INTENSIFICATION OF MIXING AND HOMOGENISATION OF CULTURE MEDIUM IN PHOTOBIOREACTORS FOR MICROALGAE PRODUCTION

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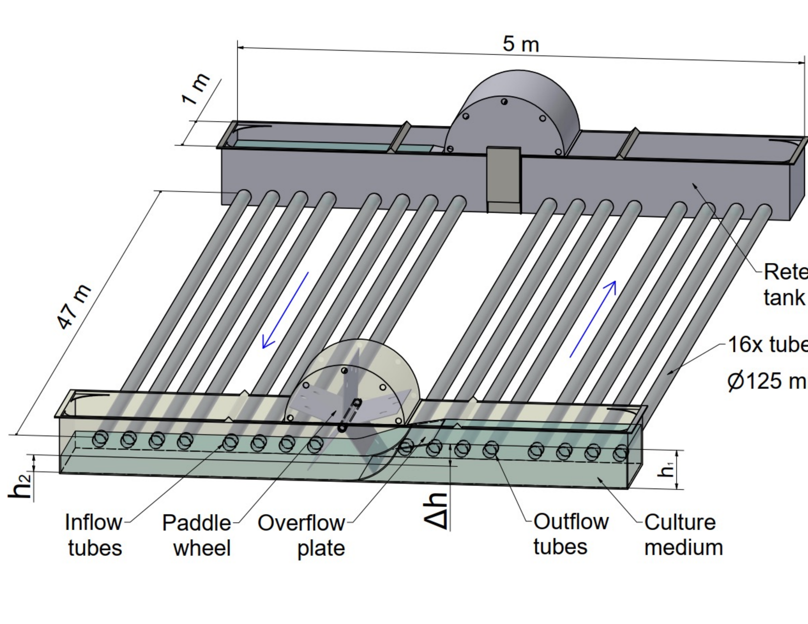
Objectives

The overall objective of the present PhD thesis was to study and optimize the operating conditions of two cultivation systems in order to intensify microalgae production. A hybrid horizontal tubular photobioreactor (HHT PBR) and a closed flat panel photobioreactor (FP PBR) were selected for the study. Hydrodynamics in cultivation systems has a strong influence during scaling-up, since it affects all parameters important for microalgae cultivation.

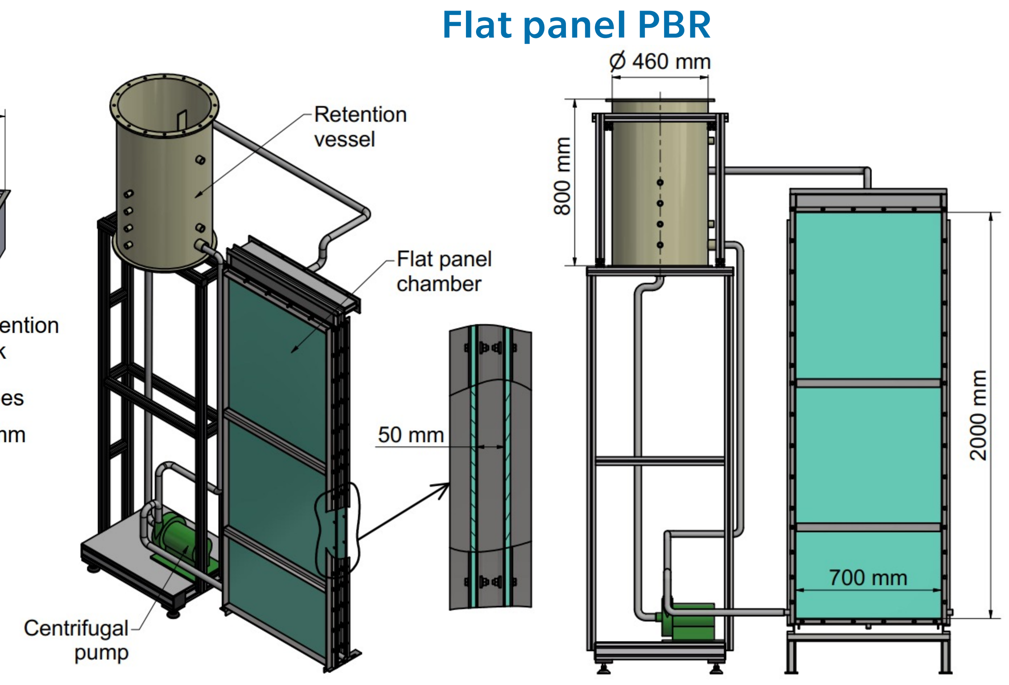
The specific objectives of this research were:

- Calibrate a mechanistic model simulating the process of microalgae cultivation in HHT PBR
- Calibrate and validate the CFD model simulating hydrodynamic conditions in HHT PBR
- Integrate the influence of hydrodynamic conditions into a mechanistic model
- Specify the influence of different operating conditions on the hydrodynamics of the culture medium and the process of microalgae cultivation in HHT PBR
- Validate the CFD model simulating hydrodynamic conditions in FP PBR
- Specify the influence of different operating configurations on the hydrodynamics in FP PBR and influence on the formation of biofilm
- Optimize the operating conditions of HHT PBR and FP PBR
- Optimize the design of the FP PBR chamber concerning the intensification of mixing and homogenization of the culture medium

Hybrid horizontal tubular PBR



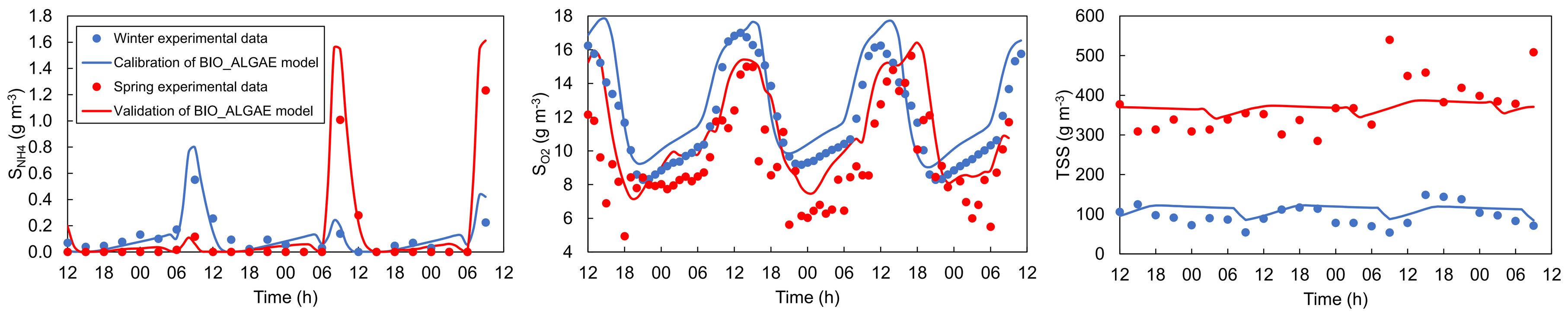
Flat panel PBR



Hybrid horizontal tubular PBR

Calibration and validation of BIO_ALGAE microalgae cultivation model

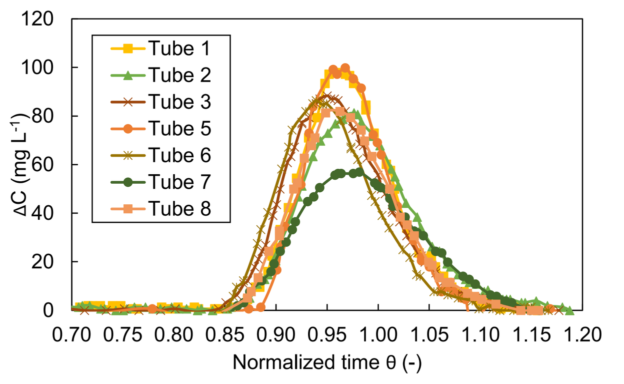
The BIO_ALGAE model was calibrated using measured data from the winter experimental campaign. The applicability of the calibrated model was validated using the measured data in the spring experimental campaign.



Hydrodynamic conditions characterization

A set of experimental tracer tests were performed in the tubes of the PBR in order to determine the residence time distribution (RTD).

RTD based on pulse input tracer technique



Tube Nr.	t_m (s)	$\bar{u}$ (m s^{-1})	u_{max} (m s^{-1})	σ_t^2 (s^2)	σ^2 (-)	D_{diff} (m^2 s^{-1})	D_{ax} (-)
1	250	0.19	0.22	368.6	0.0059	0.0261	0.0029
2	274	0.17	0.20	422.8	0.0056	0.0226	0.0028
3	282	0.17	0.20	541.8	0.0068	0.0267	0.0034
4	N/A	N/A	N/A	N/A	N/A	N/A	N/A
5	254	0.18	0.21	282.5	0.0044	0.0190	0.0022
6	295	0.16	0.19	869.0	0.0100	0.0374	0.0050
7	335	0.14	0.17	954.6	0.0085	0.0280	0.0042
8	288	0.16	0.19	676.5	0.0314	0.0314	0.0041

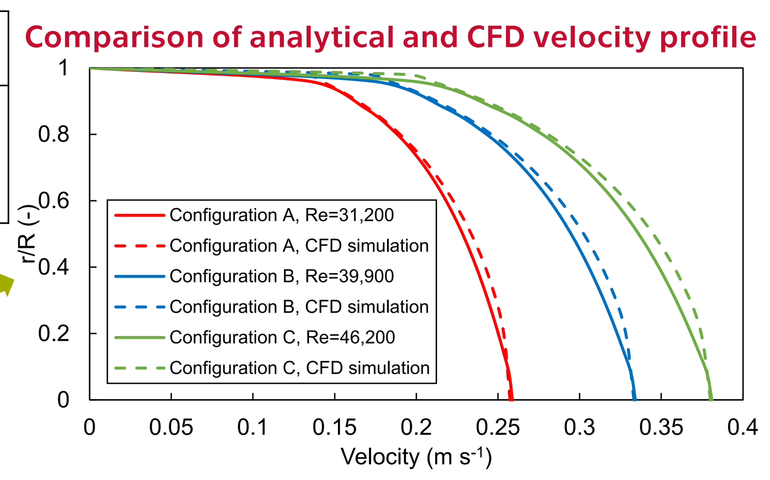
Numerical model of hydrodynamic conditions

The CFD model was calibrated by comparing the simulated velocity profile inside the tubes with the velocity profiles obtained analytically based on the experimental results of the tracer tests.

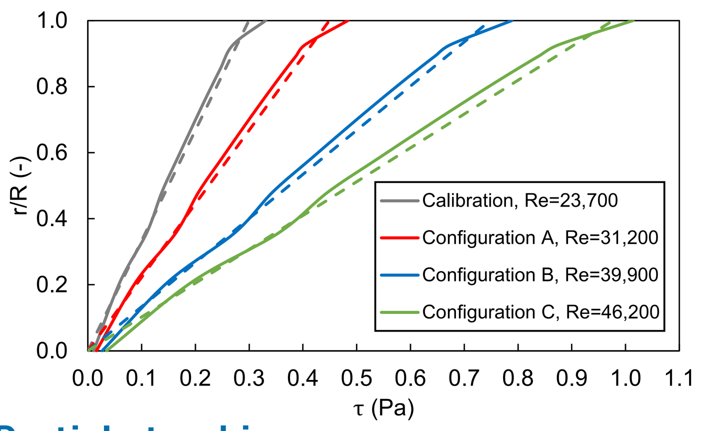
Configuration	h_1 (m)	h_2 (m)	Δh (m)	t_m (s)	$\bar{u}_{tracer}$ (m s^{-1})	$\bar{u}_{flowmeter}$ (m s^{-1})	Re (-)
Calibration	0.28	0.24	0.04	247	0.19	N/A	23,700
A	0.35	0.29	0.06	186	0.25	0.249	31,200
B	0.36	0.26	0.10	145	0.32	0.319	39,900
C	0.39	0.26	0.13	128	0.37	0.371	46,200

CFD simulations were in good agreement with the analytical profiles. Thus, the numerical predictions were preliminarily validated by the experimental data, indicating that the established CFD simulation model can be adapted to simulate the fluid field in the HHT PBR.

Comparison of analytical and CFD velocity profile



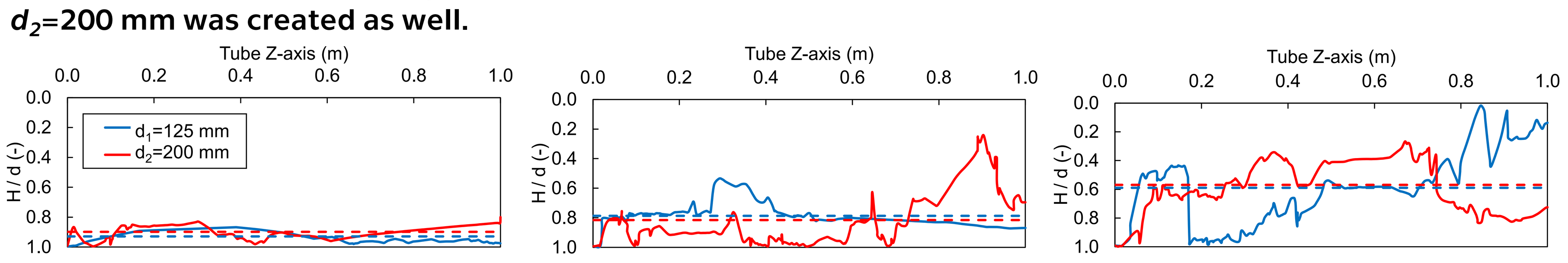
Total shear stress distribution in HHT PBR tube



The shear stress values on the wall were higher than the critical value of the shear stress at which microalgae is fixed on the transparent walls in closed systems working in controlled laboratory conditions. At values lower than 0.2 Pa, a biofilm layer is formed in a closed cultivation system. However, in order to disrupt the integrity of the already formed biofilm, it is necessary to reach values of shear stress on the wall higher than 6 Pa. Those results suggest that the biofilm could not be removed by the shear forces once it is formed in the HHT PBR.

Particle tracking

To simulate the intensity of the light radiation received by the microalgae cells from the incident light on the tube walls, it is important to monitor the distance of the cells from the irradiated wall of the tube. The cell position is thus defined as the vertical distance from the irradiated tube wall H (m). To compare the hydrodynamic conditions in geometrically similar tubes, the same CFD model for a tube with a diameter of d_2=200 mm was created as well.



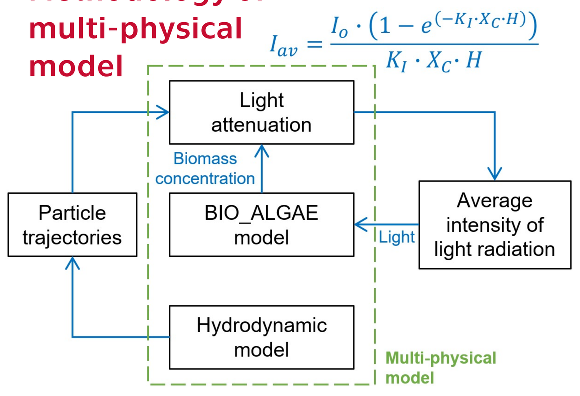
The dimensionless distance (mean value = dashed line) from the irradiated wall was comparable for geometrically similar tubes at the same flow regime. The hydrodynamic conditions based on the original CFD model for the tubes d_1 are therefore also applicable to geometrically similar systems with a different scale.

Multi-physical model

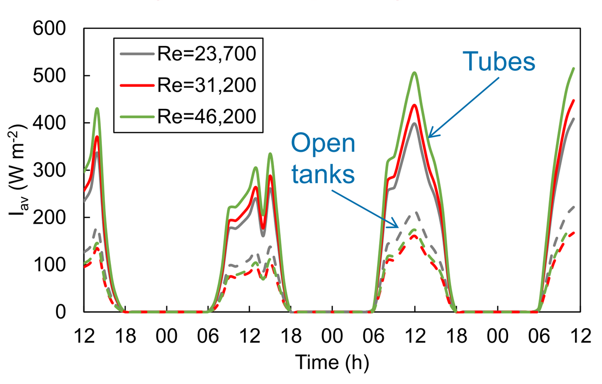
The aim of this part of the study was to integrate the influence of hydrodynamic conditions into a mechanistic BIO_ALGAE model simulating the cultivation process. It is possible to investigate the influence of operating conditions on the distribution of light in the culture medium and the production of microalgae.

Methodology of multi-physical model

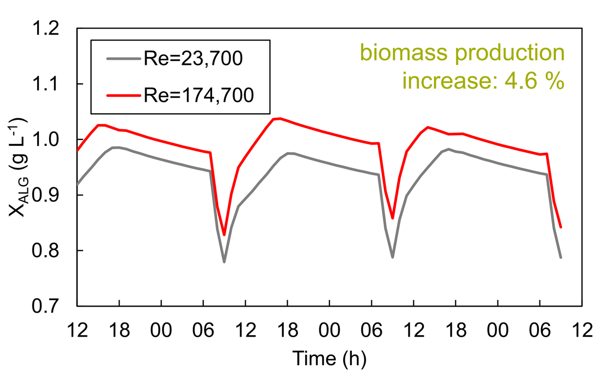
$$I_{av} = \frac{I_o \cdot \left(1 - e^{(-K_I \cdot X_C \cdot H)}\right)}{K_I \cdot X_C \cdot H}$$



Average intensity of light radiation



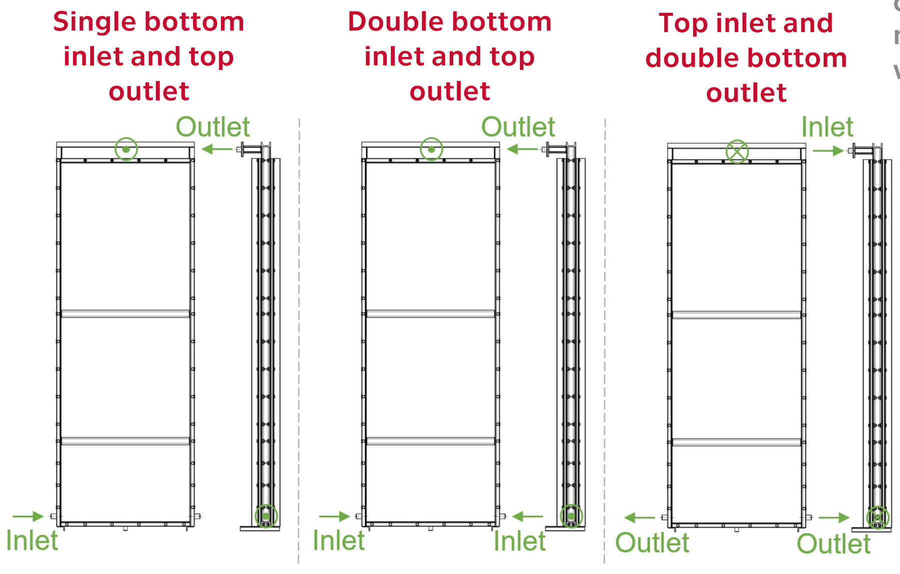
Microalgae production



Flat panel PBR

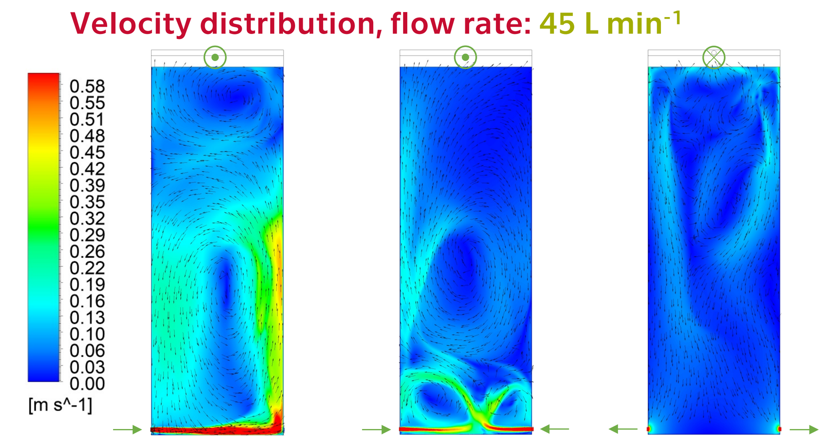
Hydrodynamics of Flat panel PBR

For each inlet and outlet configuration, the effect of flow rate on mixing and homogenization was investigated. Using the created hydrodynamic model, it is possible to optimize the operating parameters of the FP PBR.



The flow in the FP PBR chamber was measured using a pulse input tracer method. The tracer was applied to the retention vessel and consequently, the streamlines in the FP PBR chamber were visually monitored. The CFD model was calibrated and preliminary validated based on the experimental measurement.

Velocity distribution, flow rate: 45 L min^{-1}



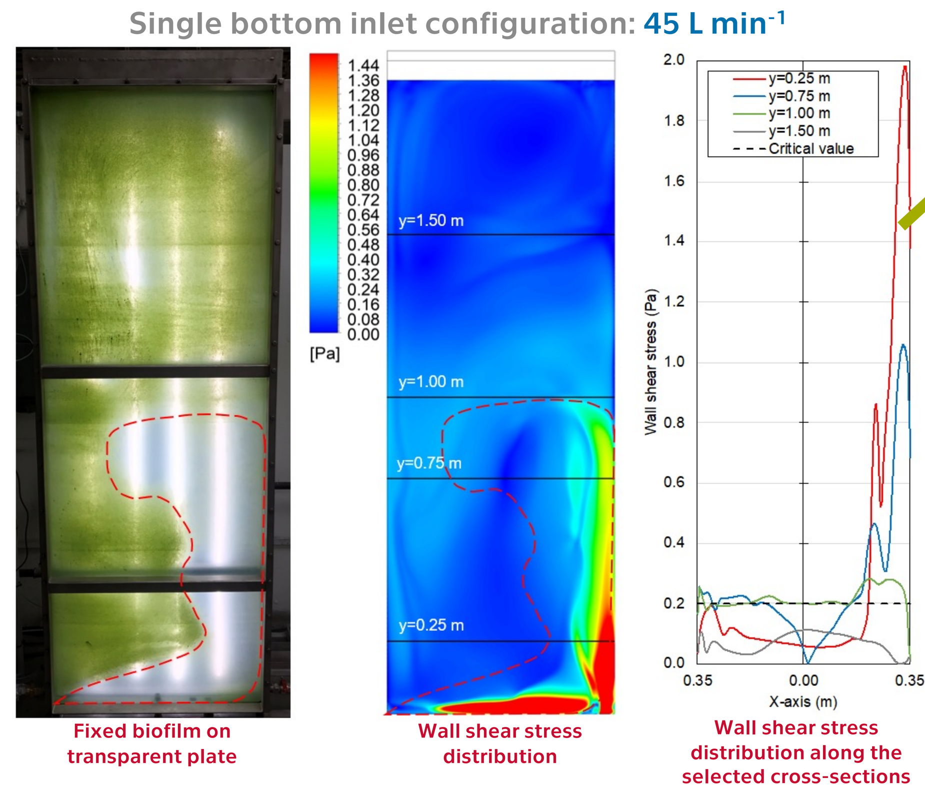
The configuration with single bottom inlet reaches the highest flow velocities. However, the flow in the chamber forms a circulation loop, which can result in the formation of dead zones. In configuration with a double bottom inlet, the flow velocities were still high. The inflows of the culture medium were directed against each other, which results in a mutual dispersion of the flow, which ensures a more uniform flow in the central part of the chamber. In the case of the top inlet configuration, the culture medium reaches the lowest velocities. However, the flow was the most uniform in the central part of the chamber.

Biofilm formation

Biofilm formation reduces light intensity entering into the system and since the light irradiation is one of the crucial processing parameters for the growth of microalgae, the removal of biofilm on the transparent wall of the PBR is a very important step to ensure sufficient and effective performance of the process of cultivation.

Comparison of experimental biofilm formation and CFD simulation of wall shear stress distribution

Single bottom inlet configuration: 45 L min^{-1}



At wall shear stress τ_w values higher than 0.2 Pa, the biofilm formation does not occur. The area with wall shear stress below this critical value accounts for 70 % of the total FP PBR transparent plate area.

The area with wall shear stress below this critical value for various operating conditions:

Configuration	Flow rate (L min^{-1})	Area with τ_w < 0.2 Pa
Single bottom inlet	45	70 %
	63	33 %
Double bottom inlet	45	86 %
	63	82 %

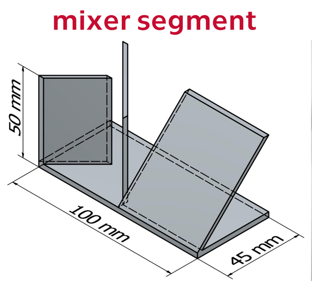
Configuration with a single bottom inlet seems to be more suitable for the elimination or separation of fixed biofilm on transparent walls of the FP PBR. However it is not possible to fully avoid formation of biofilm. Therefore, another operating or design settings of the cultivation system need to be applied.

Static mixer

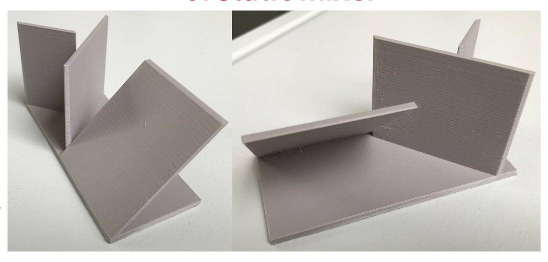
The aim of this work was to design a static mixer that could be installed in the FP PBR chamber. The static mixer should ensure the distribution of the medium flow throughout the cross-section of the chamber, ensure homogenous residence time of the culture medium in the irradiated area, and further intensify the mixing of the culture medium.

The geometry of the static mixer has been designed in order to divide the inflow stream of the medium into several individual streams that will mix with each other.
The CFD model was calibrated and preliminary validated by experimental measurement.

3D model of static mixer segment

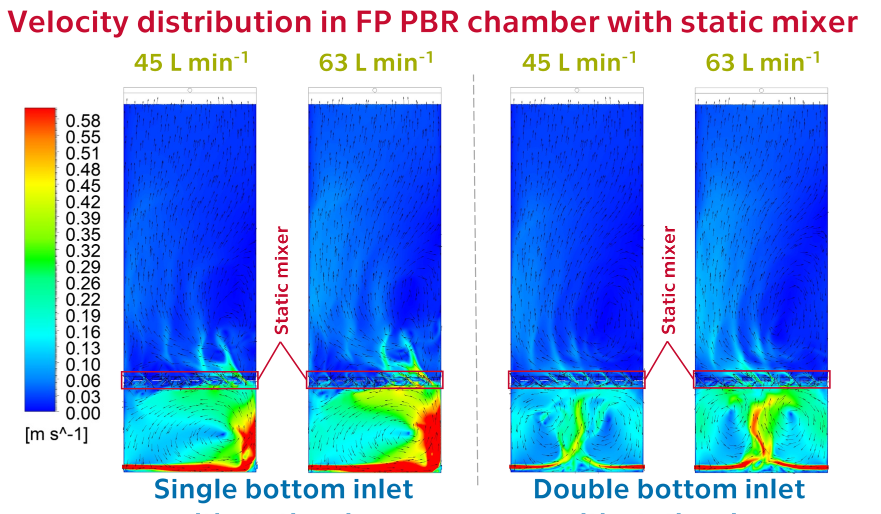


Printed segment of static mixer

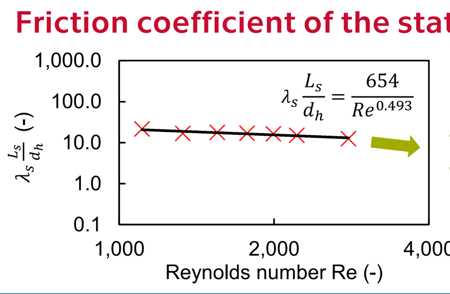


Static mixer installed in FP PBR

Velocity distribution in FP PBR chamber with static mixer



Friction coefficient of the static mixer



Similar behavior at operating conditions approaching the transition between laminar and turbulent flow regime as for conventional static mixers.

Comparison of homogenization time and HRT

Single bottom inlet with static mixer

Inflow (L min^{-1})	HRT (s)	FP PBR chamber	Homogenization time (s)
45	97	Empty	97
		Static mixer	113
63	69	Empty	75
		Static mixer	78

The homogenization time was extended by 17 % in a single bottom configuration using a static mixer at a flow rate of 45 L min^{-1}. By increasing the flow rate to 63 L min^{-1}, the ratio between the empty chamber and the static mixer chamber was reduced to 4 %.

Double bottom inlet with static mixer

Inflow (L min^{-1})	HRT (s)	FP PBR chamber	Homogenization time (s)
45	97	Empty	78
		Static mixer	65
63	69	Empty	64
		Static mixer	42

Using a double bottom inlet and a static mixer, the homogenization time was reduced by 17 % at a flow rate of 45 L min^{-1}, and by 34 % at a flow rate of 63 L min^{-1}.

Conclusion and future research prospects

Numerical models simulating hydrodynamic conditions under different operating conditions were created for selected photobioreactor designs. The applicability of these models was subsequently validated based on the experimental measurements. Following the study of hydrodynamics, the operating conditions for both devices were optimized in order to intensify the microalgae cultivation process. The created numerical model proved its applicability for geometrically similar cultivation systems, which can be useful for optimization of the existing system, scaling-up, or for designing a novel photobioreactor.

The aim of future research will be the application of created models to geometrically similar photobioreactors under full scale conditions. The influence of proposed operational and design optimizations on microalgae production will be further studied.