SaltGae
algae to treat saline wastewater

Evaluation of mixing and shear stresses in High Rate Algae Ponds for different paddlewheel designs.

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CONTEXT

Saltgae Project

- European Project, 20 partners, H2020 framework,
- Feasability of using algae to treat saline wastewater from the food industry,
- Wastewater treatment cost (EU standards) ~ €4.46 billion/year for the 15.000 EU SMEs (up to 14% companies' annual turnover)
- Goals:
  - Develop technology platform to treat WW,
  - Highlight inefficiencies,
  - Extract value from all stages of the treatment.

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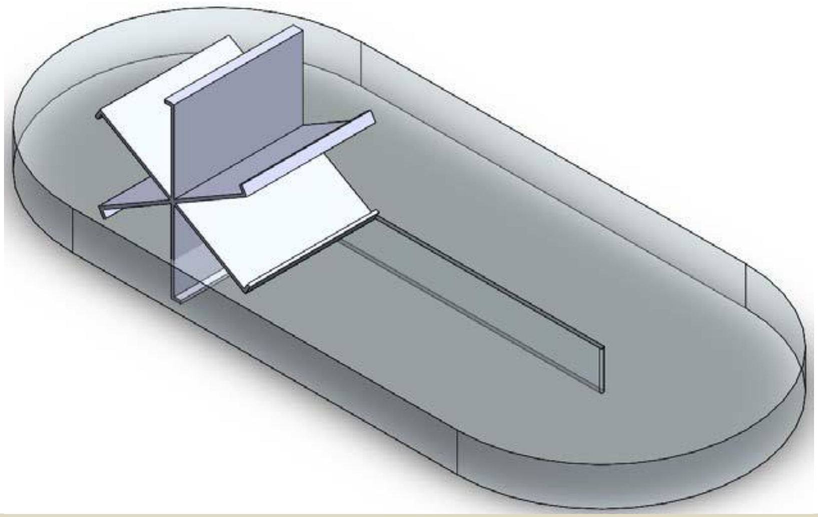
High Rate Algae Pond (HRAP) Integration and Process Optimization

- Evaluation of the design (mixing, dead zones, shear stress, …),
- Effects on the performance when scaling up,
- Evaluation of the operation (position of the paddlewheel, rotational speed, …)



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Hydrodynamic stress capacity of Micro-algae

Hydrodynamic stress:

- High pressure gradient,
- Shear stress.

Bronnenmeier & M. Markl (1981) ; Gudin & Chaumont (1991)

Micro-algae:

- *Dunaliella salina,*
- *Spirulina Platensis,*
- *Tetraselmis Suecica,*
- *Chlorella sp.*

Micro-algae	Parameter	Value	Reference
Dunaliella Salina	σ_{crit}	**18 +- 3 Pa**	[Kokkinos et al. (2016)]
	Gas entrance velocity (max)	30 m/s	[Barbosa et al. (2003)]
	Shear stress (ok)	0.05 Pa	[Hejazi et al. (2003)]
Arthrospira Platensis	Pressure vessel (max)	2 bar	[Bronnenmeier and Markl (1981)]
	Stirring velocity (max)	900 rpm	[Bronnenmeier and Markl (1981)]
	Shear stress (max)	**0.3 Pa**	[Mitsuhashi et al. (1995)]
	Shear stress (max)	0.5 Pa	[Bronnenmeier and Markl (1981)] [Bowen (1986)] [Sanchez Perez (2006)]
Tetraselmis Suecica	Shear stress (max)	**80 Pa**	[Michels et al. (2016)]
		Very sensitive	[Jaouen et al. (1999)]
Chlorella vulgaris	Pressure vessel (max)	100 bar	[Bronnenmeier and Markl (1981)]
	Stirring velocity (ok)	3000 rpm	[Bronnenmeier and Markl (1981)]
	Shear stress (ok)	1.7 Pa	[Bronnenmeier and Markl (1981)] [Bowen (1986)] [Sanchez Perez (2006)]
	Shear stress (ok)	2 Pa	[Leupold et al. (2012)]
	Nozzle pressure (max)	**100 bar**	[Joshi et al. (1996)]

Results:

- Shear stress affects micro-algae depending on:
  - Cell morphology (size, shape, presence of cell wall, etc.)
  - Physiological conditions
- *Arthrospira Platensis* seems to be shear sensitive but it can recover after being shred
- *Chlorella vulgaris* is the most shear-resistant (round shape & cell wall)
- *Dunaliella Salina* shear-sensitive (no rigid cell wall & two flagella)

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Numerical Methods

Large Eddy Simulation:

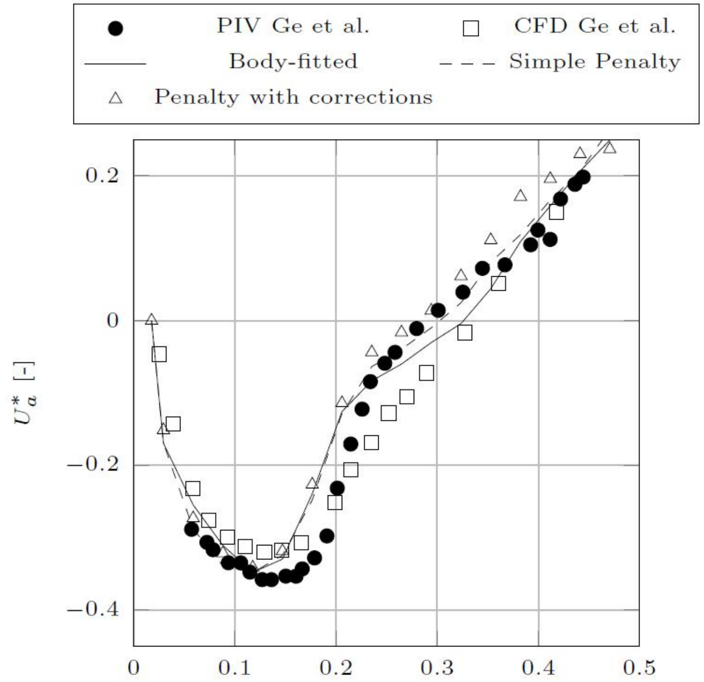
- Implicit frequency low pass filter (≡convolution with a top-hat filter),
- PIMPLE solver of OpenFOAM™ for the Navier-Stokes equations,
- Smagorinsky model for the small-scale turbulence.

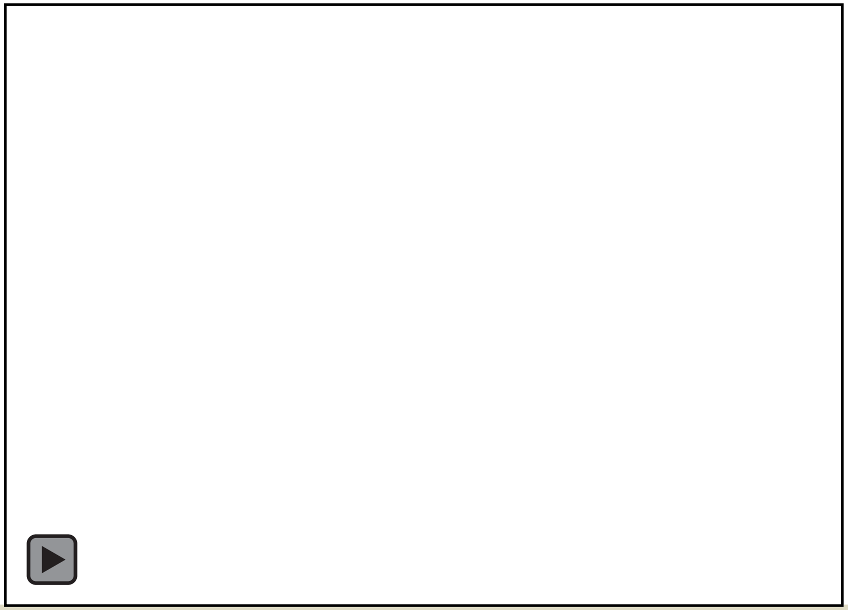
Multiphase Particle-In-Cell (MPPIC):

- Ref: **Andrews, M. J. & O'Rourke, P. J. (1996)**,
- Parcels of particles with same position, size and velocity,
- Lagrangian tracking equations accounting for collision and exchange of particles between parcels (**O'Rourke, P. J. (2009)**).

Immersed Boundary Method:

- Second Order Penalization of Velocity and Pressure
- Ref: **Specklin & Delauré, computers & Fluids, under revision (2017)**





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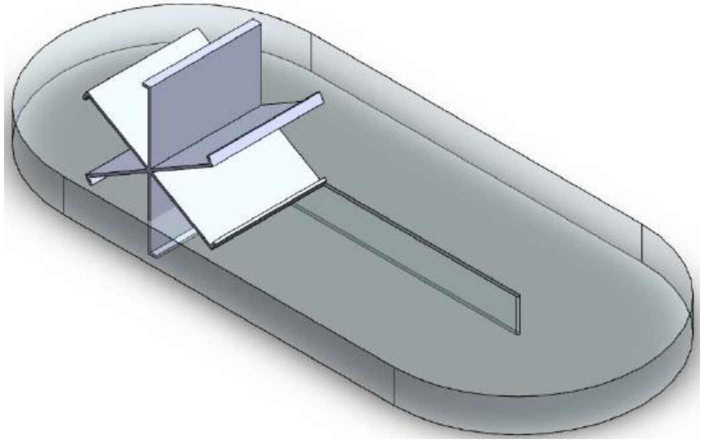
Evaluation of the performance of different sizes of HRAP: Scale-up

Small scale experiment and scaling-up:



- Small HRAP (0.91 m^3, $L/W=5$)
- Medium HRAP (1.19 m^3, $L/W=6$)
- Long HRAP (4.55 m^3, $L/W=22$)

L=length ; W=Width; Depth=20cm.

Case	Number of Mesh Cells	Min/max cell size	Number of processors	Time step (in sec) interval	Computation time for a 5 s simulation
Long HRAP	6.3 10^6	1.86 mm - 1.2 cm	48	2.5e-3 to 5e-3	29h56min
Medium HRAP	2.3 10^6	1.62 mm - 1.2 cm	24	2.5e-3 to 5e-3	39h50min
Small HRAP	1.8 10^6	1.62mm - 1.2 cm	24	2.5e-3 to 5e-3	20h37min

Evaluation of the performance:

- Dead zones,
- Shear stress,
- Mixing efficiency.

Evaluation of the performance of different sizes of HRAP: Scale-up

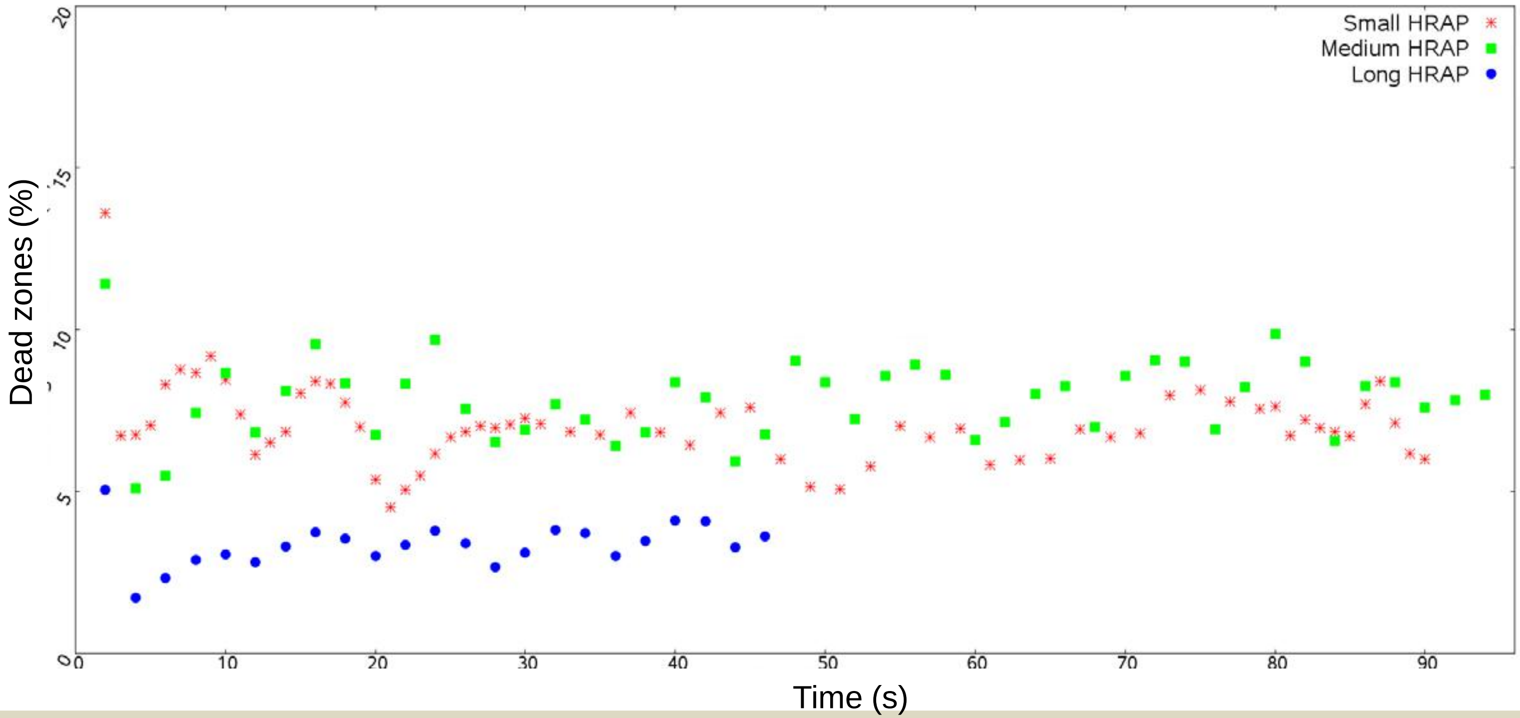
Evaluation of dead zones:

- Percentage of dead zones (DZ%) definition (Hadiyanto et al. 2013):

$$\% \, Dead \, Zones = \frac{V_{v<0.1}}{V_{pond}} . 100$$

- The DZ% oscillates around an average value after 10 seconds
- The values for the small pond are more dispersed,
- The percentage of dead zones is smaller in the long pond.

DZ% VS time



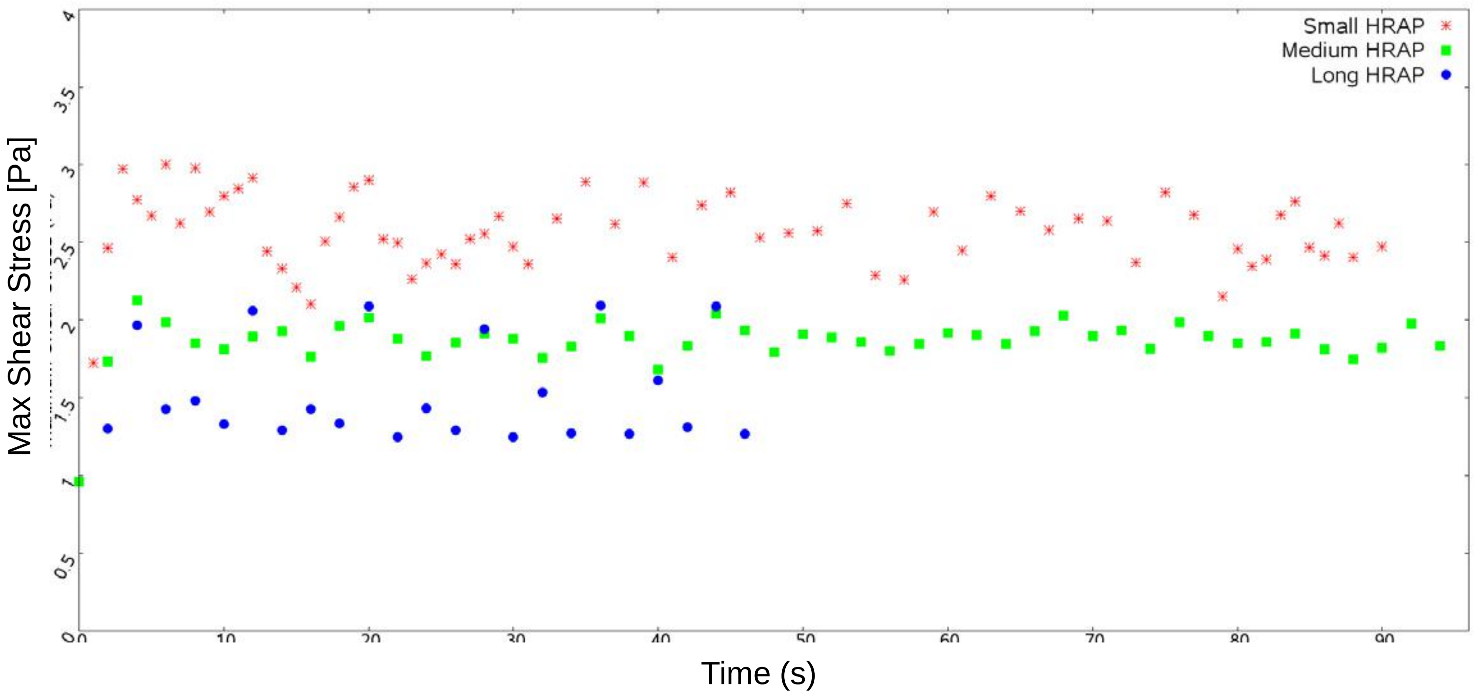
Evaluation of the performance of different sizes of HRAP: Scale-up

Evaluation of the shear stress:

- Shear stress capacity of micro-algae is **strain-dependant.**
- Maximum shear stress < 3 Pa
- Suitable for *Dunaliella S.* & *Spirulina Platensis*

- Higher shear stresses in the small pond,
- Higher value of the maximum shear stress every 8 seconds in the Long pond (= rotational speed of the paddle-wheel)

Max Shear stress VS time

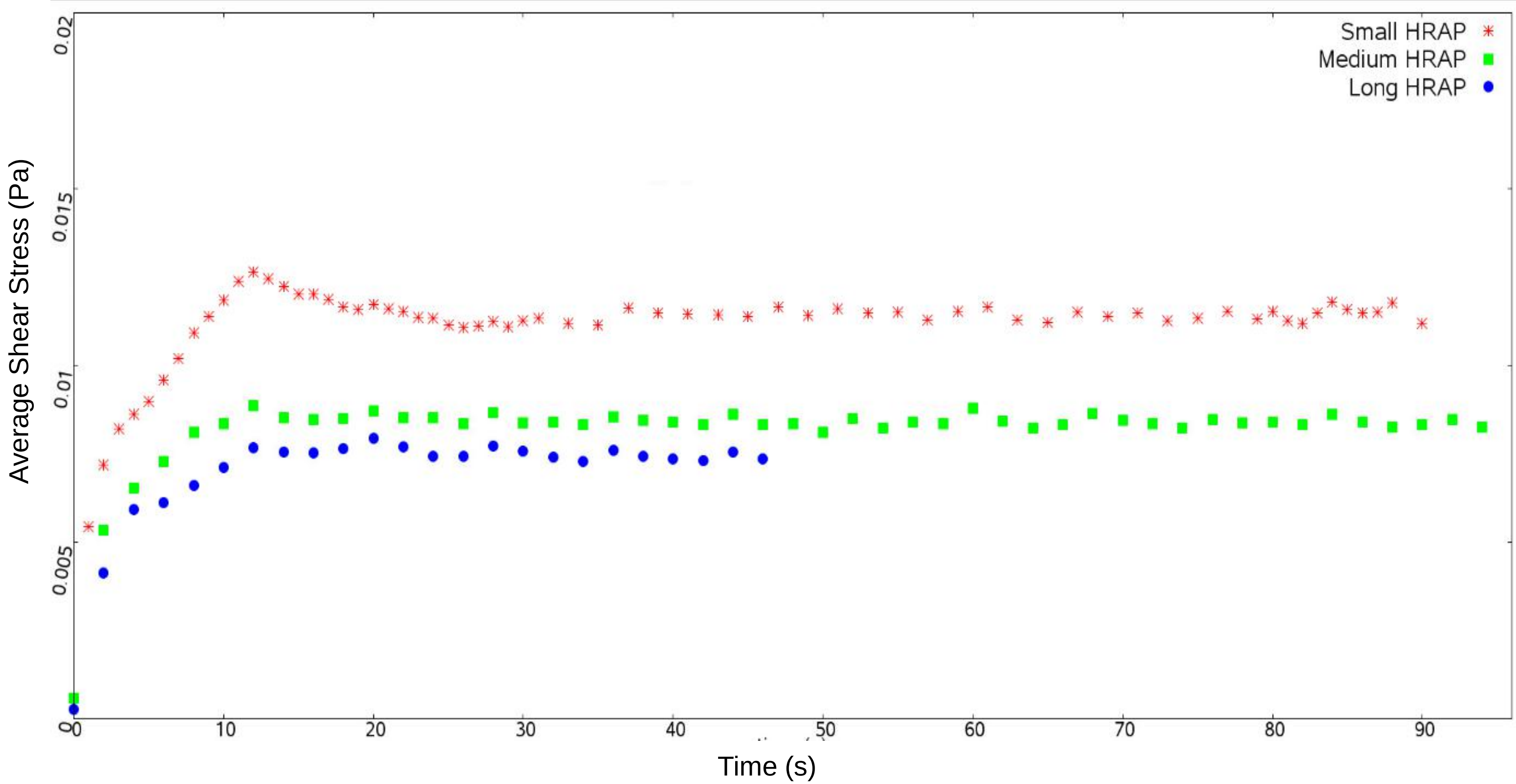


Evaluation of the performance of different sizes of HRAP: Scale-up

Evaluation of the shear stress:

The average shear stress converges to values two orders of magnitude smaller than the maximum shear stress

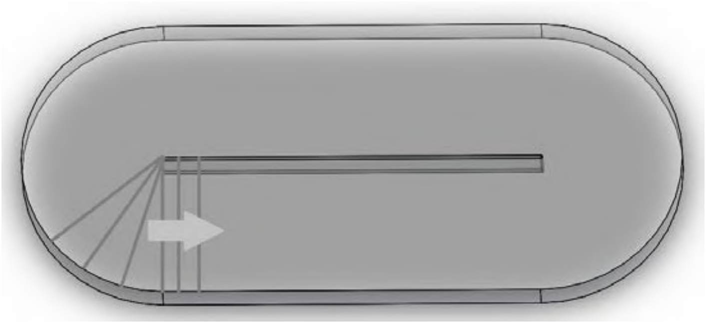
Average Shear stress (Pa) VS time (s)



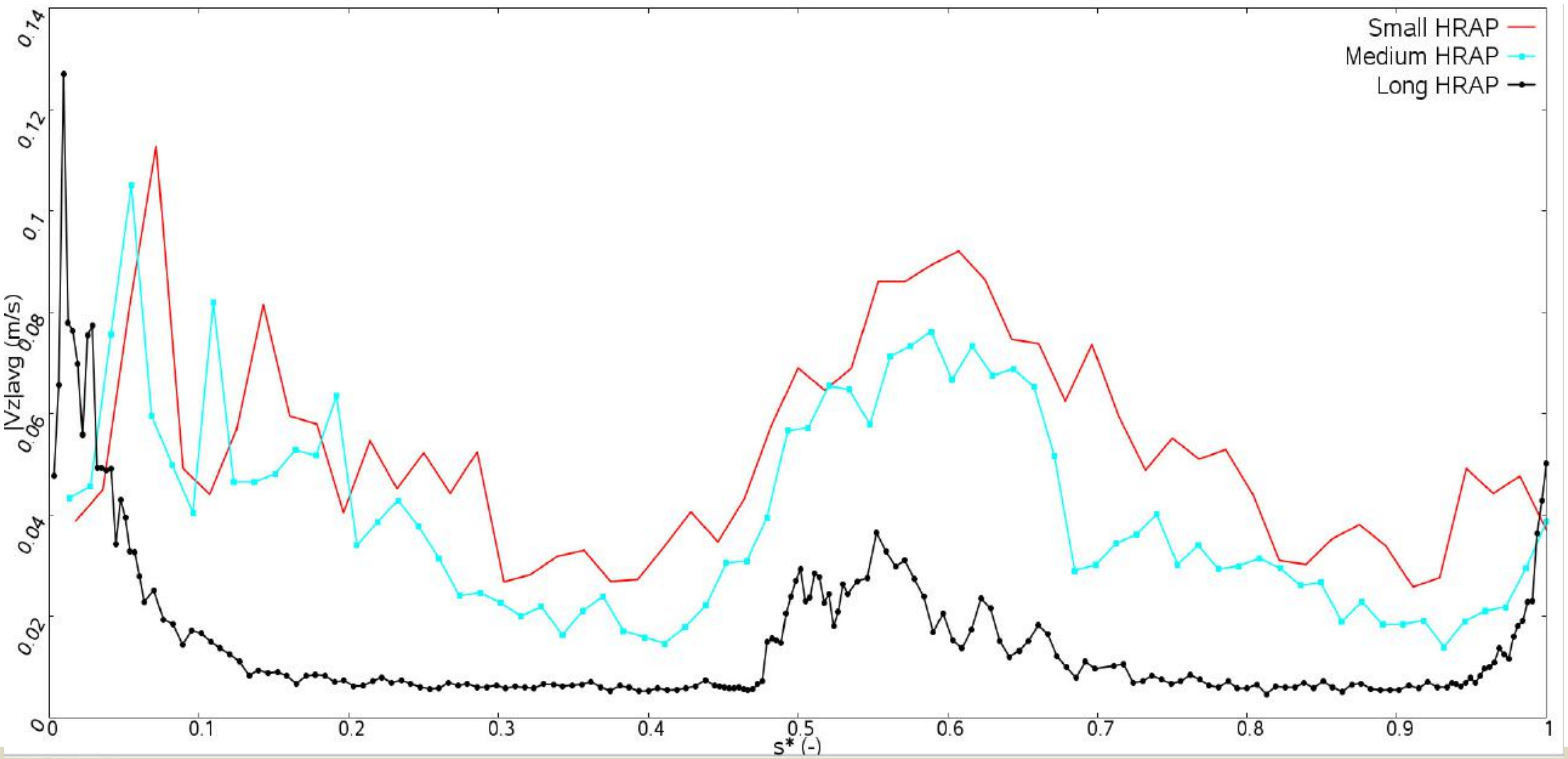
Evaluation of the performance of different sizes of HRAP: Scale-up

Evaluation of the Mixing:

- Mixing occurs mostly on the bends & in the neighbourhood of the paddlewheel



Average absolute vertical velocity (m/s) VS s* (-)



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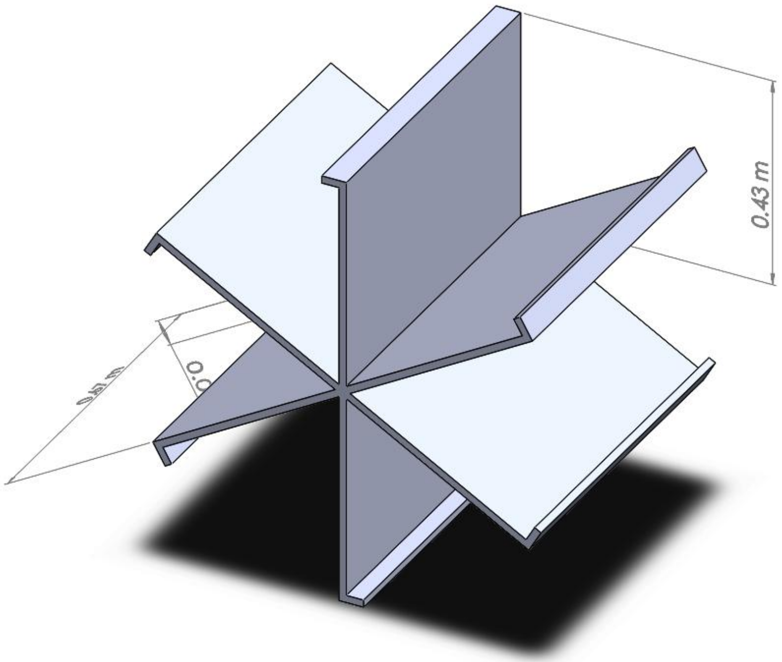
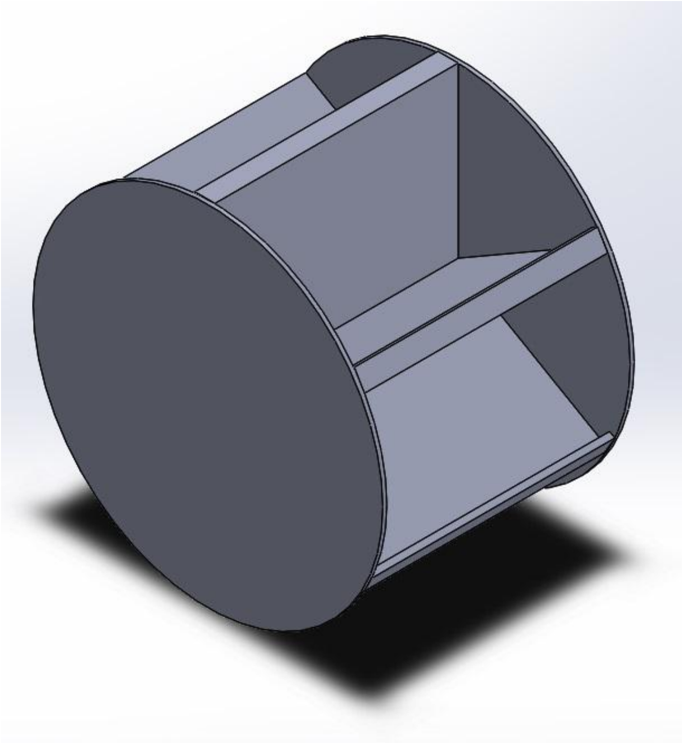
Comparison of the performance of two paddlewheel designs

Evaluation of the paddlewheel designs:

- Two types of paddlewheel to test:
  - Mixing performance,
  - Shear Stress.

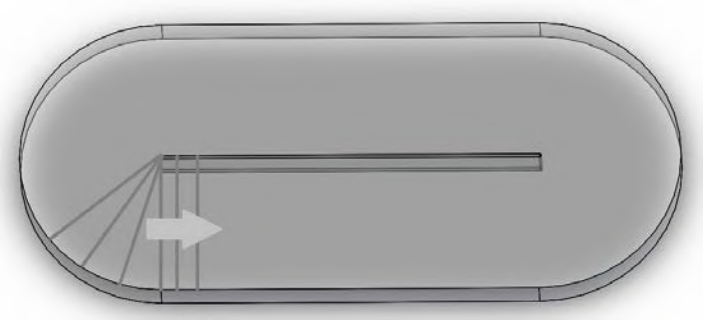




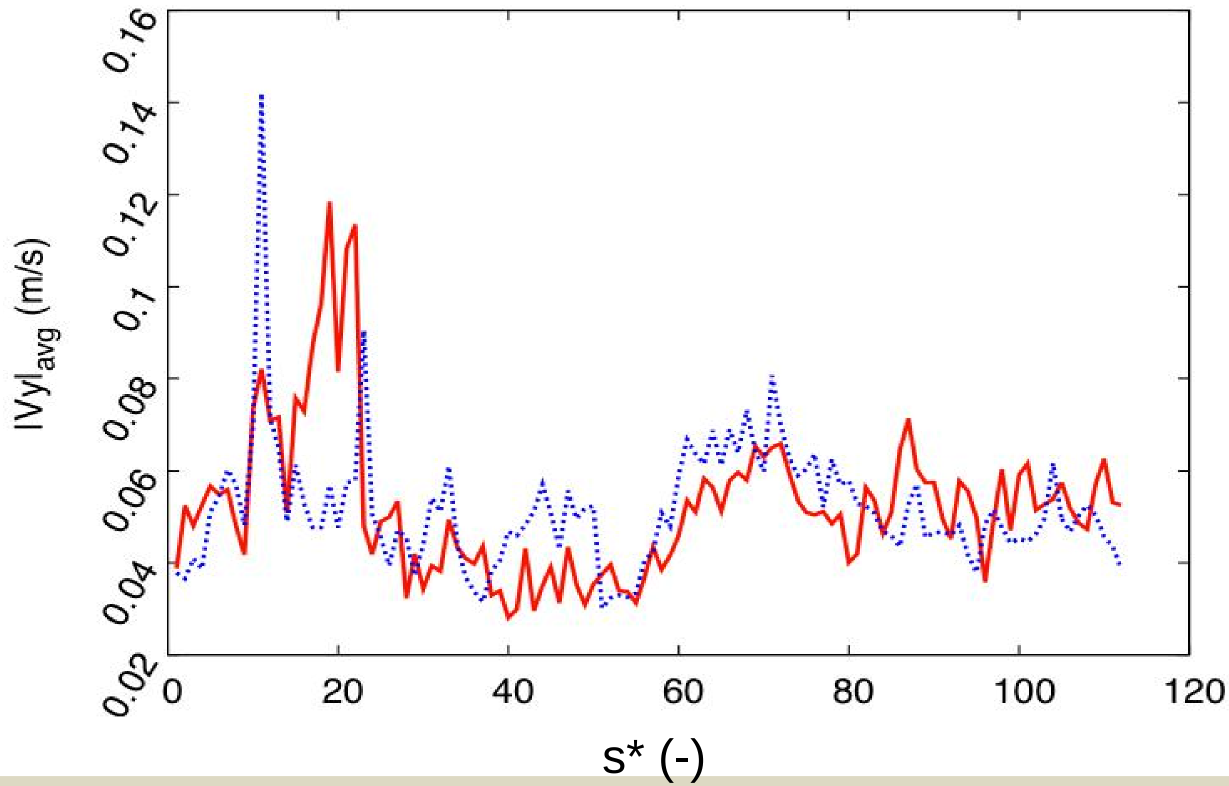
Comparison of the performance of two paddlewheel designs

Evaluation of Mixing:

- No difference of average vertical velocity between the two PW designs



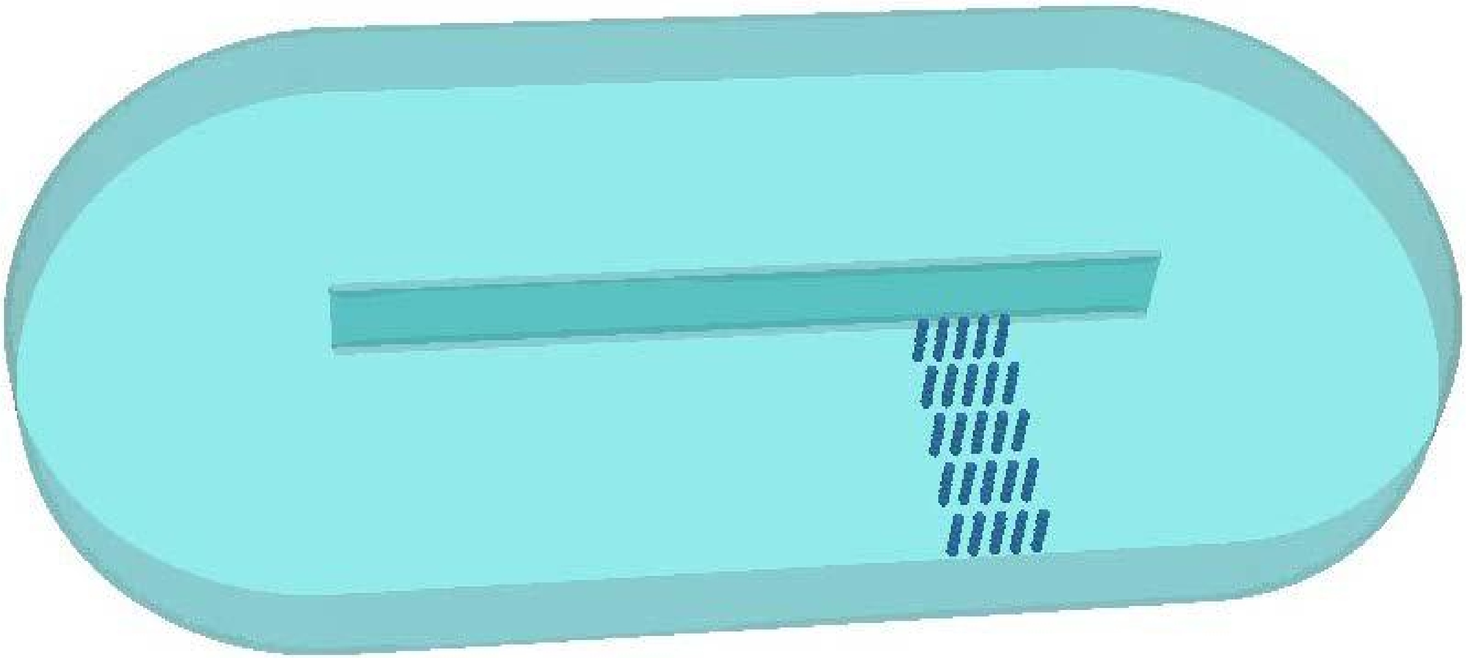
Average absolute vertical velocity VS curvilinear coordinates ‘s*’



Comparison of the performance of two paddlewheel designs

Particle tracking:

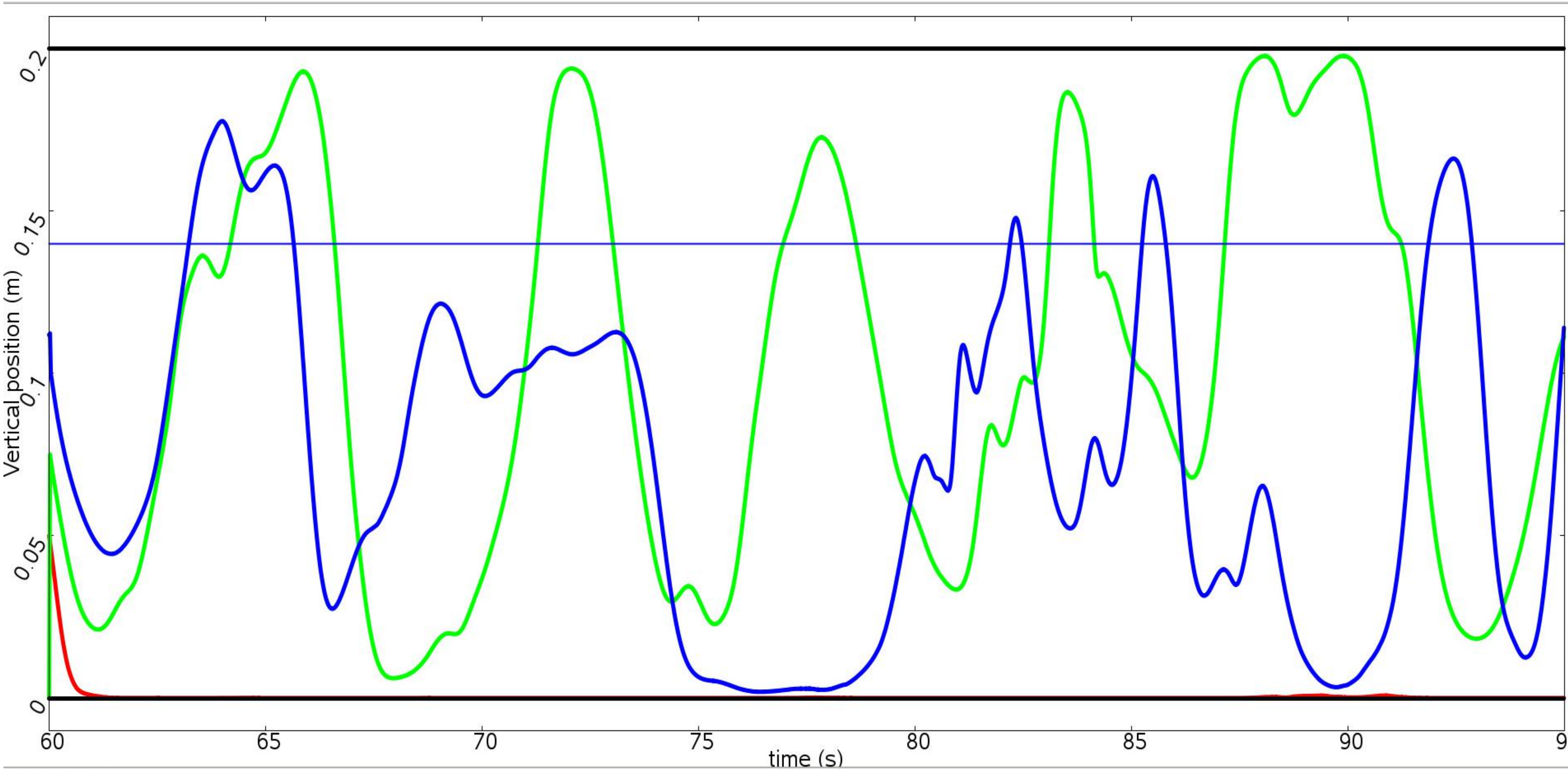
- Particle tracers injected to estimate the micro-algae trajectories
- Dark/light cycle estimation



Comparison of the performance of two paddlewheel designs

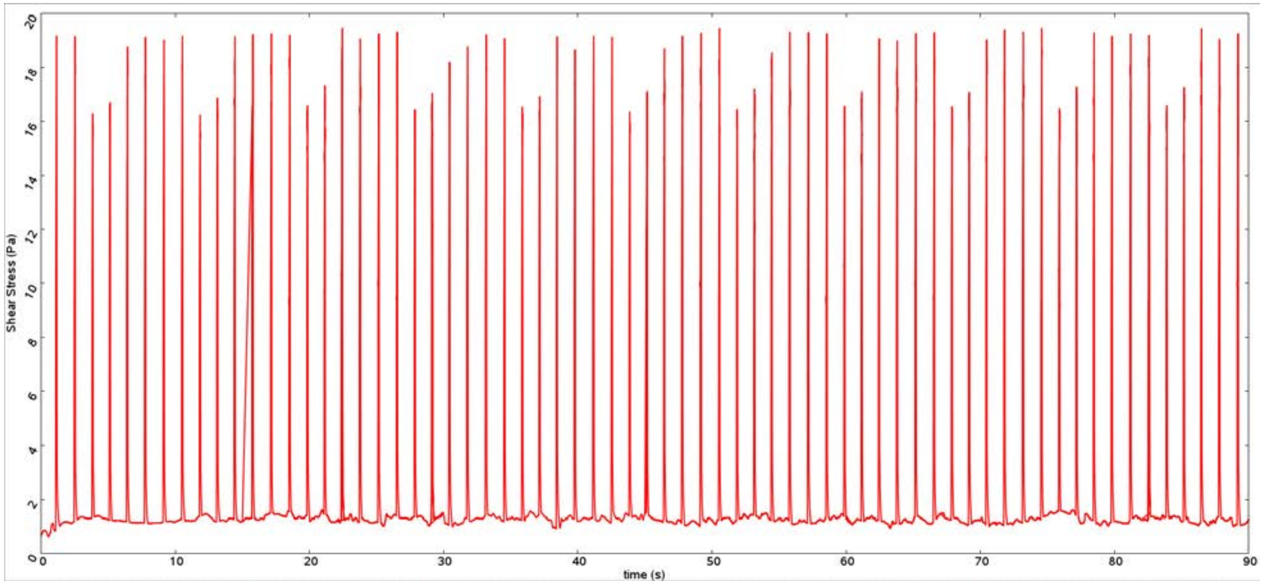
Dark and light cycles:

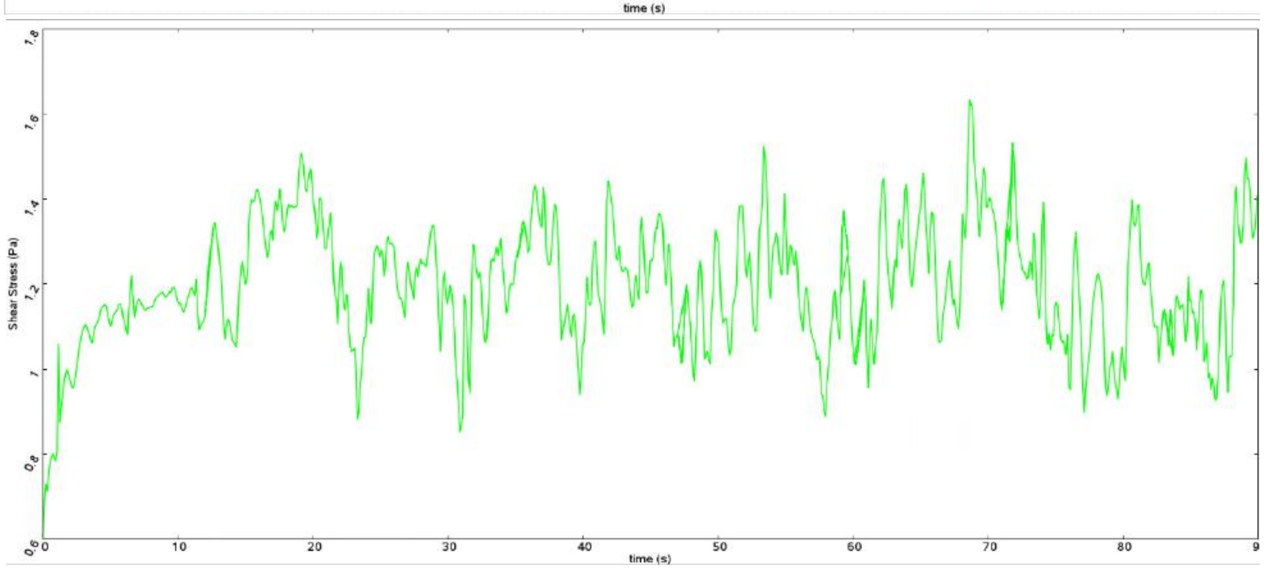
- Dark and Light cycles
- Arbitrary threshold -> Experimental data to fix the threshold.



Comparison of the performance of two paddlewheel designs

Maximum Shear stress:





- The maximum shear stress with the new design is much stable.

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Conclusion and perspectives

Conclusions:

- Shear stress sensitivity is strain-dependent,
- Here, the shear stress is not high enough to affect *Dunaliella S.* or *Spirulina Platensis*.
- Scaling up by lengthening the pond (same paddle-wheel + pond width) would maintain a low percentage of dead zones,
- The vertical mixing outside the neighbourhood of the paddle-wheel however has been shown to reduce as the length to width ratio is increased. This suggest that the design is suitable only if the mixing near the paddle-wheel proves sufficient to break any form of vertical stratification and ensure that all microalgae will be given the opportunity to spend meaningful period of time with optimal exposure to light and nutrients.
- According to the present results, the mixing performance is not affected by the geometry of the paddlewheel

Perspectives:

- Compute the energy provided to move the paddlewheel,
- Compare the mixing performance for different positions of the paddlewheel in a 5 m3 pond

Thanks for listening!

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