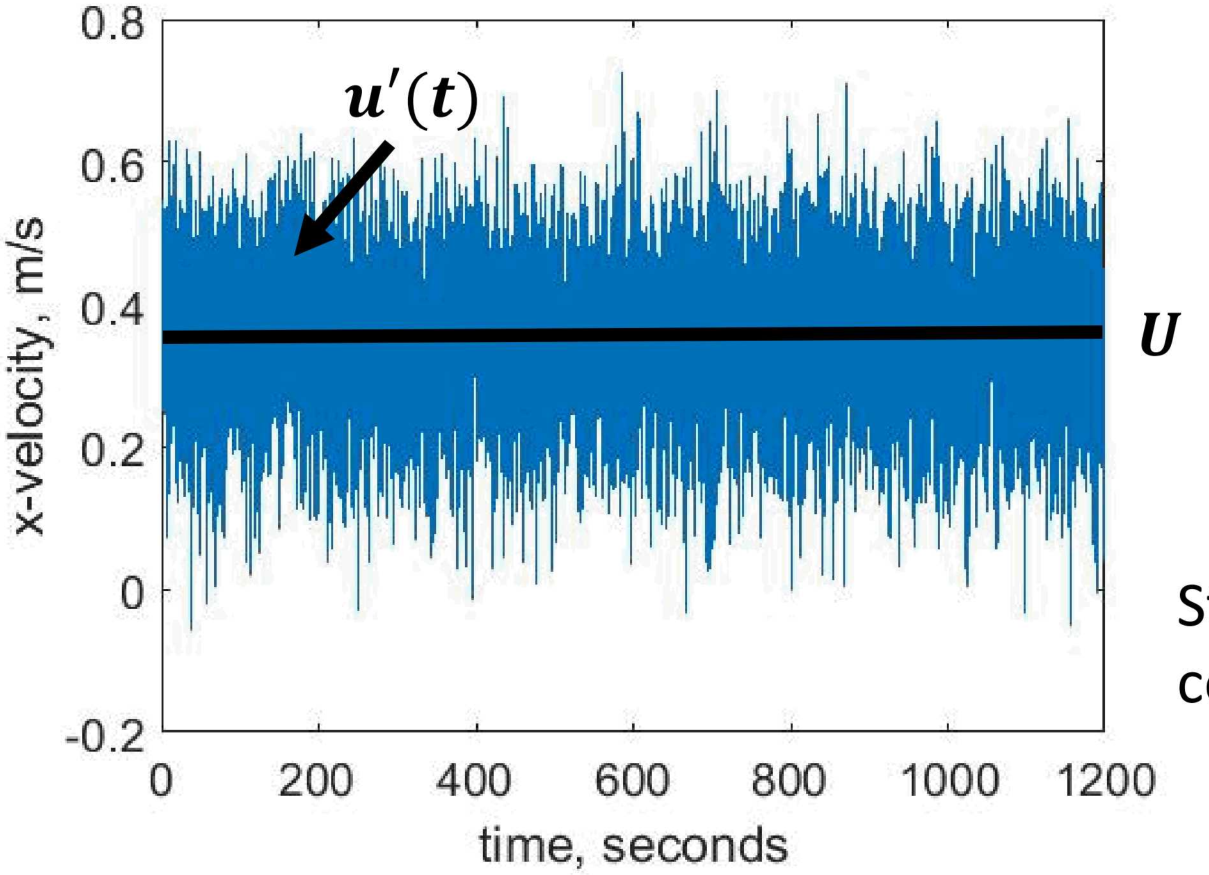
Location of cross-sectional planes for experimental velocity measurements

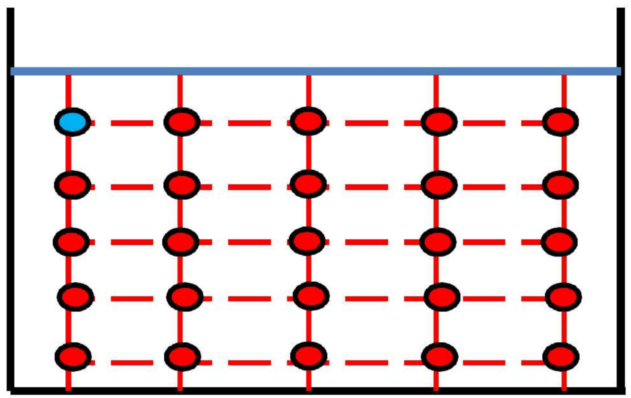


The ***"x's"*** show the location of the 16 velocity measurements ***for each plane***. The ***"o's"*** show the measurements along the ***centerline***

Adapted from: Quiroz-Arita, Carlos, Myra L. Blaylock, Patricia E. Gharagozloo, David Bark, Lakshmi Prasad Dasi, and Thomas H. Bradley. " Biotechnology and Bioengineering 117, no. 4 (2020): 959-969.

Experimental velocity describes Reynolds decomposition which includes the steady mean velocity and the fluctuating component



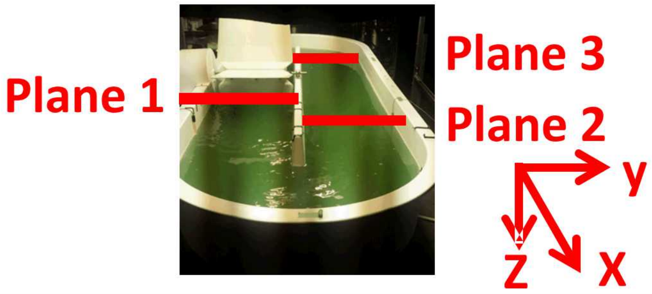


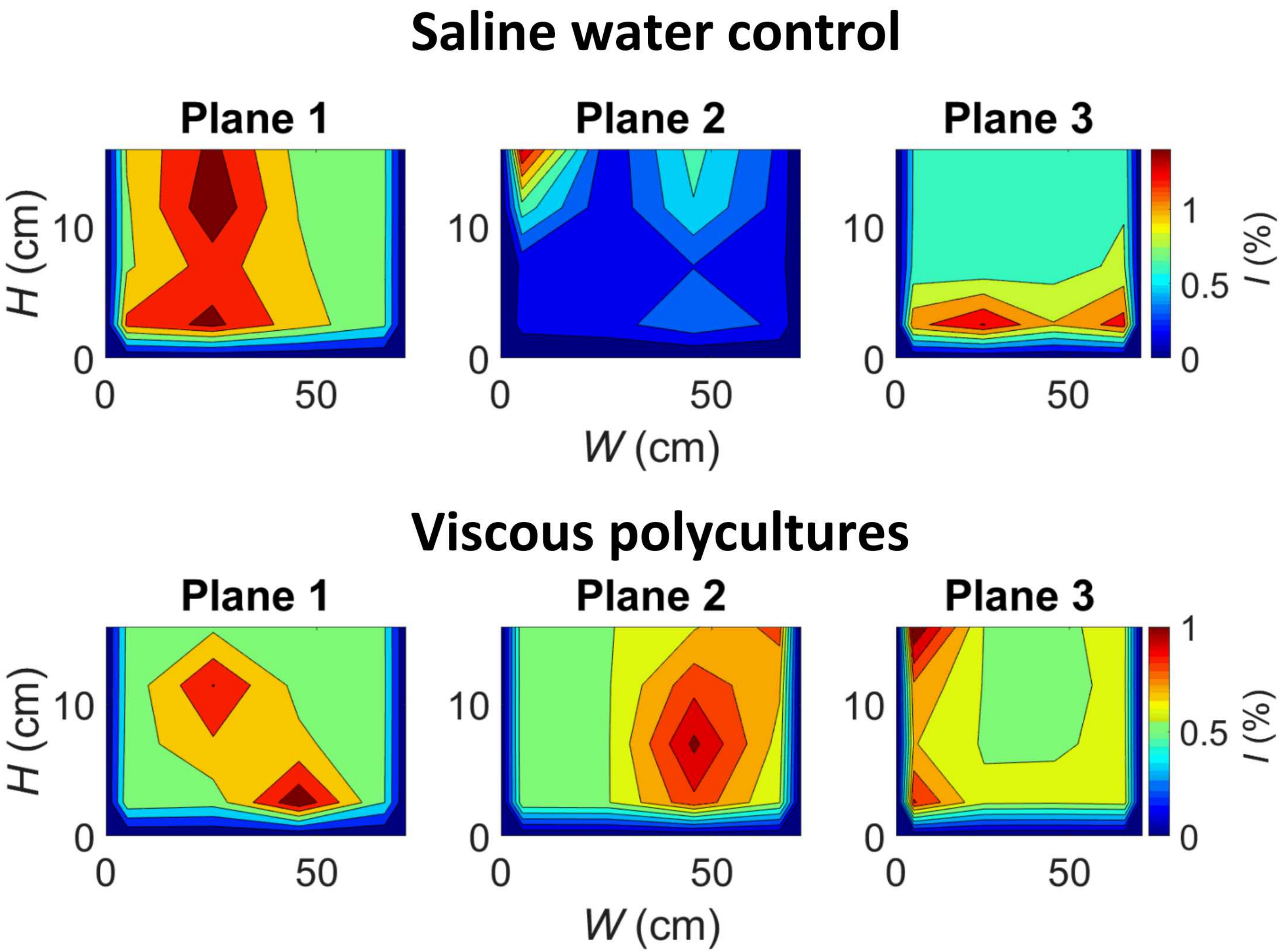
Reynolds decomposition

Steady mean velocity ($\boldsymbol{U}$) with a fluctuating component ($\boldsymbol{u'(t)}$): $\boldsymbol{u(t) = U + u'(t)}$

Adapted from: Quiroz-Arita, Carlos, Myra L. Blaylock, Patricia E. Gharagozloo, David Bark, Lakshmi Prasad Dasi, and Thomas H. Bradley. " Biotechnology and Bioengineering 117, no. 4 (2020): 959-969.

Viscous polycultures reduce turbulence intensities in the system





$$I = \frac{u'(t)}{U}$$

Other authors:

- Nezu and Rodi. J. (1986) : **2.8%**
- R.A. Labatut *et al.* (2015) : **3.84%**
- Quiroz-Arita, C., *et al*. (2020) : ***1 - 1.4%***

Adapted from: Quiroz-Arita, Carlos, Myra L. Blaylock, Patricia E. Gharagozloo, David Bark, Lakshmi Prasad Dasi, and Thomas H. Bradley. " Biotechnology and Bioengineering 117, no. 4 (2020): 959-969.

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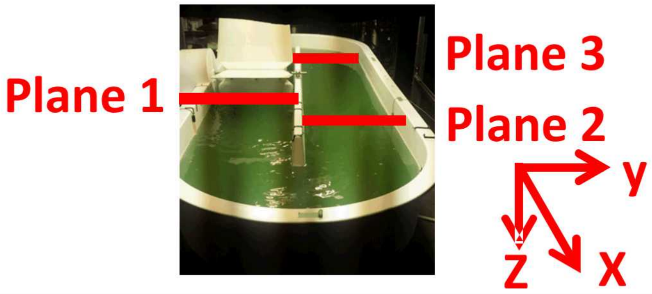
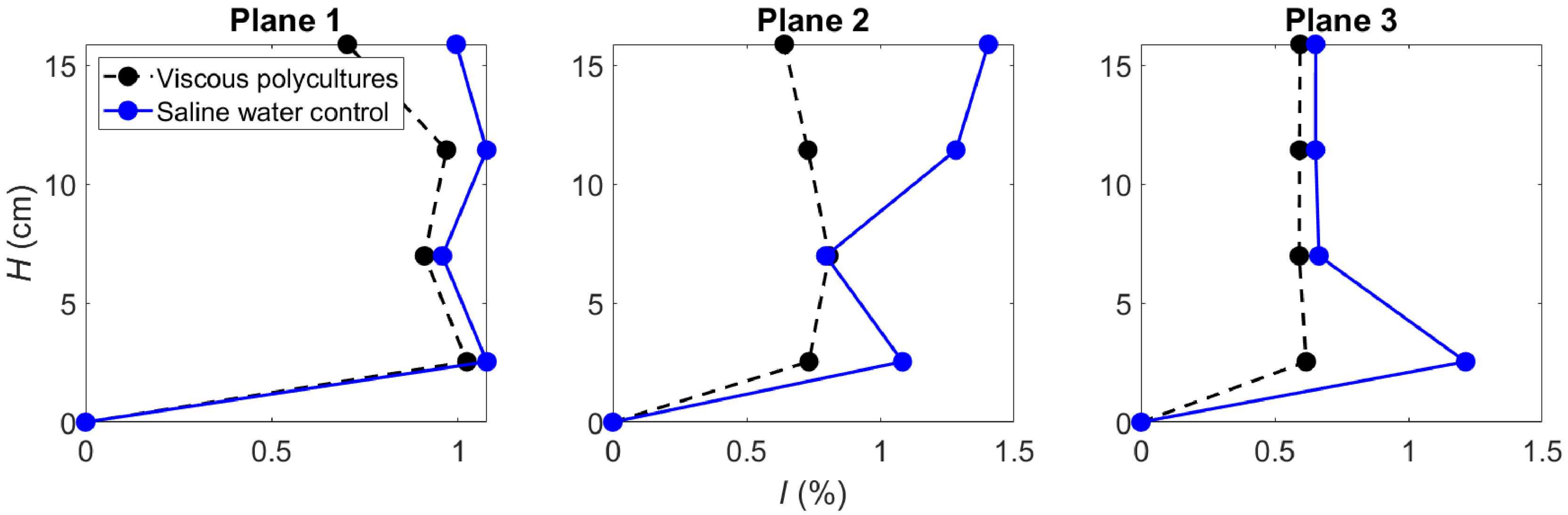
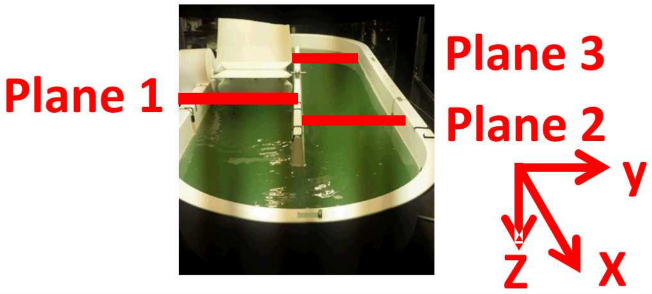


Comparison of the turbulence intensity (%) on the cross-sectional planes

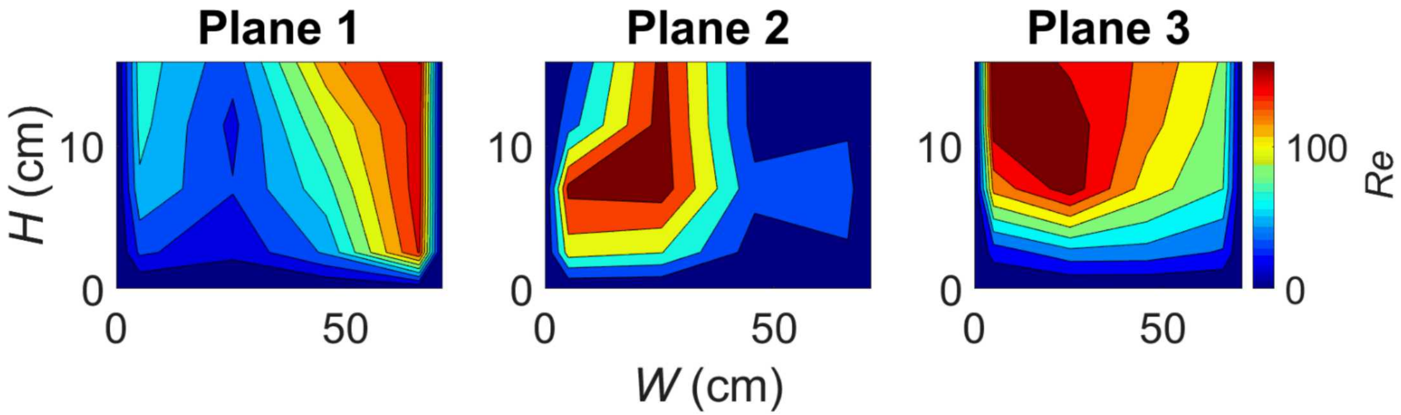


The experimental results demonstrate ***two flow regimes*** for the conditions at the stationary phase (high viscosity) relative to lag phase (low viscosity)

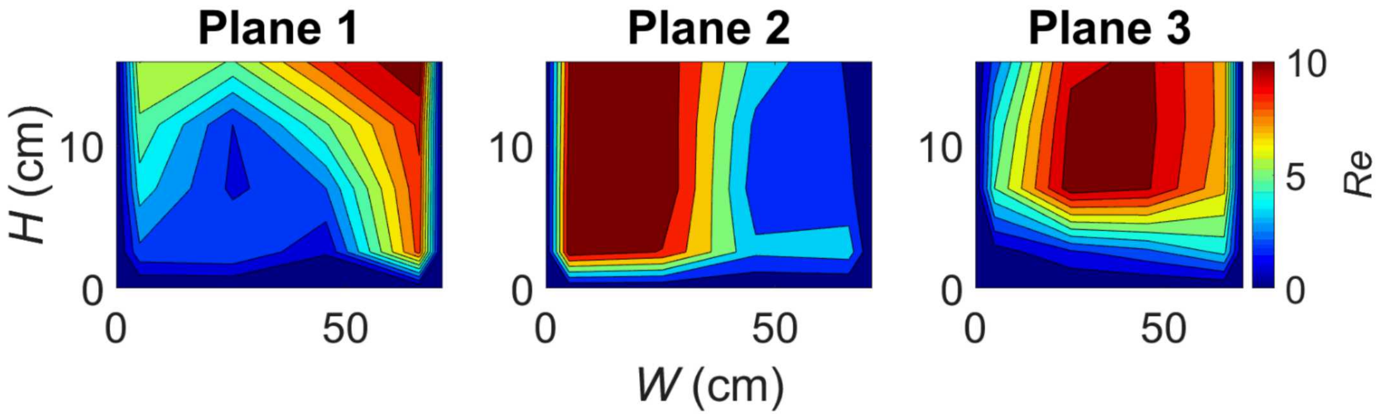
Viscous polycultures reduce the Reynolds number in the system



Saline water control



Viscous polycultures



$$Re = \frac{\rho U L}{\mu}$$

where,

$\boldsymbol{Re}$ = Reynolds number

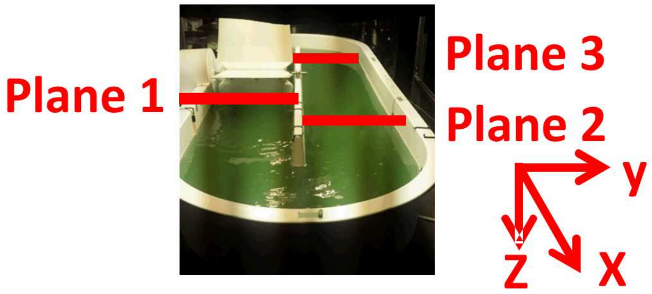
$\boldsymbol{\rho}$ = density

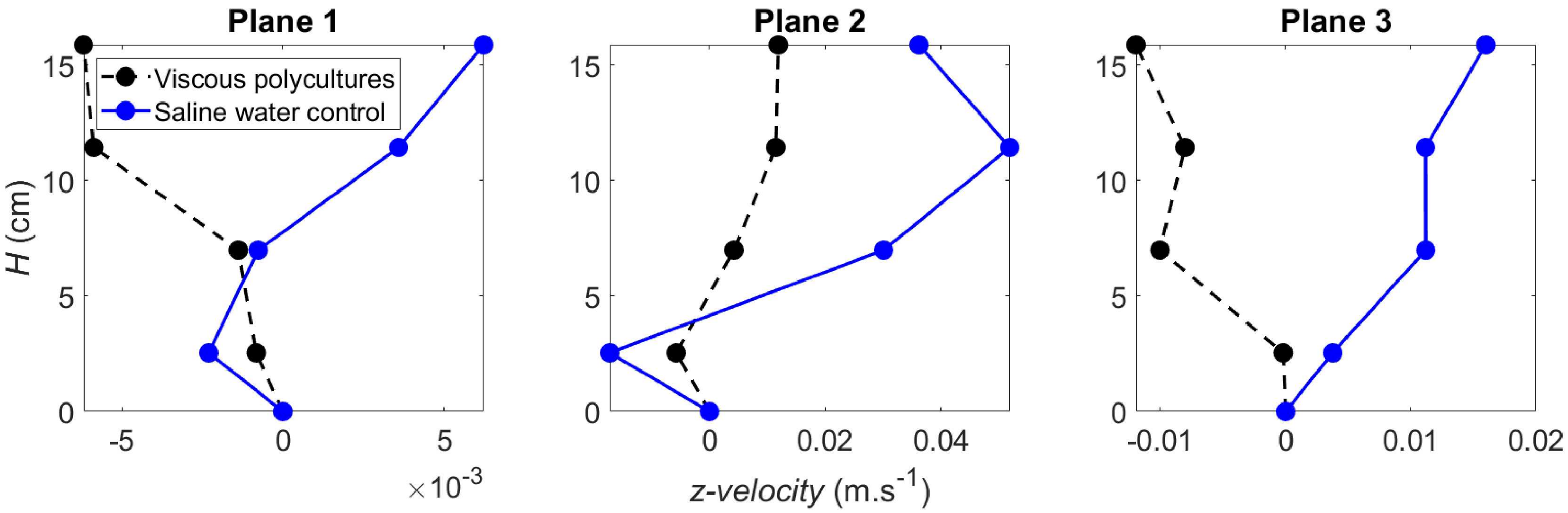
$\boldsymbol{U}$ = speed

$\boldsymbol{L}$ = characteristic length

μ = dynamic viscosity

Viscous polycultures increase viscous forces and change mixing regime in the system





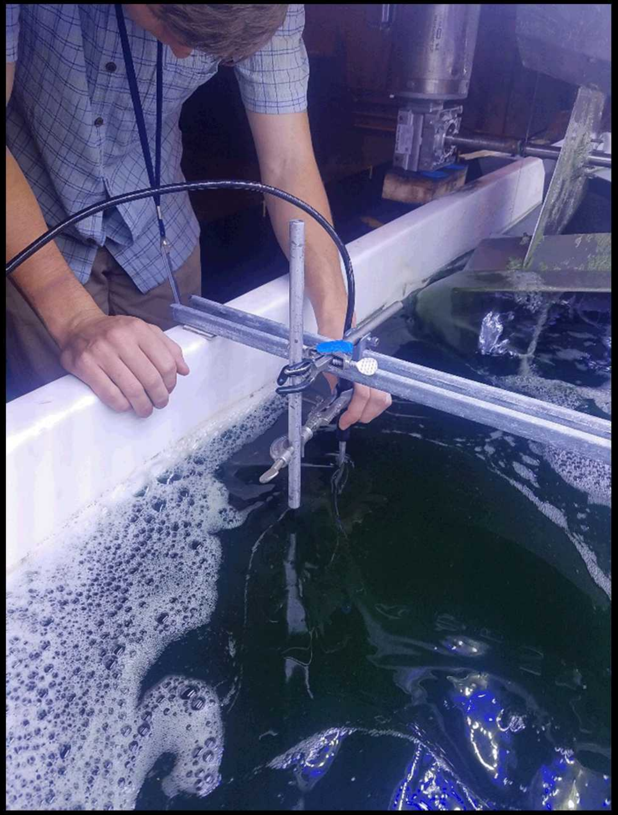
Shear stress = $\tau_{total} = \tau_{laminar} + \tau_{turbulent} = -\mu \frac{du}{dz}$

The ***shear stress*** in high viscosity polycultures overcome the inertial forces of the paddlewheel, ***developing laminar flows***

Conclusions

Our experimental fluid mechanics work of viscous polycultures demonstrated that:

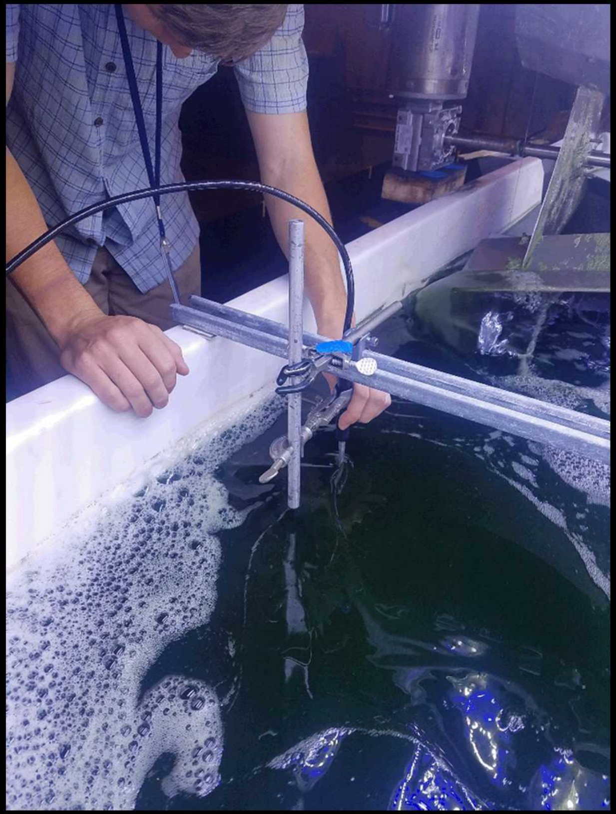
i. Cultivation of polycultures increase the viscous forces, reducing turbulence intensities and *Re* in pilot-scale raceways



Viscous cyanobacterial polycultures, Sandia National Laboratories Algae Raceway Testbed

Conclusions

i. Differences in viscosities observed in polycultures can change the energy requirements to mix and transport cultures in these systems to ensure a well-mixed state
ii. Our future efforts will seek to study the sustainability implications of mixing and transporting viscous polycultures



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QUESTIONS?

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