KNOWLEDGE IN ALGAL CULTIVATION TECHNOLOGY

2 PONDS OPTIMISATION

2.1.1 Modelling

One approach to test new designs is building a range of prototypes while second technique is more theoretical computational fluid dynamics (CFD). CFD can model and solve the equations of fluid flows and enables engineers to develop several flow designs to resolve the most favourable RAP characteristics without having to build and test all the concepts. Accuracy of CFD models depends heavily on the computation time; point mesh density and various simplifications used.

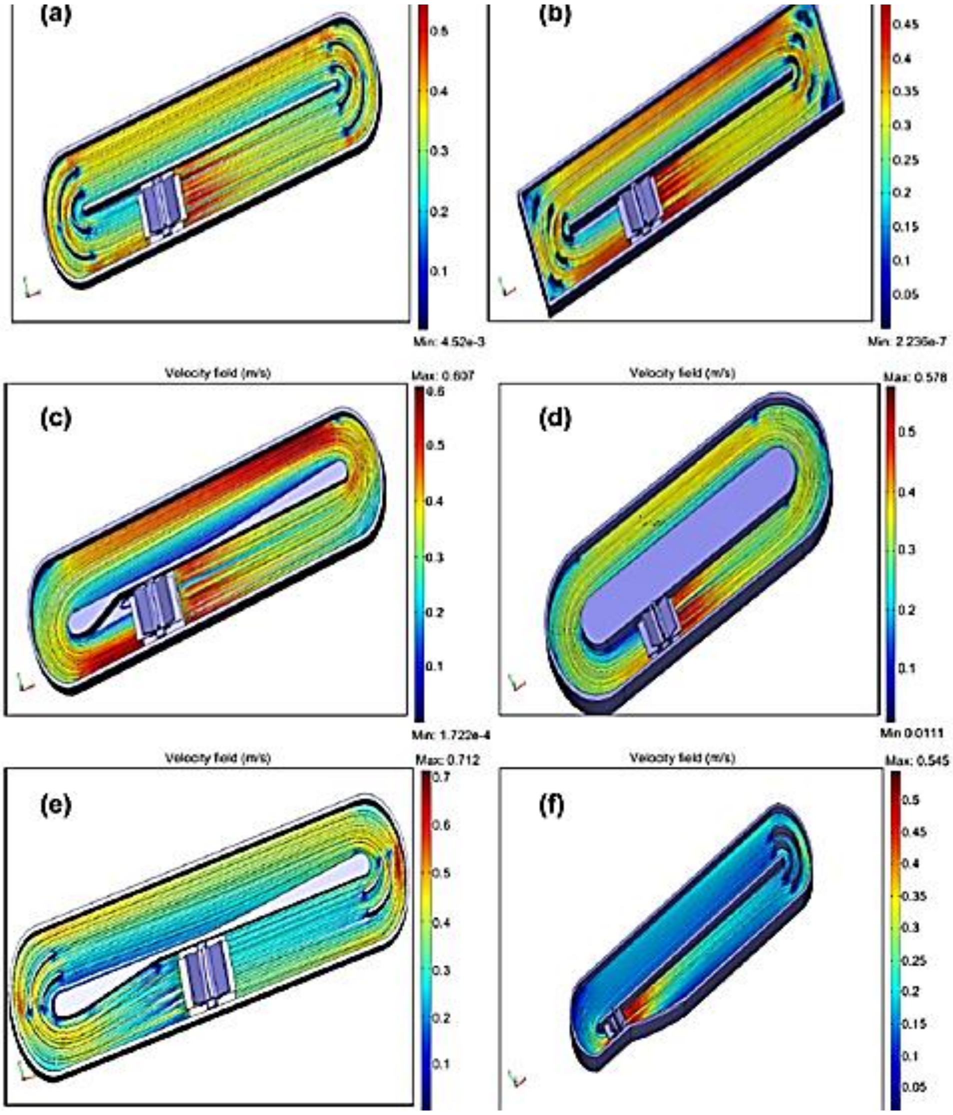


Figure 1: Some of the possibilities of raceway ponds to reduce the dead zones volume. Flow speeds at the surface of clockwise flow in all geometries, in which red is high velocity and blue is low velocity (Hadiyanto et. al., 2013)

CFD is nevertheless not the absolute approach for facing fluid flow problems due to computer hardware limitations, where even a trivial input error in model can lead to weeks of computations

(Hadiyanto et. al., 2013). CFD is a practical approach that works well when engineers use it together with physical and mathematical analytical approaches while at the end still building prototype models (Jupsin et al., 2003).

From a fluid dynamics point of view in RAP, most of the energy loss and stagnation area development is due to the fluid moving around a turn. This happens because the curve applies a force on the flowing water to change its direction (Figure 1). It is less obvious how to decrease an energy loss or drop in a pressure around the curve. To resolve a most favourable design for a small energy use and smooth flow, the results from CFD suggest that pressure increases in turning points. The CFD goal is to identify and remove regions where parts of the flow become separated from the main flow, it is usually desirable to avoid a great pressure drops as this indicates a significant energy loss.

Modularity in one of the key factors for lowering the construction cost. Lightweight aggregate concrete can be produced using a variety of lightweight aggregates. At production plant styrofoam was used as lightweight aggregate. This way blocks weight was designed so that block could be easily moved either by one or two persons. To perform such an approach terrain preparation is important step, especially if pond depth varies. After all ground levelling is done, two workers can do the work in a matter of hours without machinery. Each time block is placed in exact position joints are made only with gun spray filled with polyurethane foam (Figure 10). After blocks were placed, a prefabricated foil was placed on site to perfectly suit the pond geometry (Figure).

Figure 10: Modularity in one of the key factors for lowering the construction cost (source Algen)

Figure 11: Placing prefabricated foil made on concrete blocks - where no welding on site is needed (source Algen)

Pond design was developed using parameterized technology; a number of parameters govern the pond geometry and all production documentation is produced automatically: this is true for the basic mould production, tailoring and cutting of the foil, paddlewheel production and similar.

For the basic pond geometry we have selected a designed that bring in experience in CFD modelling (although the pond itself has not been CFD modelled – yet). Raceway pond does not have a single middle wall, but rather a guided turns with a diameter, where in addition ground level is lower for 10 cm than in other places of pond to keep the cross-section constant (Figure 12). In addition, flow deflectors are placed in both ends of a pond.

Figure 12: Computational fluid dynamics was taken in into consideration by lowering the ground level on both ends, making radial turns and placing flow deflectors (image source Algen)

Geometry of a paddlewheel was carefully designed so that power consumption per paddlewheel is below 180W for 500m^2 pond (actual power depends on the flow velocity and pond depth).

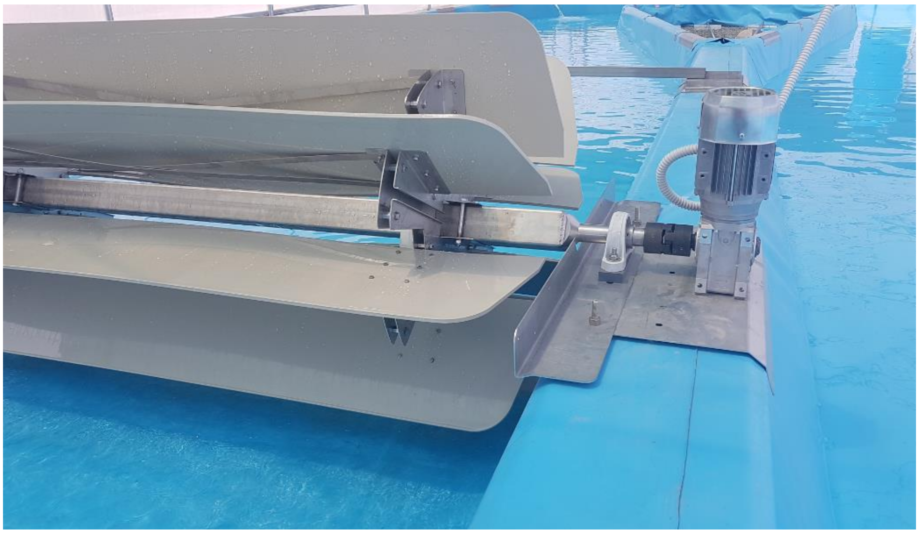


Figure 13: Computational fluid dynamics was taken in into consideration by lowering the ground level on both ends, making radial turns and placing flow deflectors (image source Algen)

In the process of pond design we have built a small pond that consists only of round sections of the normal raceway pond. This pond was used for validation purposes and will be used as an inoculation pond. An alternative mixing was installed with three decentralised vertical mixers. It was shown that performance is good only if the water level was greater than 25cm (Figure14).

Figure 14: Testing decentralised mixing performance

Existing pond design still requires too much labour cost for placement of pre-fabricated modules (500m^2 pond requires more than two person days). Even greater issue is positioning the foil (either prefabricated or welded on site). Adjustments to foil position is difficult job for a number of people at the same time. It has turned out that the thermal expansion of the foil is a serious problem (aggravated by the greenhouse temperatures), so we are switching the foil material for the next ponds.
For the next pond a test will be made using Expanded polystyrene blocks cut to size and an alternative pond lining using polyurea spraying will be used (Figure 15).

Figure 15: Model pond made from modular EPS coated with polyurea (image source Algen)

3 RAP NUMERICAL/MATHEMATICAL MODELLING

Numerical modelling has been used to better understand and optimize the design of the RAP to be used in the demo plants. The use of modelling allows the evaluation of different designs (or operating conditions) without the need to construct costly physical prototypes. This has been used to investigate the fluid dynamics and mixing in the pond and the effect of the paddle wheel (which has been explicitly modelled using the Immersed Boundary Method). Parameters used for the design optimization have included the evaluation of dead zones and the effect of shear stress and vertical mixing of algae.

3.1 Numerical simulation of the particulate flow in a RAP

Raceway Algae Ponds (RAP) are the most common ways to grow micro-algae at large scale. In the present study, different sizes and shapes of RAP are evaluated by performing numerical simulations of fluid flow in different ponds with different shape ratios L/W, where L is the pond length and W its width. The purpose of those tests is to provide a numerical characterisation of the flow behaviour in terms of mixing. Since a new RAP is to be constructed in the facilities of one of the SaltGae project partners, Arava Building, the original design, presented in Figure and two alternative configurations are simulated to assess the effects of scaling-up.

The simulations are performed using OpenFOAM™. The LES approach (with a Smagorinsky model) is chosen to account for the unsteady turbulent flow. With an appropriate grid size, it allows for better resolution of turbulent mixing and improved hydrodynamic modelling. However, the high number of cells required to achieve accurate mixing predictions, increases significantly the computational cost of simulations. For instance, the longest numerical simulation presented in Section 3.4 took four months to compute 100 seconds of simulations with particle tracking on 48 processors with a 6.4×10^6 mesh cells. This period of flow time was necessary to reach steady state with a transient solver and then capture one full circulation of injected particles. Note that the fastest particles take more than 100 seconds to travel around the pond. There are other faster methods, like RANS and URANS methods, to account for turbulence, but they are unable to fully capture the unsteady nature of the flow. One of the main goals of this deliverable is to evaluate the mixing system. To do so, the immersed boundary method is used to account for the paddle-wheel and fluid flow interaction. The approach ensures that the movement of the fluid induced by the rotation of the paddle-wheel is correctly accounted for. To predict the movement of the micro-algae in the pond, particle-tracers are injected at the neighbourhood of the paddle-wheel. The tracking of such particles is performed by the Multiphase Particle-In-Cell method (MPPIC) developed by (Andrews, M. J. and O'Rourke, P. J.,1996).
In Section 3.3, different sizes of RAP (0.91 m^3, 1.19 m^3, and 4.55 m^3) and shapes ($\frac{L}{W} = 5, 6$, and 22) are considered. The results of this first study contributed to the design of a larger RAP (4.59 m^3, $\frac{L}{W} = 12$) which is currently being constructed in the Arava Building site. The mixing is evaluated in section 3.4 by computing the particle vertical path.

3.2 Numerical methods

This section presents the numerical methods used to perform the simulation of the fluid-particulate flow in the RAP with the design presented in Fig. 16. The Large Eddy Simulation method has been chosen to account for the turbulent flow. The particle movement and interaction with the fluid flow has been taken into consideration using the Multiphase Particle-In-Cell (MPPIC) method developed by (O'Rourke, P. J., 2009). Finally, the interaction between the solid paddle-wheel and the fluid-particulate flow has been solved by an immersed boundary method.

3.2.1 *Large Eddy Simulation*

Preliminary numerical simulations of the flow generated by the movement of the paddle-wheel show that it is inherently three-dimensional and unsteady. Therefore, the Large Eddy Simulation (LES) approach has been used to model the turbulent flow in the RAP. This method resolves the large scales of turbulence whereas the smaller scales are modelled using a subgrid model. The threshold between the two scales is defined through a frequency low pass filter. When solving the governing equations with a finite-volume type discretization, the integration of the solution over control volumes is equivalent to a convolution with a top-hat filter (Zhiyin, Y., 2015). This filtering method is named implicit filter and will be used in the present simulations. The smaller scales are therefore those smaller than the grid size.

The incompressible form of the Navier-stokes equations are solved using an iterative segregated type pressure velocity coupling assuming Newtonian fluids (PIMPLE solver of OpenFOAM™). The algorithm solves the pressure equation with successive velocity correction at step each time step (OpenFOAM, 2016). Four such corrections have been used in the current computations. A GAMG (Geometric Agglomerated algebraic Multi-Grid) solver with a Gauss-Seidel smoothing is used to solve the velocity and the pressure systems.

The Smagorinsky model accounts for the small-scale turbulence and is set with the following default coefficients:

$$C_e = 1.048$$
$$C_k = 0.094$$

3.2.2 *Multiphase Particle-In-Cell Method*

The Multiphase Particle-In-Cell Method (MPPIC) accounts for the movement of the particles in the fluid and their interaction. The method was originally developed by (Andrews, M. J. and O'Rourke, P. J., 1996) to simulate a large variety of particulate flows, from dense to dilute. The method predicts the movement of a large amount of particles by defining groups of particles called "Parcels" or macro-particles. Each parcel contains a pre-defined amount of particles defined in terms of their initial position, size and velocity. These parcel properties are updated at each time step solving Lagrangian tracking equations accounting for collision and exchange of particles between parcels (O'Rourke, P. J., 2009).

3.2.3 *Immersed Boundary Method*

The interaction between the solid and the fluid is modeled by the Immersed boundary method (IBM) developed in (Specklin, M., 2016). It accounts for the movement of the paddle-wheel and the induced movement of the fluid.

3.3 Evaluation of the performance of different sizes of RAP: Scale-up.

Simulation results for three different sizes of RAP are presented in this section. The purpose is to provide useful information on the fluid flow with a view to determining the most effective hydrodynamic conditions in a commercial scale RAP. The mixing efficiency, the shear stress and the dead zones were evaluated for the following three configurations:

- Small RAP (0.91 m^3, $\frac{L}{W}$ =5): 3.5m long, 1.4m wide and 0.2m deep [Figure],
- Medium RAP (1.19 m^3, $\frac{L}{W}$ =6): 4.5m long, 1.4m wide and 0.2m deep,
- Long RAP (4.55 m^3, $\frac{L}{W}$ =22): 16.5m long, 1.5m wide and 0.2m deep.

The geometry of the small RAP was designed by the partner *Arava Building*. A paddle wheel (represented in Figure 16) at 7.5 rpm generates the fluid circulation and mixing in the whole system. The simulation parameters (Number of mesh cells, time step, spacing, computaion time, etc.) are summarised in the table below.

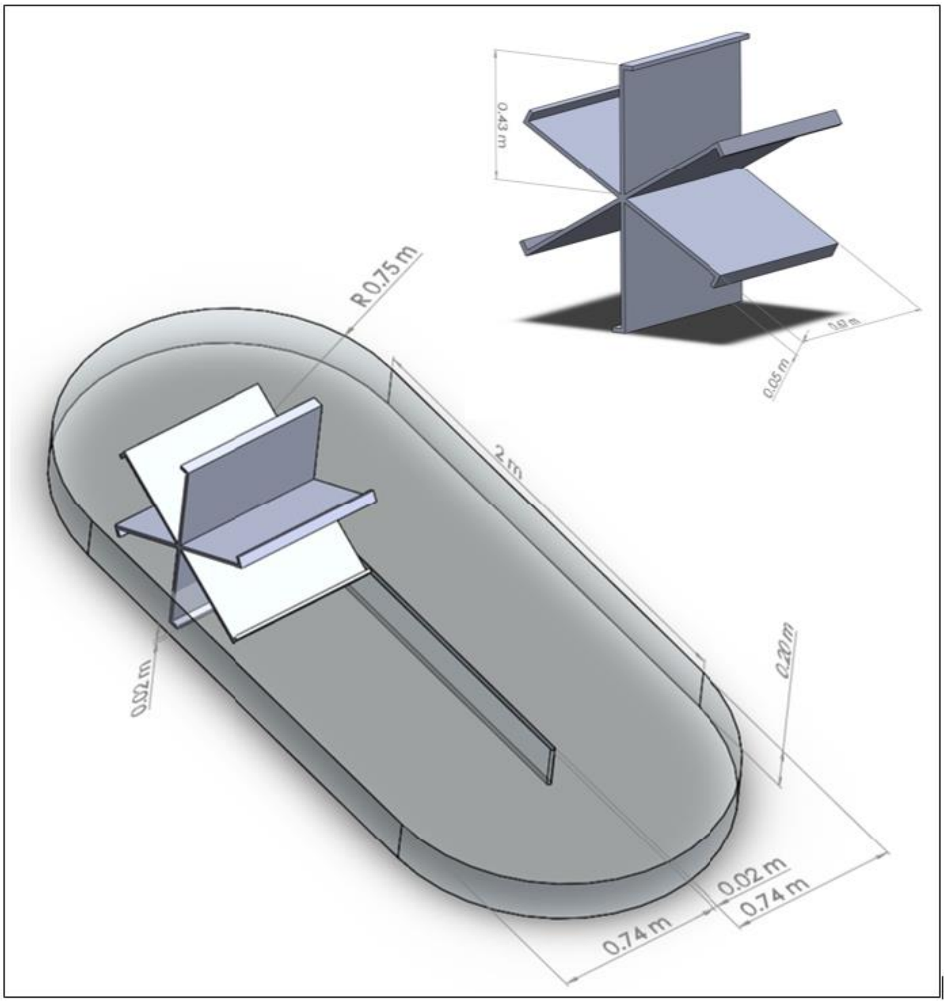


Figure 16: Raceway Algae Pond Designed by Arava Building

Case	Number of Mesh Cells	Min/max cell size	Decomposition type	Number of processors	Time step (in sec) interval	Computation time for a 5 s simulation
Long RAP	6273226	1.86 mm - 1.2 cm	Scotch	48	2.5e-3 to 5e-3	29h56min
Medium RAP	2339615	1.62 mm – 1.2 cm	Scotch	24	2.5e-3 to 5e-3	39h50min
Small RAP	1847075	1.62mm – 1.2 cm	Scotch	24	2.5e-3 to 5e-3	20h37min
RAP Section 3.4	6352624	1.62mm – 1.4 cm	Scotch	48	1e-3 to 5e-3	42h

Table 1: Characteristics of the numerical simulations

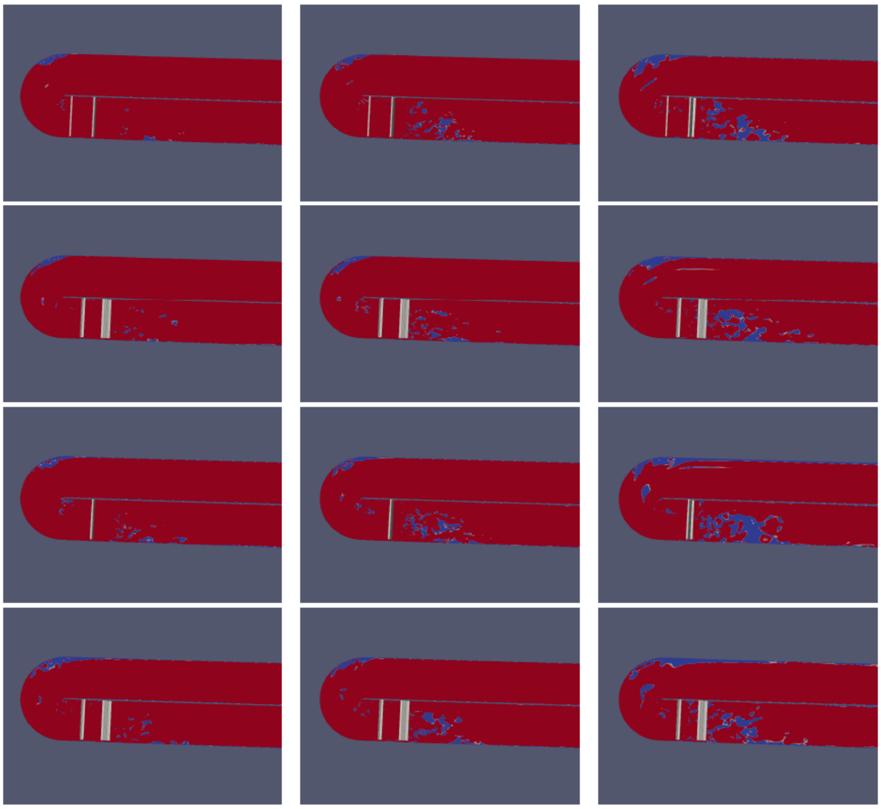
3.3.1 Evaluation of Dead Zones

Micro-algae need a suitable amount of light to fully develop and grow. They cannot survive without light but a too long exposure can also cause damage. Therefore, it is essential to avoid “Dead zones” in the pond, where the micro-algae can be trapped, either in a light or dark zone.

The dead zones is defined here as region of flow where the magnitude of the fluid velocity is smaller than 0.1 m/s (Hadiyanto, H., 2013).

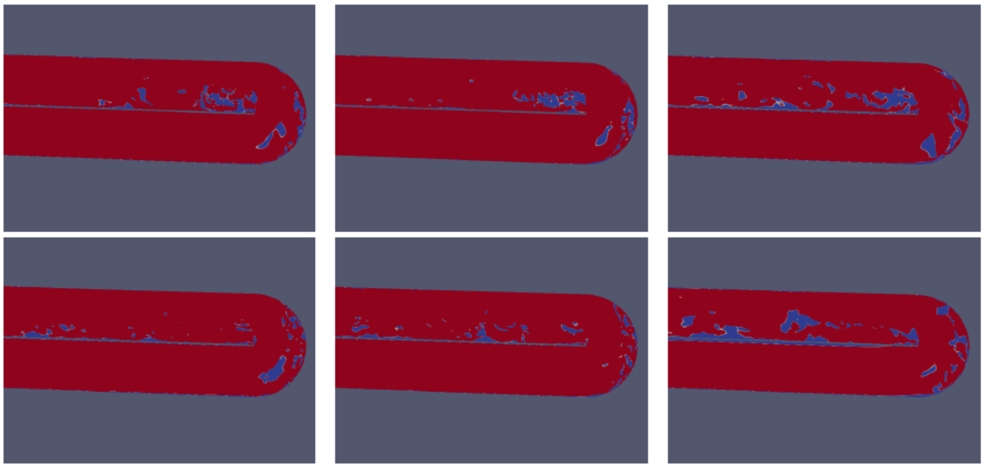
Figure 17 and Figure 18 present the dead zones and their evolution through a one cycle (revolution around the RAP) (blue zones) which are shown to be primarily located at the first bend of the long pond (with the paddle-wheel) and at the second bend. The contour plots provides show that the shapes of the dead zones evolve with time and depth. Figure highlights that the dead zones are mostly located at the upper left corner of the bend and at the right hand side of the paddle-wheel. The former dead zones are generated by the presence of eddies created by the movement of the paddel-wheel. It is unlikely that a particle will remain trapped there because the highly transient nature of these localised flow features. This is partially confirmed by Figure that presents the time-evolution of the velocity streamlines in the neighbourhood of the paddle and at the centre of the channel. The figure shows that there is a good vertical mixing near the paddle-wheel, with evidence that the streamlines move vertically up and down. The streamlines outside the neighbourhood of the paddle-wheel are initially parallel to the bottom wall. But over time, the vertical mixing is enhanced and spreads along the horizontal direction. The last image of Figure present the velocity streamlines in the middle of the pond, after the paddle-wheel. It shows that the streamlines are parallel to the bottom and that the vertical mixing is scarce.

To fully confirm the assumption that the dead zones near the paddle-wheel do not trap the particles, numerical simulations of the fluid flow with particle-tracers, initially at the right hand side of the paddle-wheel, were performed. Figure shows that dead zones are also located at the right bend and behind the central wall in the upper channel. The paterns of the dead zones in Figure also evolve with time. By injecting and tracking particle-tracers, one can predict if a particle can be trapped in those zones.



y=-0.1 y=-0.15 y=-0.2

Figure 17: Dead zones at the left bend of the Long RAP for three slides normal to the vertical direction; at the middle of the pond (y=-0.1m), at y=-0.15m and near the bottom (y=-0.2m); and at different times (from top to bottom) = 20s, 30s, 40s and 46s



y=-0.1 y=-0.15 y=-0.2

Figure 18: Dead zones at the right bend of the long RAP at the middle of the pond (y=-0.1m), at y=-0.15m and near the bottom (y=-0.2m); and at different times (from top to bottom) = 30s and 40s

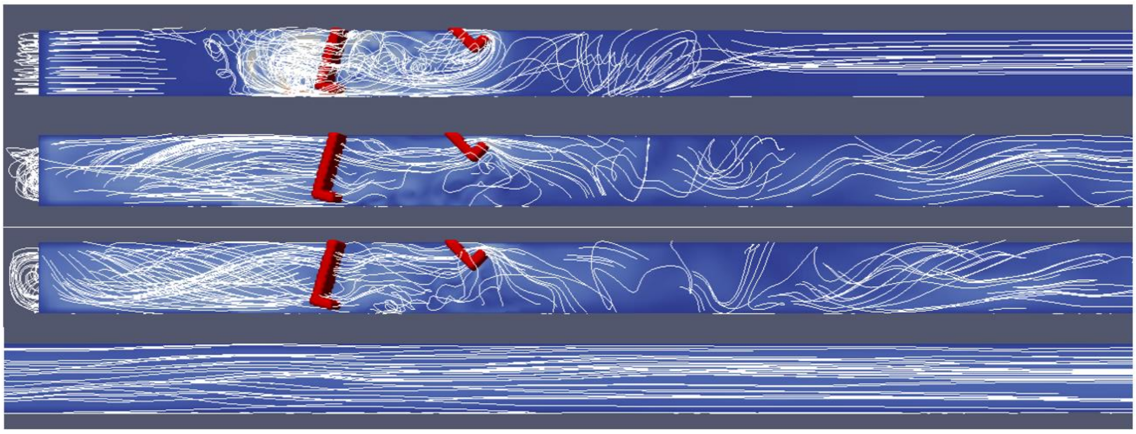


Figure 19: Streamlines at the neighbourhood of the paddle-wheel (the first three images from top to bottom at t=1s, 47s, and 71s) and at the centre of the channel (last image, at t=71s)

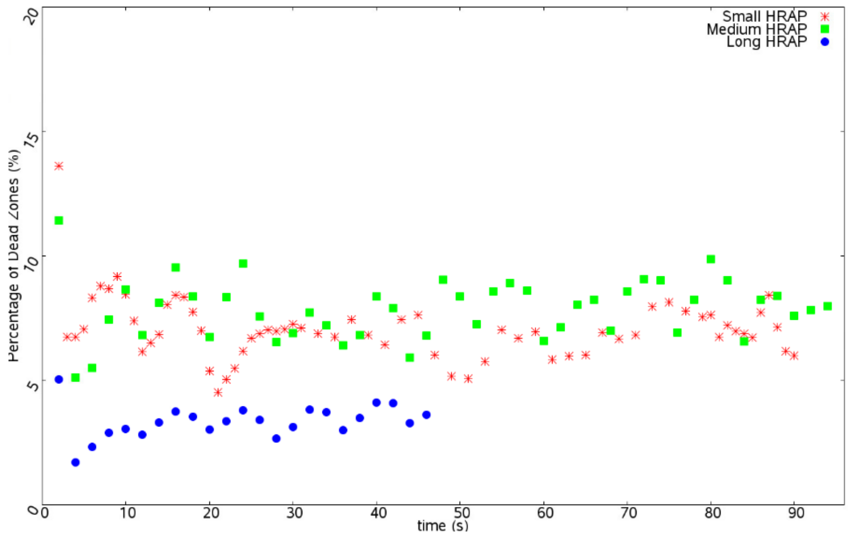


Figure 20: Percentage of Dead zones vs time for three different geometries: the small, medium and long RAP

The percentage of dead zones in the pond is defined as follows:

$$\% \, Dead \, Zones = \frac{V_{v<0.1}}{V_{pond}} \, .100 \qquad (1)$$

Where $V_{v<0.1}$ is the volume of liquid were the magnitude of the velocity is smaller than 0.1m/s, and V_{pond} is the entire volume of the liquid in the pond (Hadiyanto, H., 2013) . Figure presents the time-evolution of the dead zones percentage for the three different geometries. The figure shows that after just 10 seconds of simulation, the percentage of dead zones oscillates around an average value presented in Table 2. The values for the small pond are the most dispersed, with a maximum difference of 32% between the extreme values and the average value. For the medium pond and the long pond, the difference is of 25% and 22% respectively. The figure and the table show that in the long pond, the percentage of dead zones is smaller than for smaller ponds and vary less over time.

Case	L/W	% Dead Zones
Long RAP	22	3.42%
Medium RAP	6	7.89%
Small RAP	5	6.80%
Results from [02 – Hadiyanto, H. (2013)]	5	14%

Table 2: Average percentage of dead zones for different shape ratios

3.3.2 Evaluation of Shear Stress

A suitable degree of mixing is necessary for the micro-algae (M.A.) growth and development. A paddle-wheel, presented in Figure , is used in the present study to provide such mixing. It has been noted that the mixing must ensure an optimum amount of light to the M.A. However, shear stresses generated by high flow velocities can also damage the cells preventing them to fully develop or even causing their death. Therefore, the mixing degree has to account for the optimum light-mixing threshold (M_{light}) but also the shear stress sensitivity of the micro-algae.

The sensitivity to shear stress strongly depends on the cells' morphology (size, shape, presence of cell wall, etc.) and their physiological conditions. For instance, the micro-algae *Dunaliella salina* is highly sensitive to shear stress. Stresses higher than 18 Pa can kill it. *Dunaliella salina* possesses two pairs of flagella that can be shredded by high shear stresses suppressing the microorganism motility and possibly killing it. *Arthrospira platensis (or Spirulina platensis)*, is sensitive to shear stress because it is shred into pieces for stresses higher than 2 Pa. But it can easely recover (up to a several orders of magnitude higher shear stress threshold).

Figure and Figure show the time-evolution of the maximum and average shear stresses for the three shape ratios. Figure shows that the maximum shear stresses are all below 3 Pa which is suitable for both *Dunaliella salina* and *Arthrospira platensis* strains. The small pond presents higher shear stresses than the two others. Also, it has been observed that for the long RAP, a higher value of the maximum shear stress arises every 8 seconds which is the rotational speed of the paddle-wheel (1 revolution every 8 seconds). Further analysis is necessary to confirm the relationship between the two phenomena. Figure shows that for all three cases, the average shear stress converges to values two orders of magnitude smaller than the maximum shear stress.

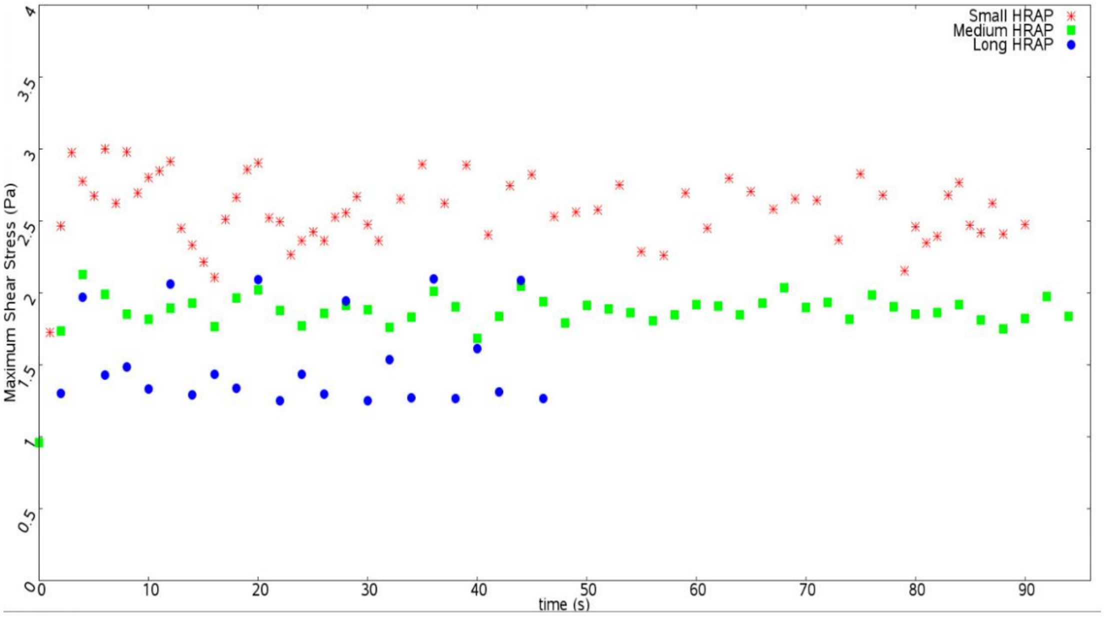


Figure 21: Maximum shear stress versus time for three different geometries: the small, medium and long RAP

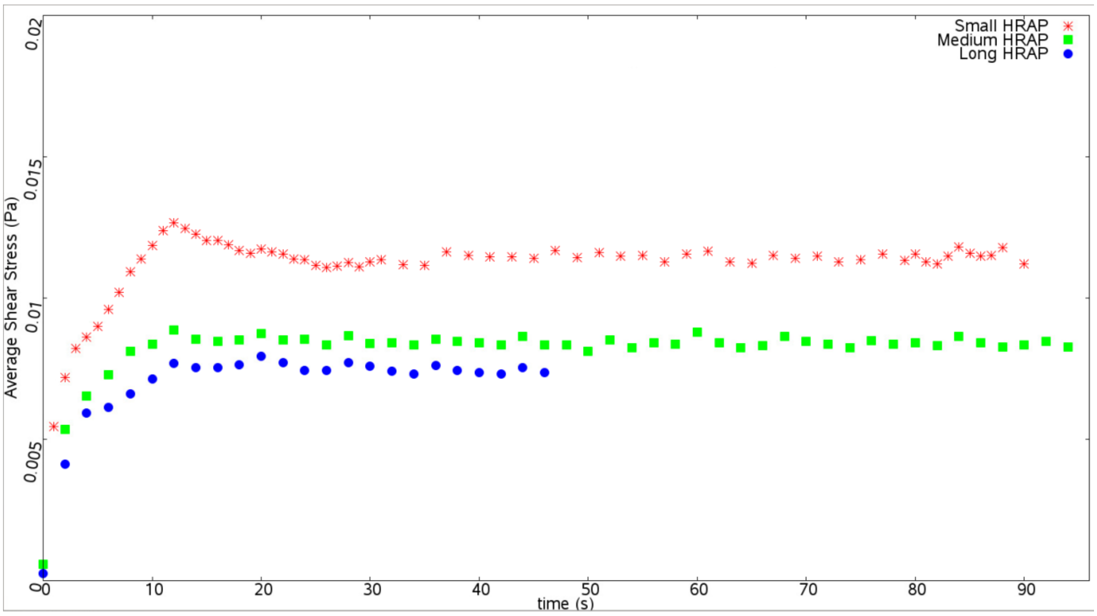


Figure 22: Average shear stress versus time for three different geometries: the small, medium and long RAP

The preliminary results presented in this section confirm that even for sensitive micro-algae strains such as *Dunaliella salina*, the shear stress is not high enough to affect the micro-organisms. They also suggest that scaling up by lengthening the pond without changing the paddle-wheel and the pond width (Long pond) would maintain a low percentage of dead zones and in fact decrease it. 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. The purpose of the next section is to quantify the effect of changing the pond's shape ratio on mixing. The particulate transport model based on the MPPIC parcel transport method is used for this purpose.

3.4 Evaluation of mixing in a 5m³ RAP

Preliminary simulation results presented in the previous section were used to determine the dimension and shape of the new RAP to be built for the Israeli demonstration site by Arava Building Facilities. The following characteristics were selected:

- Scale-up RAP (4.59 m^3, $\frac{L}{W}$ = 12): 12m long, 1m wide and 0.2m deep, Figure 2.

More detailed simulations have been set-up to provide more detailed information on its hydrodynamics and particulate transport characteristics. The aim is to provide information to support operation of the pond and help interpret its performance as a biological reactor.

The parameters of the simulation are reported in Table 1. The simulation run for 50s of flow time (2 months of computational time) to reach an established unsteady state. Then, 200 particle parcels were injected and their evolution modelled and tracked using the MPPIC algorithm. Figure 2 reports the geometry of the pond and the path of all 200 particles covering a period 100 seconds (4 months of computational time). The plot confirms that the particles are not trapped in the neighbourhood of the Paddle-wheel but travel around the pond.

Because of the turbulent nature of the flow, the particles do not follow a straight path and take a much longer time (high than 100 seconds) to circulate around the pond. From Figure 2, the minimum discharge velocity is 0.1m/s which means that for a purely horizontal flow in the same conditions, a particle would take less than 30 seconds to travel around the pond.

The lengthening of circulation time is not an issue since it is the vertical mixing which ensures that M.A. does not remain trapped in regions with low light exposure necessary to its development. In order to evaluate the light exposure, the vertical path of all 200 particles has been computed. The path of 6 individual particles is presented in Figure . Light penetration into the particulate fluid depends on the fluid characteristics and the cell density (related to the dry weight). In this study, let us assume that light penetrates into the water to a depth of 6 cm and that below, the amount of light is too low for the micro-algae. defining a so-called dark zone. The dark and light zones are delimited in Fig.16 by the horizontal blue dashed-line. The plot shows that the 3 particles alternate between dark and light cycles. This prevents the M.A. from lack of light or a light inhibition. Therefore, and for the present 3 particles, the vertical mixing can be deemed satisfactory. A quantitative study for all particles is currently carried out in order to confirm these results. Also, the analysis of the data should consider that the dark and light threshold is strain-dependent and fluid-dependent. Information about light penetration might be provided by one of the Saltgae partners and should improve the present data-analysis.

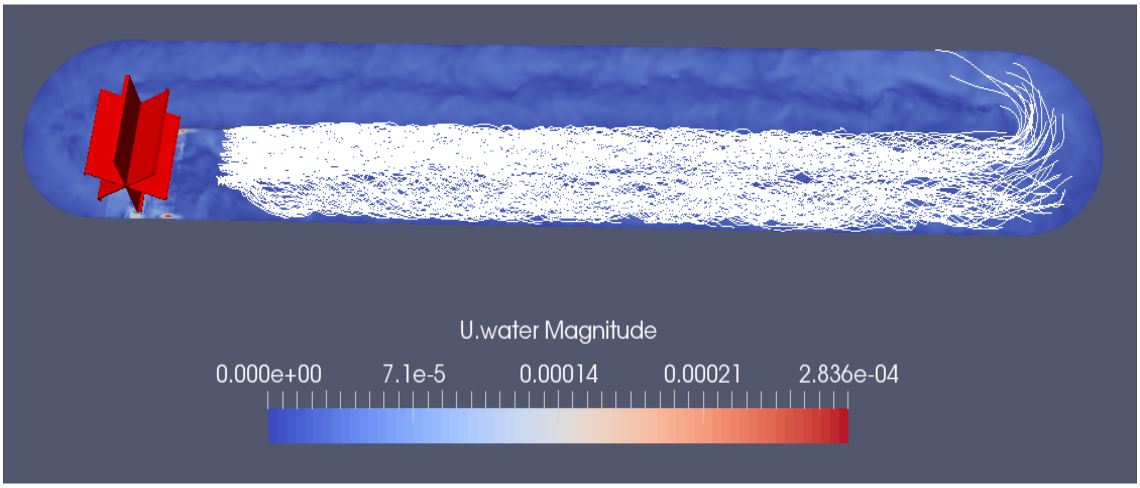


Figure 23: Path of 200 different particles in a RAP

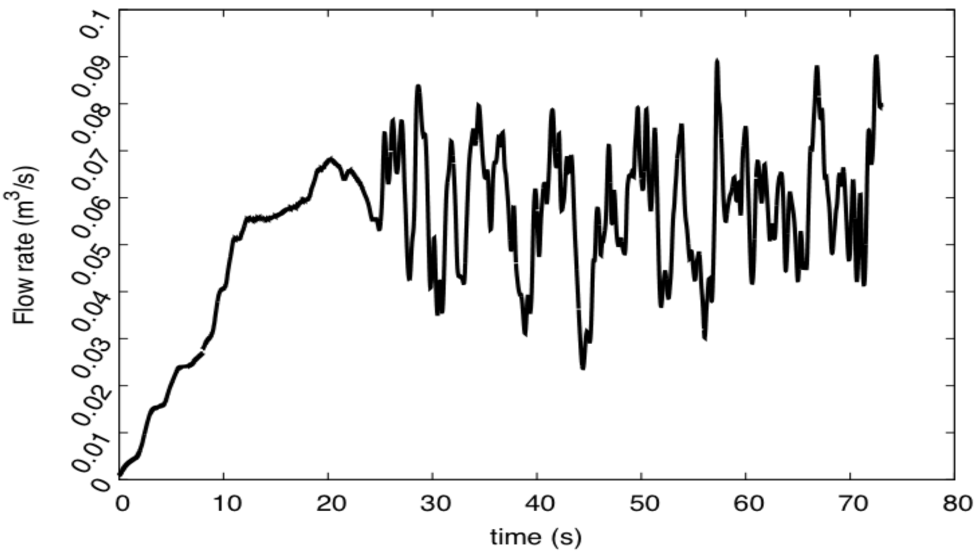


Figure 24: Flow rate versus time in the RAP

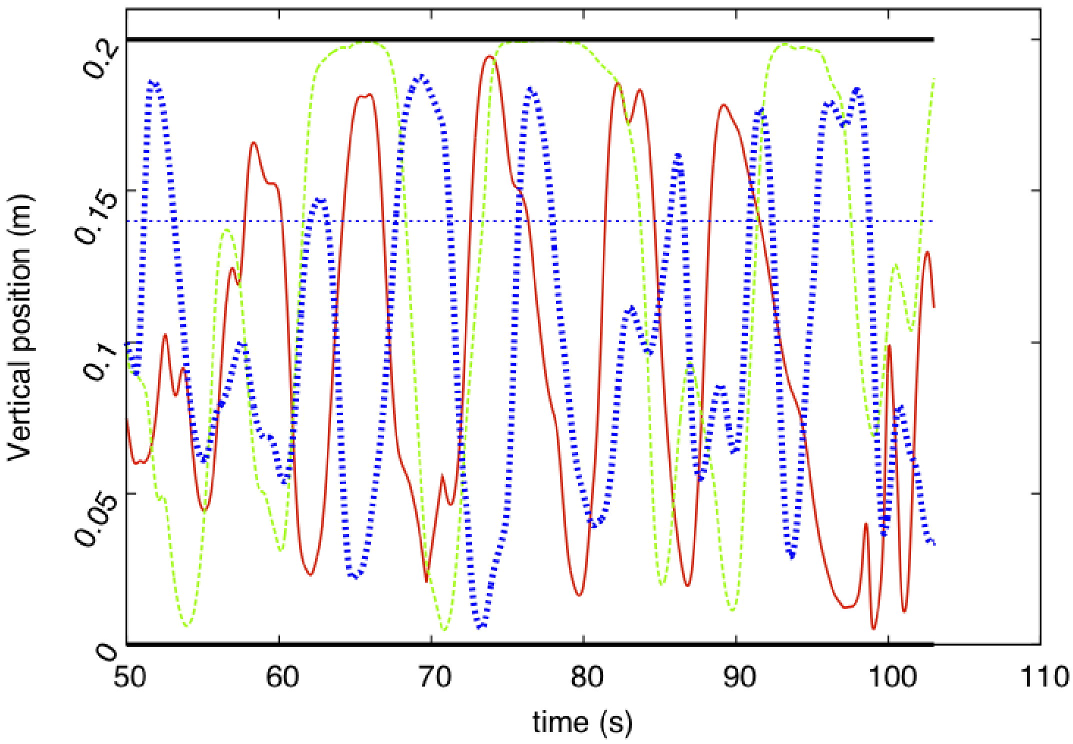


Figure 25: Vertical path of three particles graphs

3.5 Conclusions

The design of High Rate Algae Ponds has been evaluated in terms of mixing, presence of dead zones and shear stress. Numerical simulations of the fluid flow in four RAP with different sizes and shapes have been performed to that end. The fluid, particles and solid interaction have been fully captured by the LES method (Smagorinsky model), the MPPIC Method and the IBM implemented in OpenFOAM. The effects of scaling up the RAP on the mixing performance and shear stress have been studied with three different RAP sizes (0.91 m^3, 1.19 m^3, and 4.55 m^3). The results show that the low-velocity zones are mostly present in the bends, behind the central wall and at the right side of the paddle-wheel. In the latter, the pattern of the zones highly evolves with time which suggests that particles are not trapped in those zones. Particles injected at the neighbourhood of the paddle-wheel and tracked confirm that this zones are not "Dead Zones", where the micro-algae are trapped and cannot have enough light (or are too exposed) and die. The percentage of dead zones is also shown to be higher for smaller ponds.

The shear stress has been evaluated by computing the time-evolution of the average and maximum shear stress. The results show that both the maximum and the average shear stress decrease for bigger RAPs. Still, the maximum shear stress values, for the present paddle-wheel rotational velocity, are not high enough to have a negative impact on cells. Indeed, even the most sensitive strains (*Dunaliella salina*) can handle much higher stresses. According to the present results, the vertical mixing outside the neighbourhood of the paddle-wheel for the long pond is scarce. To improve mixing, it is suggested that a RAP with a smaller shape ratio is more appropriate.

The simulation of the particulate flow on a bigger pond (4.59 m^3) with a smaller size shape ($L/W = 12$) have also been conducted. Vertical paths for 200 particle parcels were computed showing that particles alternate between light/dark zones. This behaviour helps the M. A. to access light to achieve photosynthesis but also avoid over-exposure, which can produce cell damage. A full quantitative analysis is currently being carried out to confirm if all particles alternate between light and dark cycles, and quantify those that are trapped. This will be used to help interpret operational results on M.A. growth observed during demonstration.

Simulations of the fluid flow in a similar 4.59 m^3 –RAP with different positions of the paddle-wheel are also on-going to study its effect on the mixing, shear stress and dead zones. Also, two different shapes of paddle-wheel are tested to improve the paddle-wheel design. Finally, an estimation of the power required to move the two different paddle-wheels will be undertaken.

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Table 3: References

