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# Experimental study of the mixing and flow properties of fractal oscillating grids in water.



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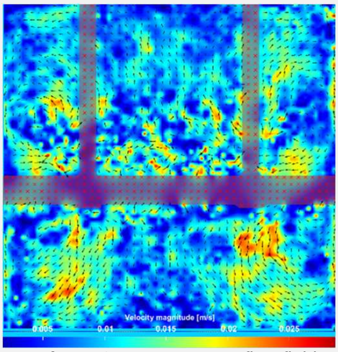



**Figure 0.** Instantaneous flow field generated by a simple Cartesian oscillating grid.

If a biochemical process deals with micro-organism cultures, the mixing device used in the bioreactor should promote all the transfer phenomena (nutrients, gas-liquid, light, …) while limiting the mechanical stress induced on the micro-organisms. With this comment in mind, we propose to design a photobioreactor (PBR) stirred by fractal oscillating grid systems for the culture of shear-sensitive microalgae. Oscillating cross-barred grids generate almost isotropic and homogeneous turbulence with a weak (almost null) mean flow. Grids with fractal geometries were used as fixed grids to generate downstream, isotropic and homogeneous turbulence in wind and water channels. Therefore, our work is the first implementation of a fractal oscillating grid flow. Flow characterisation experiments namely Planar Laser Induced Fluorescence (PLIF) and PIV (Particle Imaging Velocimetry) are performed, with the aim to determine the best conditions (grid pattern, oscillation frequency and amplitude) *a priori* for microalgae cultures.

## Introduction

The promotion of transfers within a reactor is often the keystone of the enhancement of a chemical or biochemical process. In the case of microorganism cultures within a bioreactor, this transfer intensification should not be accompanied by a shear stress increase inducing mechanical stress on the microorganisms leading to their lysis. This is especially true for the culture of some shear-sensitive microalgae (red microalgae, diatoms, dinoflagellates, …). The culture of this kind of photosynthetic micro-organisms can be performed in several designs of photobioreactors (PBR) with different and geometries to capture $CO_2$ and produce interest products (lipids for biodiesel production, proteins, pigments or carbohydrates for health, food or cosmetic purposes). Each PBR configuration or geometry offers a compromise between intense mixing and high shear stress. Among the classical configurations, we can mention the raceway ponds, the stirred tank, the tubular, the flat plate, the bubble column and the airlift PBR **[1 – 5]**.

The aim of this PhD work is to design an innovative PBR stirred by a fractal oscillating grid system for the culture of shear-sensitive microalgae. This type of system is classically composed by a cross-barred grid (Cartesian mesh) vertically oscillating with a specific frequency $\nu$ and amplitude (peak to peak) $A$ around an equilibrium position $z_{\mathrm{eq}}$ in a fluid medium contained in a prismatic tank (Figure 1). The grid oscillatory motion induces turbulence in the fluid medium whose properties can be monitored thanks to the oscillation and grid geometry parameters. The generated turbulence is considered nearly isotropic and homogeneous and with almost no mean flow; the flow is therefore virtually shear-free according to the generated turbulence. Oscillating grid systems were used to study interfacial and stratified flows and particles sedimentation and flocculation. More recently, they were used to study transfers in micro-organism cultures and biofilm degradations **[6 – 7]**.

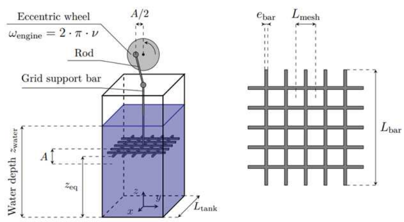



**Figure 1.** Simplest configuration of an oscillating grid system in water.

Grids with fractal geometries were used as fixed grid in wind or water tunnels to generate a downstream, isotropic and homogeneous turbulence **[8]**. Such grids are designed in an iterative way by the repetition of a base pattern - composed of $N$ bars of length $L_0$ and width $e_0$ - over several size scales. The bar length and width for a pattern at the iteration $i$ are linked to those for the same pattern at the iteration $i-1$ respectively by ratios $\mathrm{ratio}_L$ and $\mathrm{ratio}_e$. These ratios are kept constant iteration after iteration. In our work, a classical Cartesian grid is used as a reference case and $4$ fractal grids (with $3$ fractal patterns: Cartesian, square and "I") constitute the core of our study.

Before any microalgae culture, the first part of our work aims to perform a parametric study of the properties of the flow generated by the investigated fractal oscillating grid systems. Based on this study, the best *a priori* configuration of fractal oscillating grid system will be selected to perform microalgae cultures.

### Material and Methods

To study the properties of the fractal oscillating grid flow, 2 optical flow visualisation methods – PLIF (Planar Laser Induced Fluorescence) and PIV (Particle Imaging Velocimetry) – have been implemented. In our case, both methods involve a vertical laser sheet generated by a continuous laser Dantec Dynamics RayPower and a scientific camera LaVision Imager M-lite 5M. Our parametric study is summarised in the Table 1 and focuses on the variation of the grid type and of the oscillation frequency and amplitude; each combination is investigated. The grid geometries and features are summarised in the Table 2.

**Table 1.** Parameters levels for the parametric study of the fractal oscillating grid flow.

| $\nu$ levels [Hz] | $A$ levels [m] | Grid type |
|---|---|---|
| 0.5 | 0.02 | Simple Cartesian |
| 1.0 | 0.035 | Fractal Cartesian |
| 2.0 | 0.05 | Fractal square pattern |
| | | Fractal “I” pattern square fitting |
| | | Fractal “I” pattern rectangle fitting |

With the PLIF method, our aim is to evaluate the mixing time in the PBR stirred by oscillating grid as a function of the above-mentioned parameters ($\nu$, $A$ and grid type) by recording the dispersion of a fluorescent dye (in our case, rhodamine 6G). Classically, calibration between the intensity of the local fluorescence radiation and the local dye concentration is performed. However, in our case and due to the wide range of dye concentrations (between injection concentration $10^{-3}$ $[\mathrm{mol/L}]$ and the final concentration when homogeneity is reached $10^{-8}$ $[\mathrm{mol/L}]$), such a calibration was not possible, and fluorescence absorption phenomena arise, limiting the method to qualitative considerations.

With the PIV method, 50 $[\mu\mathrm{m}]$ polyamide particles (reflecting the vertical laser sheet radiation) are dispersed in the fluid medium. Two-dimensions vector fields of fluid velocity are obtained after image and PIV processing by several Matlab codes (image normalisation, grid masking algorithm) and by PIVlab (a Matlab app dedicated to PIV treatments). With the PIV method, several vertical laser planes, some across the grid bars and some across the grid bars and holes, are investigated to evaluate the potential inhomogeneity of the flow. The obtained vector fields from PIV measurements are analysed each velocity field is broken down into a mean flow contribution, an oscillatory contribution and purely turbulent fluctuations according to a triple decomposition method **[9]**.

### Results and Discussion

For the evaluation of the mixing time according to the grid types and the oscillations parameters, the results for each grid can be gathered by defining an oscillation-based Reynolds number $Re_{\mathrm{osc}}$ (see below). Figure 2 depicts the expected decrease of the mixing time as $Re_{\mathrm{osc}}$ increase (meaning that $\nu$ and/or $A$ increase).

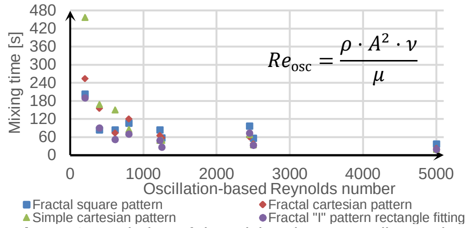



**Figure 2.** Evolution of the mixing time according to the oscillation-based Reynolds number for each grid.

The fractal nature seems to enhance the mixing performances at low Reynolds number although it is risky to conjecture on which grid seems to perform better at high Reynolds number. To answer this question, the repeatability of each point should be evaluated. Thus, the Figure 3 shows the variation of the mixing time according to $Re_{\mathrm{osc}}$ for the simple Cartesian grid with each measurement point repeated 5 times (the error bars depict the standard deviation).

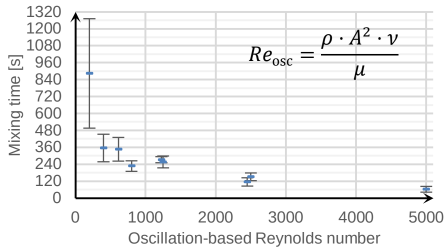
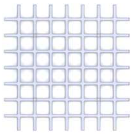
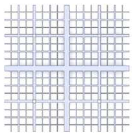
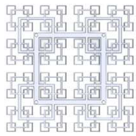
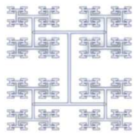
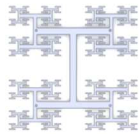



**Figure 3.** Evolution of the mixing time according to the oscillation-based Reynolds number for the simple Cartesian grid with 5 replications for each measurement point.

The poor repeatability, illustrated by these important error bars, can be attributed to an important non repeatable mean flow and a relative precision about the position of the injection point. It thus appears that the mixing time could not be the most relevant indicator to compare the grids with each other. Indeed, for our final application (culture of shear-sensitive microalgae), flows properties (turbulence variables, shear rate, …) could be more interesting to compare the grids performances. Therefore, we decided to focus our work on PIV measurements.

Figure 4 depicts the flow decomposition into a mean contribution, an oscillatory contribution (RMS values) and purely turbulent fluctuations (RMS values) for a statistically permanent flow generated by 1000 complete oscillations of the simple Cartesian grid with $\nu = 0.5$ [Hz] and $A = 0.05$ [m]. For each $z$ coordinate, the associated mean value of the RMS value of the turbulent fluctuations can be compared to the classical Hopfinger and Toly relations (Figure 4) **[6 – 7]**. Despite favourable set-up conditions for a strong mean flow (large oscillation amplitude compared to the grid mesh size, water volume as high as it is wide) and significant side effects near the free surface and the tank bottom, our results remain in a good agreement with the Hopfinger and Toly's decay laws.

**Table 2.** Grid geometries and features used for the parametric study of the fractal oscillating grid flow.

| **Features** | **Simple Cartesian** | **Fractal Cartesian** | **Fractal square pattern** | **Fractal "I" pattern square fitting** | **Fractal "I" pattern rectangle fitting** |
|---|---|---|---|---|---|
| **Pattern design** |  |  |  |  |  |
| $N$ | 2 | 2 | 4 | 3 | 3 |
| $L_0$ [mm] | 234.0 | 234.0 | 132.9 | 140.8 | 145.1 |
| $e_0$ [mm] | 5.5 | 9.5 | 8.7 | 4.9 | 12.1 |
| ratio$_L$ | 0.488 | 0.480 | 0.500 | 0.452 | 0.426 |
| ratio$_e$ | 1.000 | 0.500 | 0.500 | 0.901 | 0.526 |

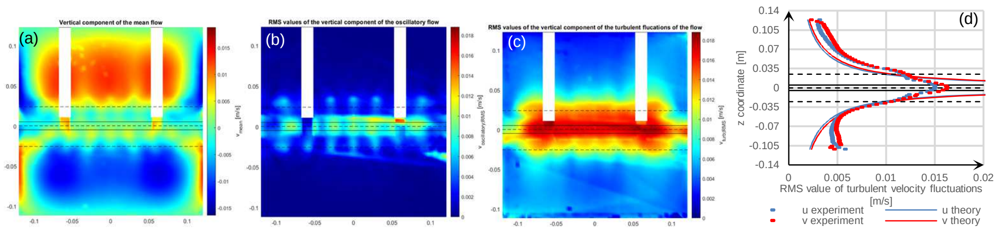



**Figure 4.** Decomposition of the vertical velocity component of the flow generated by the simple Cartesian grid with $\nu = 0.5$ [Hz] and $A = 0.05$ [m]. (a) Mean flow. (b) Oscillatory flow (RMS values). (c) Turbulent fluctuations (RMS values). (d) Turbulence decay along the $z$ coordinate (comparison with the Hopfinger and Toly relations).

## Conclusions

The aim of this project is the design of a photobioreactor stirred by a fractal oscillating grid system for shear-sensitive microalgae culture. To define the best *a priori* oscillating grid configuration (grid pattern, oscillation parameters) for microalgae culture, flow visualisation and characterisation are firstly performed by PLIF and PIV. Due to the important variability of our PLIF results for the evaluation of the mixing time, we have decided to focus on the PIV measurements. Due to the important treatment time to analyse the PIV images and vector fields, the complete parametric study is not already achieved at the time of writing these lines. However, this study is going to be completed before March 2023 (the beginning of the first microalgae cultures).

***Acknowledgments***

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