Design of an innovative photobioreactor stirred by fractal oscillating grids for microalgae culture – Determination of the mixing time

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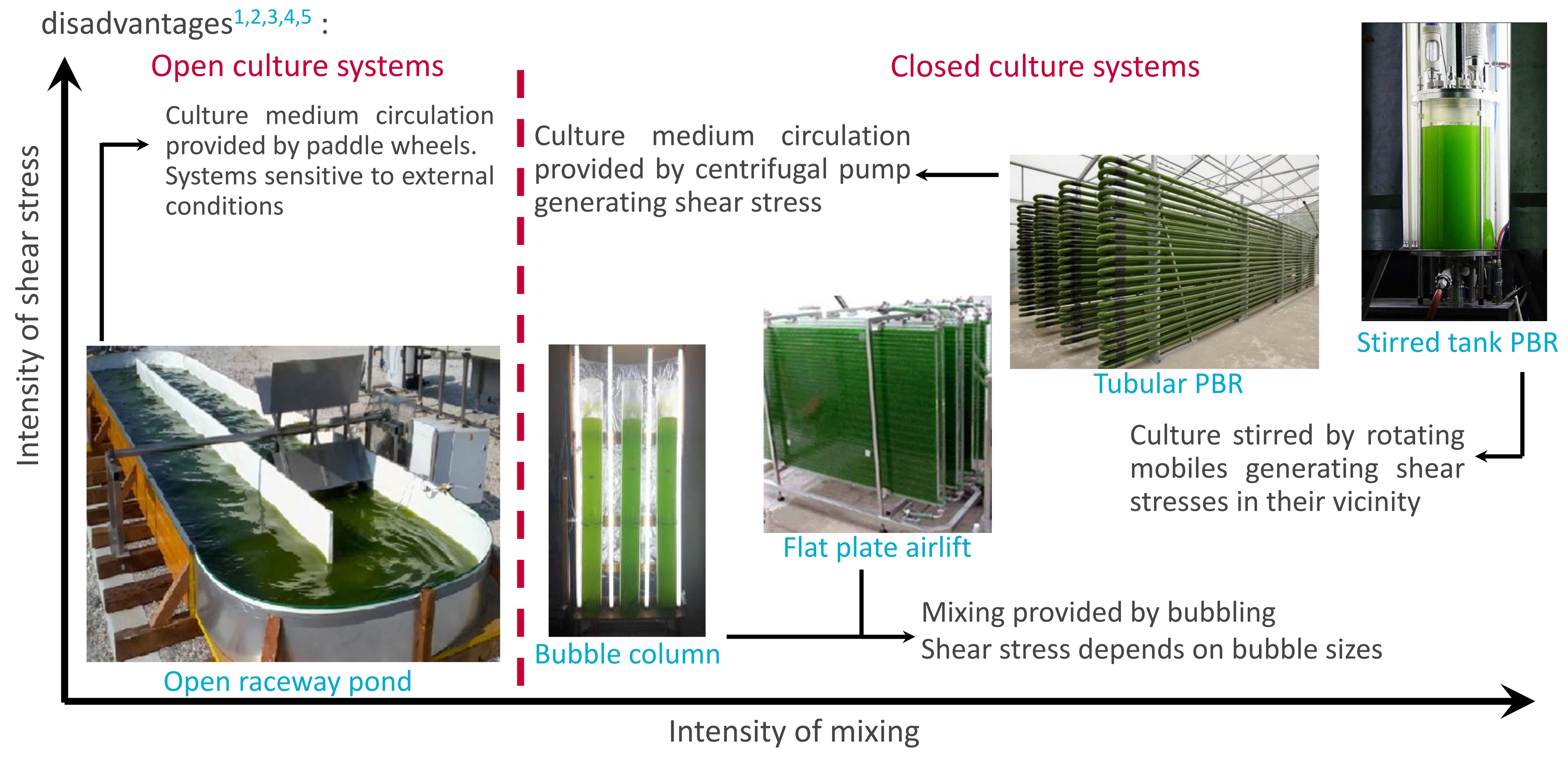
Introduction and context

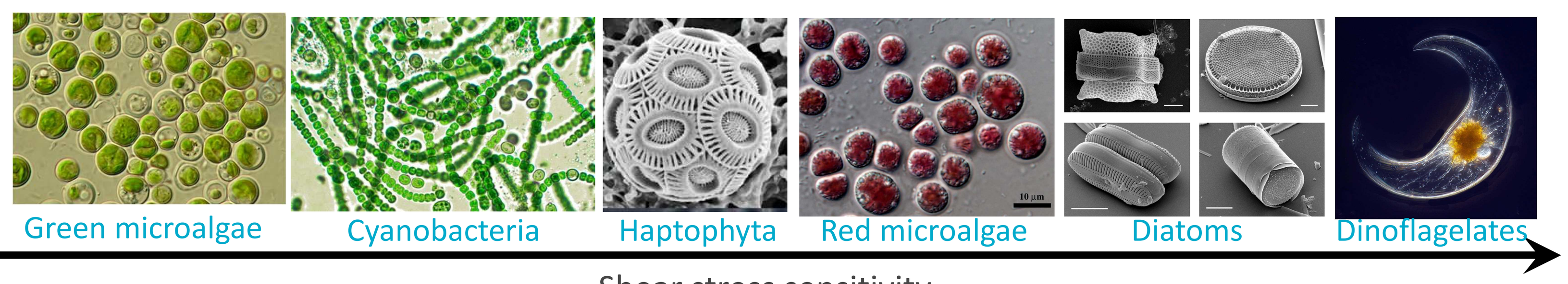
Microalgae and photobioreactors

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 **transfers intensification** should not be accompanied by a **shear stress** increase inducing mechanical stress on the microorganisms that can lead to their lysis.

For the culture of **microalgae**, heterogenic group of photosynthetic microorganisms, several configurations and geometries of **photobioreactors (PBR)** are available, each with its own advantages and disadvantages[1,2,3,4,5] :



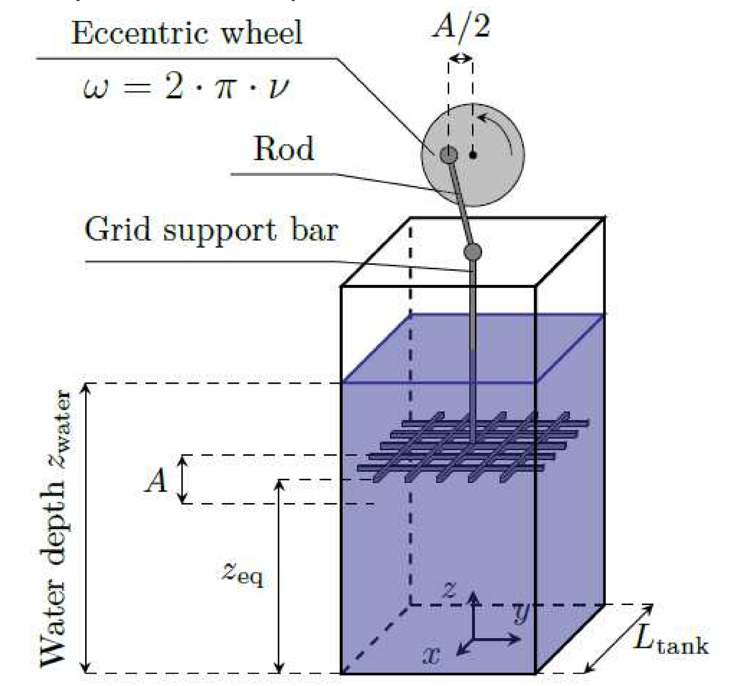
Classification of microalgae according to their **shear stress sensitivity**:[2]



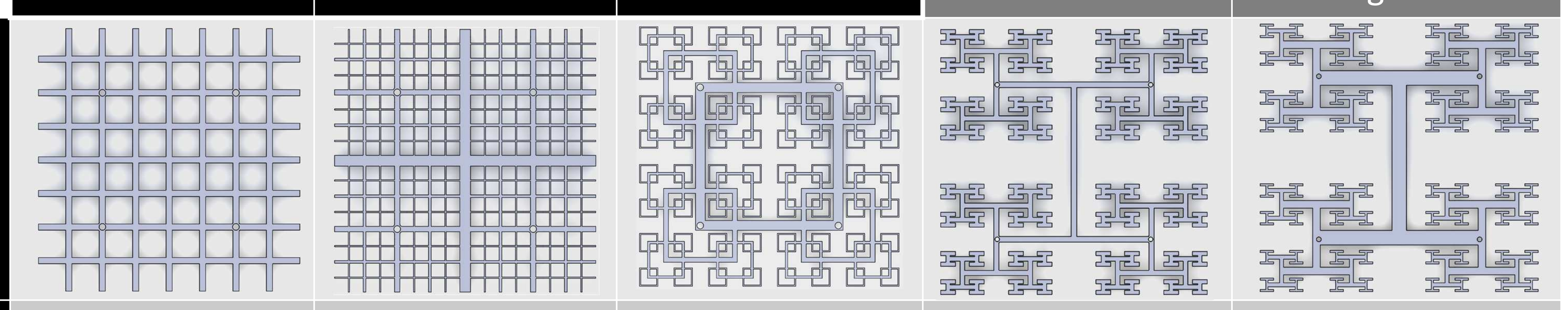
Microalgae culture aims: CO_2 capture and absorption, production of interest products as lipids (which can be transformed into biodiesel), photosynthetic pigments, proteins, vitamins or carbohydrates used for therapeutic, food or cosmetic purposes[1,3,4,5].

Oscillating grid turbulence and fractal grid designs

Our thesis aim is to **design a PBR stirred by an oscillating grid**, stirring system classically used in fluid mechanics experiments to generate **near isotropic shear-free turbulent flows**. The turbulence generated by an oscillating grid system can be monitored by the oscillation and grid parameters. This kind of stirring system was mainly used to study stratified and interfacial flows and sediments and particles sedimentations[6,7].



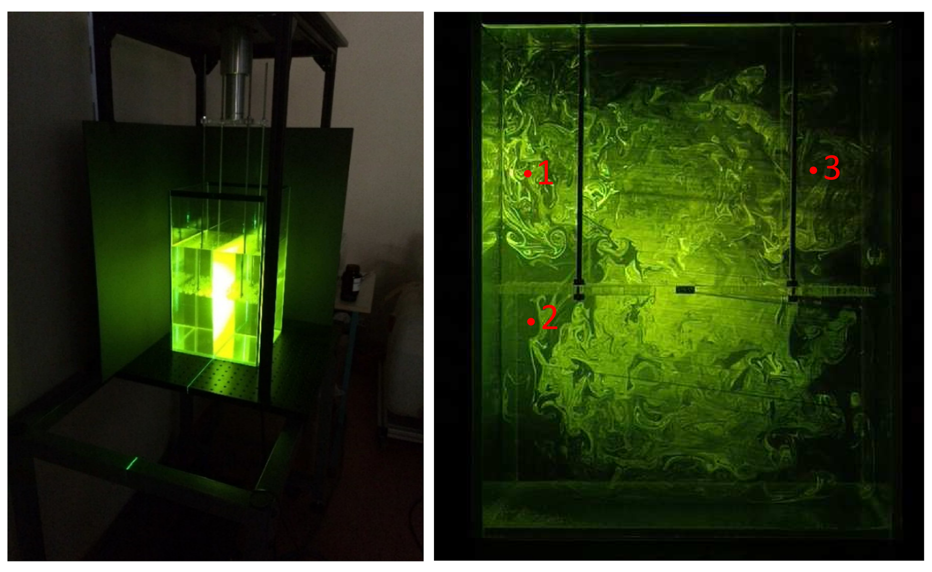
Each grid used have a **fractal geometry** and is constructed in an iterative way from a base pattern (cross, square, I-shaped) made of N bars of length L_0 and width l_0. The bar length and width for a pattern at the iteration i are linked to the bar length and width for the same pattern at the iteration $i-1$ respectively by ratio$_L$ and ratio$_l$. These ratios are kept constant iteration after iteration. The simple cartesian grid is just a specific case of a fractal cartesian grid with ratio$_l = 1$. All the grids tested have the same solidity (ratio between the bar surface and the full surface of the grid): 0.3. Fractal grids were used as fixed grids to generate downstream turbulence in water or wind tunnels. Our work therefore constitutes the first implementation of a fractal oscillating grid flow[8].

	Simple cartesian pattern	Fractal cartesian pattern	Fractal square pattern	I-fractal pattern: Square fitting grid	I-fractal pattern: Rectangle fitting grid
Pattern design					
Solidity	0.3	0.3	0.3	0.3	0.3
N	2	2	4	3	3
L_0 [mm]	234	234	132.9	140.8	145.1
l_0 [mm]	5.5	9.5	8.7	4.9	12.1
ratio$_L$	0.49	0.48	0.5	0.45	0.43
ratio$_l$	1	0.5	0.5	0.9	0.53

Preliminary experiments and results

Principle of the PLIF method

The first experiment for the PBR characterisation is the **determination of the mixing time** according to the grid geometry and the oscillation parameters (ν, A, z_{eq}). This kind of experiments are performed by a Planar Laser Induced Fluorescence (**PLIF**) method: the dispersion of **a fluorescent dye** (Rhodamine 6G) in the fluid medium (water) illuminated by a **laser sheet** (generated by a continuous laser Dantec Dynamics RayPower) is record by a scientific camera (LaVision Imager M-lite 5M) with an optical filter cutting the laser radiation off.



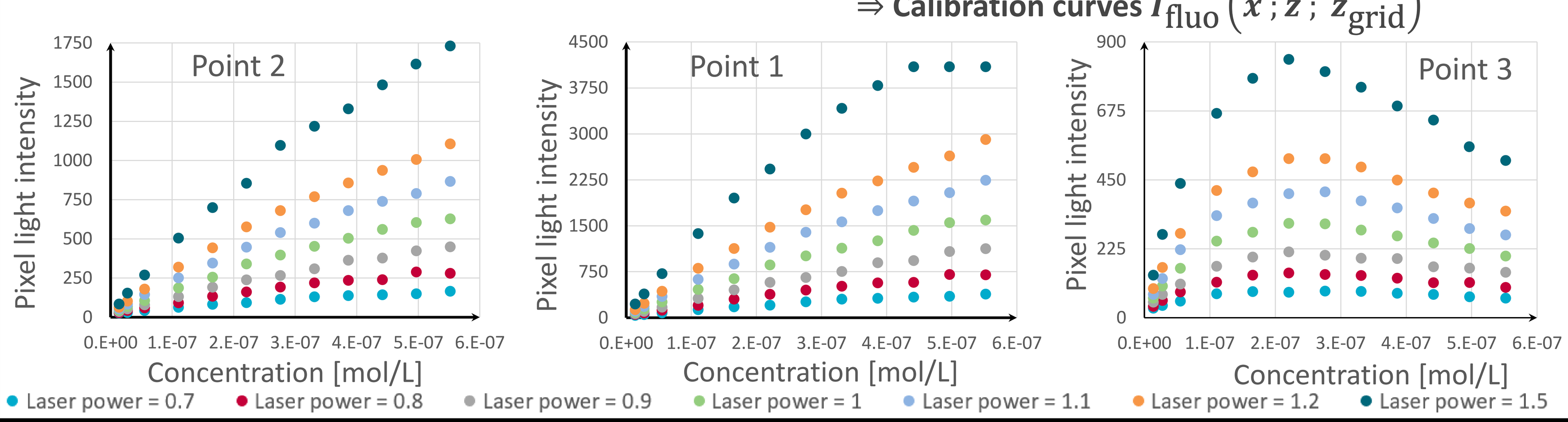
The local fluorescence radiation is linked to the local dye concentration, the laser radiation power and the optic set-up.

$$I_{fluo} = \eta_{optic} \cdot I_{laser} \cdot e^{\varepsilon \cdot L \cdot C} \cdot \eta_{quantum} \cdot V \cdot C$$

⇒ Calibration curves $I_{fluo}(C)$

C depends on the location (x and z) on a considered picture ⇒ calibration pixel by pixel. Due to the vertical movement of the grid, the calibration curves depend on the grid position z_{grid} too ⇒ grid tracking algorithm.

⇒ **Calibration curves** $I_{fluo}(x\,;z\,;z_{grid})$



Determination of the mixing time according to the oscillation parameters

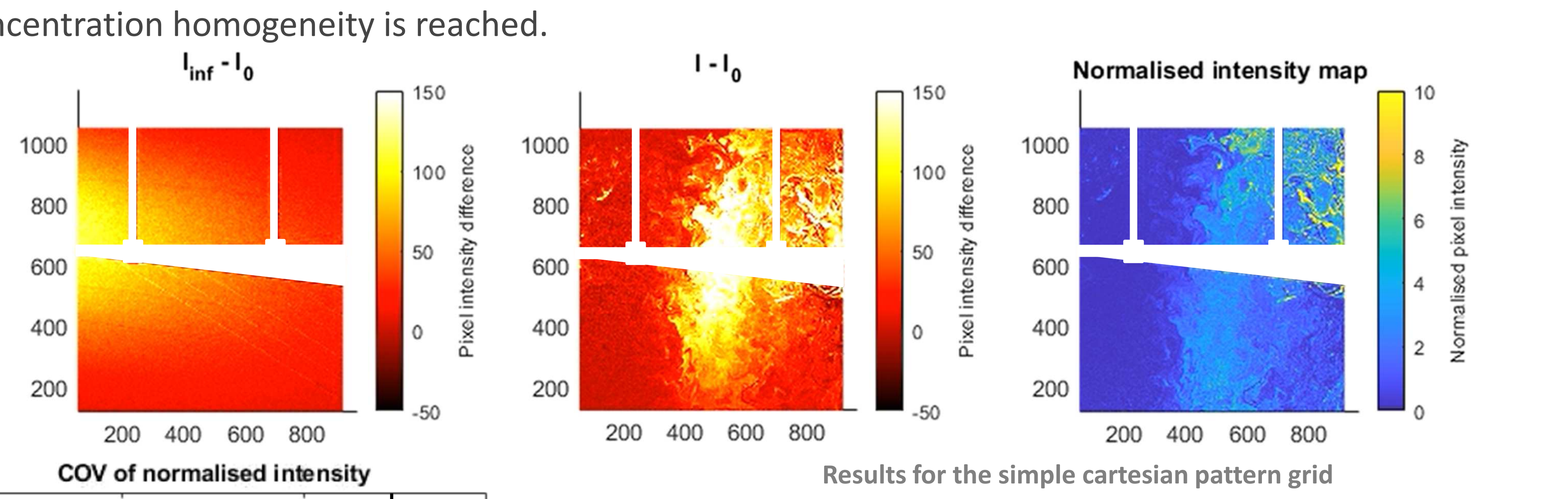
The calibration of the PLIF is limited in our case due to **saturation and Beer-Lambert absorption** resulting in a **hook effect**. Instead of dealing with calibration, we propose the use of the **normalised pixel intensity** I_{norm} to overcome the heterogeneity of the pixel intensity due to the laser illumination.

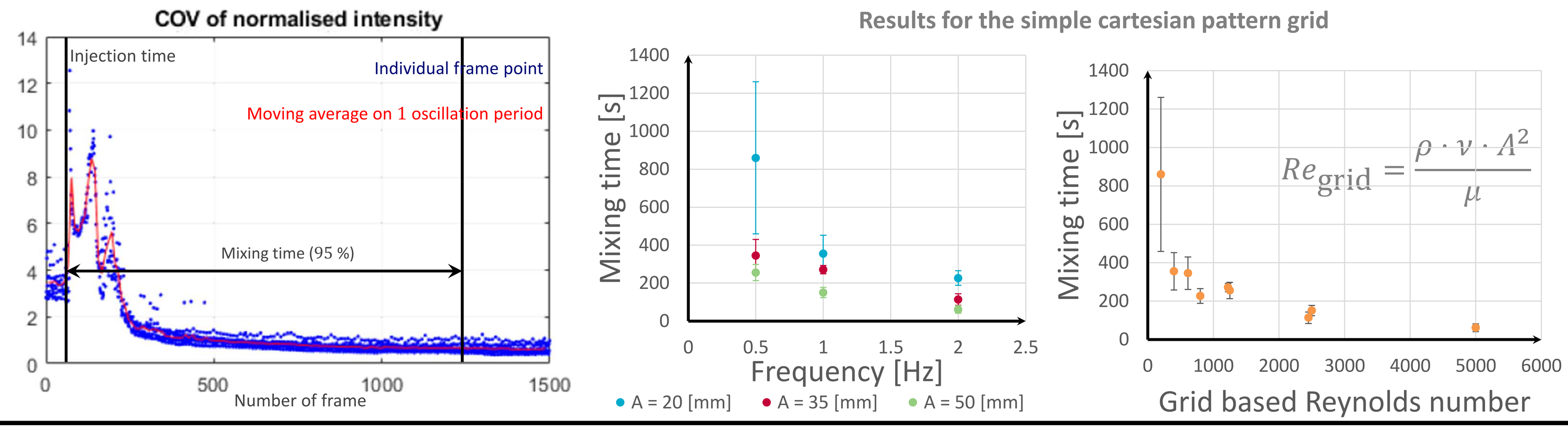
$$I_{norm} = \frac{\left|I\left(x;z;z_{grid}\right) - I_0\left(x;z;z_{grid}\right)\right|}{\left|I_\infty\left(x;z;z_{grid}\right) - I_0\left(x;z;z_{grid}\right)\right|}$$

Before injection, $I_{norm} \to 0$

After the injection, $I_{norm} \to 1$

With I_0 the considered pixel intensity before the dye injection and I_∞ the considered pixel intensity when the dye concentration homogeneity is reached.





Project perspectives

The evaluation of the mixing time by the PLIF method seems to be subject to a great variability. This variability can be attributed to the presence of a **non-repeatable mean flow**, the presence of which may or may not be confirmed by **PIV (Particle Imaging Velocimetry)** measurements (scheduled during the last quarter of 2022 to complete the hydrodynamic study). The results of the mixing time determination study will give us a tendency of which grid is the best for a mixing application, even if this will not be, in our opinion, the most discriminating performance criterion for microalgae culture. To identify the **areas of high shear stress** (which we believe is the most critical parameter) in the PBR, experiments using the **bioluminescence** ability of the dinoflagellate (shear-sensitive microalgae) *Pyrocystis fusiformis* will be developed and performed. All the results of the hydrodynamic and turbulence study will be used to select the, a priori, best configurations to perform microalgae cultures and evaluate the **culture performances** of the fractal oscillating grid stirred PBR. Besides all this, **DNS (Direct Navier-Stokes) simulations** will be performed with OpenFoam to simulate the flows generated by fractal oscillating grid systems. The simulation results will be compared to the experimental PIV results.

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