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Optimization of Hydrodynamics by Installation of Static Mixer in Flat Panel Photobioreactor

Vojtech Belohlav[a,b,*], Tomas Jirout[a], Lukas Kratky[a]

[a]Czech Technical University in Prague, Faculty of Mechanical Engineering, Department of Process Engineering, Technicka 4, 16607, Prague, Czech Republic
[b]Universidad Politécnica de Cataluña, Department of Hydraulic, Maritime and Environmental Engineering, Environmental Engineering and Microbiology Research Group-GEMMA, Jordi Girona 1-3, 08034, Barcelona, Spain
vojtech.belohlav@fs.cvut.cz

Hydrodynamic conditions in pilot or industrial cultivation systems significantly affect the process of microalgae cultivation. It is necessary to ensure sufficient mixing and even distribution of the flowing medium in the entire irradiated area of the photobioreactor (PBR). It is also important to prevent the formation of dead zones in which sedimentation or uneven retention of microalgal cells could occur. In order to intensify the mixing of the processed medium and homogenizes the flow in the entire cross-section of the flat panel PBR chamber, the static mixer was designed. A numerical model of hydrodynamic conditions in PBR with static mixer was validated based on the experimental measurements. Validated model allows a detailed investigation of local hydrodynamic parameters in the PBR chamber. The designed static mixer significantly reduces the homogenization time of the processed medium in the PBR chamber. According to the results, installation of static mixer proved it is possible to eliminate the formation of dead zones.

1. Introduction

Hydrodynamics is important parameter for proper microalgae cultivation in photobioreactors (PBR). It is important to ensure sufficient mixing of the culture medium in cultivation systems (Huang et al., 2014). Due to the higher biomass concentrations or large layer thicknesses of the culture medium, light scattering can occur, which can significantly affect the efficiency of the cultivation system (Cicci et al., 2014). This can lead to the formation of dark zones in the culture medium, where the cells do not receive a sufficient amount of light radiation (Zhang et al., 2013). The flow regime is also important in terms of microalgal biofilm formation on transparent components that could decrease irradiation of culture medium. Therefore, it is necessary to provide sufficient shear stress on the walls of the transparent components. On the other hand, excessively high flow velocities should be avoided to prevent cell stress (Acién Fernández et al., 2001) and to avoid unnecessary energy consumption.

Moreover, achieving a sufficiently intensive mixing of the processed culture medium can be complicated due to the scale-up complexity as well (Schreiber et al., 2017). The scale-up of a flat panel PBR by extending the height of the plates is limited by hydrostatic pressure, which would place more emphasis on the robustness of the structure. The distance between the transparent plates is limited by the light ability to penetrate through the culture medium layer. Janssen et al. (2003) and Zhu et al. (2013) report that a gap greater than 50 mm between transparent plates results in a reduction in total microalgae production. Thus, it seems that the only way how to effectively scale-up the flat panel PBR is to install parallel panels side by side. However, for scaling-up by enlarging the gap between the transparent plates, it is necessary to ensure sufficient mixing of the culture medium in order to provide homogenous light irradiation of all microalgae cells. Huang et al. (2014) in their work investigated the influence of internal mixing elements on the total production of microalgae in the FP PBR with a gap between transparent plates of 150 mm. By installing internal plates, an increase in the residence time in the irradiated area was achieved, which also resulted in an overall increase in the production of microalgae. Wang et al. (2014) described the increase in the production of microalgae depending on the installation of internal elements that extended the residence time of the culture medium in the chamber with a

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distance between transparent plates of 80 mm. The installed internal elements caused not only the increase of microalgae production but also provided the uniform growth conditions of microalgae cells at different locations inside the PBR chamber. Degen et al. (2001) in their work confirm the positive effect of internal mixing elements on the production of microalgae in the culture medium. All mentioned designs work on the principle of extending the residence time in the FP PBR chamber. The inner elements thus divide the PBR chamber into several segments. However, there is no local intensification of mixing in the FP PBR chamber.
The Computational fluid dynamic (CFD) method, which allows to simulate parameters affecting the hydrodynamics in the system, can be used for a detailed description of hydrodynamic conditions in the PBRs. The application of a numerical model can replace complex experimental measurements (Pires et al., 2017). Using the numerical simulations, it is possible to investigate the formation of dead zones in the culture medium (Gómez-Pérez et al., 2015), or the influence of the geometry and internal modifications, such as static mixers, on the process of cultivation. The results of numerical simulations can help to optimize the geometry of the cultivation system (Bitog et al., 2011), however, each numerical model needs to be validated using basic experiments that can determine whether the model corresponds to real hydrodynamic conditions (Pires et al., 2017). From the definition of numerical models, it is possible to define the limitations, which need to be considered during the evaluation of the results.
The aim of this study was to achieve a homogeneous retention time of the processed medium in the irradiated area of the PBR chamber and at the same time to intensify the mixing. A static mixer was designed in order to meet the hydrodynamics requirement and also to allow easy replaceability and maintenance for microalgae processing technology. The influence of the static mixer on the hydrodynamics of the processed medium was tested experimentally and numerically.

2. Material and methods

2.1 Flat panel PBR with static mixer

The volume of the processed medium in the flat panel photobioreactor (FP PBR) chamber is 75 L. The height of the chamber is 2.0 m and the width is 0.7 m. Transparent plates are placed on both sides of the chamber. The chamber is irradiated on one side of the PBR chamber and the intensity of light radiation can be regulated. The distance between the transparent plates is 0.05 m. Inlet and outlet ports are located on the chamber so that it is possible to change the inflow and outflow of the processed medium from the FP PBR chamber. Two inlet necks are located on either side of the bottom part of the FP PBR chamber. One outlet neck is located in the middle of the top part. FP PBR is described in detail in Belohlav et al. (2019). The diagram of the cultivation system, in which the FP PBR chamber is installed, is shown in Figure 1a. The culture medium is pumped from the retention vessel (V-102) by a centrifugal pump (P-103) into the FP PBR chamber (PBR-101). Using the valve V1.1, it is possible to adjust the flowrate of processed medium in chamber PBR-101 according to the ultrasonic flowmeter (FM). Using the valves V2.1 and V2.2, it is possible to change the configuration of the inlet from the one side (single inlet configuration) or two sides (double inlet configuration) of the PBR-101 chamber.

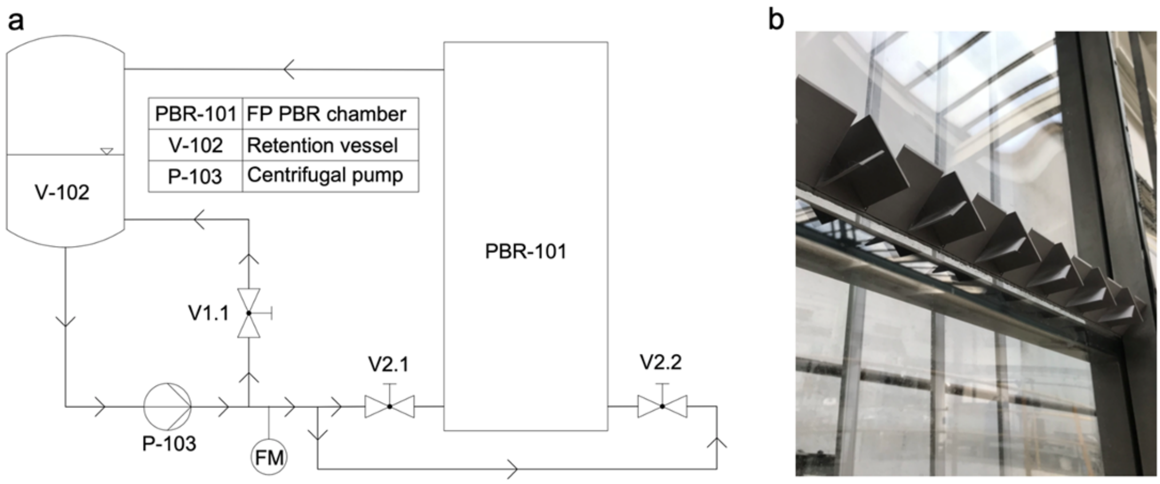

Figure 1: Flat panel PBR system with static mixer, a – schematic diagram of PBR system, b- installed static mixer in PBR chamber

The static mixer (Figure 1b) is located at a distance of 0.46 m from the bottom inlets of the FP PBR chamber. The geometry of the static mixer has been designed to divide the input stream of the medium into several individual streams that will mix with each other. The geometry was further adapted to create flooding behind the blades of the static mixer. The formation of floods behind the blades should result in the formation of eddies and mixing of the processed medium. The static mixer consists of a pair of blades. The blades perpendicular to the transparent walls of the FP PBR direct the flow of the processed medium to the left side of the PBR chamber. By changing the flow direction, the stream of the processed medium can be mixed by the stream directed by the blade inclined to the transparent walls of FP PBR. Reduction of flow cross-section by geometry of blades results in a local increase in flowrate velocity. The entire static mixer consists of seven segments, which were placed along the width of the FP PBR chamber. The geometry and application of the static mixer is protected as a utility model (CZ 34865 U1, registered Feb 23, 2021).

2.2 Description of experiments

Based on experimental measurements, the flow of the culture medium and the homogenization time in the FP PBR chamber were monitored. The pulse-input tracer method (phenolphthalein reacted with sodium hydroxide) was used for monitoring of flow. The tracer was applied to the retention vessel V-102). By setting the valves on the FP PBR chamber (V2.1 and V2.2), the flow of the processed medium for two different configurations was monitored. The first measurement was provided for configuration with single inlet from one side of the chamber. The second configuration correspond the double inlet from both sides of the chamber. Monitoring of flow of the processed medium can be used for validation of the numerical model and for monitoring of hydrodynamic conditions in the irradiated area of the FP PBR chamber. The homogenization time of the processed medium in irradiated area of the chamber was measured as well. The homogenization time determines the time when the monitored tracer is completely dispersed in the entire FP PBR chamber. By comparing the measured homogenization time with the hydraulic retention time (HRT), it is possible to compare the effect of the inlet configuration and the installation of the static mixer on the mixing and homogeneity of the flow in the FP PBR chamber. To compare the function of the static mixer, it is possible to use the results of experimental measurements and hydrodynamic model of the empty chamber FP PBR, which was described in detail in Belohlav et al. (2020). In order to be able to study the effect of the flow of the processed medium on the hydrodynamics in the chamber, all measurements were performed for two flowrate values: 45 L min^{-1} and 63 L min^{-1}. All measurements were repeated several times.

2.3 Numerical model setup

From the analytical calculation of FP PBR operating conditions, it can be assumed that the flow regime was in the range of low turbulent Reynolds number. Therefore, the Re-Normalization Group (RNG) k-ϵ model was used to simulate the fluid dynamics behavior in FP PBR. The hydrodynamic conditions in developed 3D model of FP PBR with static mixer were numerically simulated with the software ANSYS FLUENT CFD 19.1.
The structure of the mesh in the inlet and outlet part of the chamber corresponds to the empty chamber. In the part of the static mixer, the mesh was refined in order to simulate the flow in this area. The total mesh contains 6,676,576 elements with a 2 mm maximum size. The inflation function was applied in the area close to the wall of the model with the maximum size of 0.1 mm. Computations were performed until the calculation converged at a residue of 10^{-5} between two iterations. The mesh quality was checked using skewness reaching the value of 0.23. To simulate the hydrodynamic conditions in the FP PBR model, the inlet was defined by the inlet velocity, and the same conditions were defined for the outlet as well. The flow velocities in the inlet and outlet were selected comparable to the flow simulation in an empty chamber. Specifically, the inlet and outlet velocities were set according to the flowrate of the processed medium during the experimental measurements corresponding to velocities of 2 and 2.8 m s^{-1} for single inlet configuration, and velocities of 1 and 1.4 m s^{-1} for both inlets in double inlet configuration. Properties and physical parameters were set in the model by considering the processed medium as water.

3. Results and discussion

3.1 Homogenization of flow in PBR chamber

The measured values were simultaneously compared with the results of measurements in an empty chamber (Belohlav et al., 2020). The measured values for single inlet configuration are shown in Table 1. The homogenization time is extended when using a static mixer in a single inlet configuration in comparison with empty chamber. At a flowrate of 45 L min^{-1} and 63 L min^{-1}, the homogenization time in the chamber with the static mixer is extended by 16 s and 3 s, respectively. According to the increasing flowrate of the processed medium, the difference in homogenization time compared to the empty chamber decreases. In the chamber with the static mixer and in the empty chamber, the homogenization time is greater or equal to the HRT. The mixing of the processed medium is not sufficiently homogeneous in the whole chamber, which is caused by the formation of dead zones. The dead zones can cause uneven residence time in the irradiated area during the microalgae cultivation, which can result in an overall reduced productivity of microalgae cells.

Table 1: Single inlet configuration – comparison of homogenization time and HRT in empty FP PBR chamber and FP PBR chamber with static mixer

Inflow (L min^{-1})	HRT (s)	PBR configuration	Homogenization time (s)
45	97	Empty chamber	97
		Chamber with static mixer	113
63	68	Empty chamber	75
		Chamber with static mixer	78

In the double inlet configuration (Table 2), the opposite behaviour occurs compared to the empty FP PBR chamber. Specifically, the homogenization time is 13 s shorter at a flowrate of 45 L min^{-1} and even 22 s shorter at a flowrate of 63 L min^{-1}. In the double inlet configuration, there is an overall significant reduction in homogenization time in the chamber with the static mixer in comparison with the empty chamber. Moreover, due to more intensive mixing the homogenization time is lower than the HRT for selected operating conditions.

Table 2: Double inlet configuration – comparison of homogenization time and HRT in empty FP PBR chamber and FP PBR chamber with static mixer

Inflow (L min^{-1})	HRT (s)	PBR configuration	Homogenization time (s)
45	97	Empty chamber	78
		Chamber with static mixer	65
63	68	Empty chamber	64
		Chamber with static mixer	42

3.2 CFD model validation

The tracer was applied to the retention vessel and consequently, the streamlines in the FP PBR chamber were monitored. A model for a flowrate of 45 L min^{-1} was created to validate the CFD model. Validation of the developed CFD model is needed in order to determine its usability for simulation of various conditions of FP PBR with the static mixer. The comparison of tracer measurement and trajectory contours for each setting mode are shown in Figure 2. The contours illustrate the movement of the processed medium in the FP PBR chamber with the static mixer.

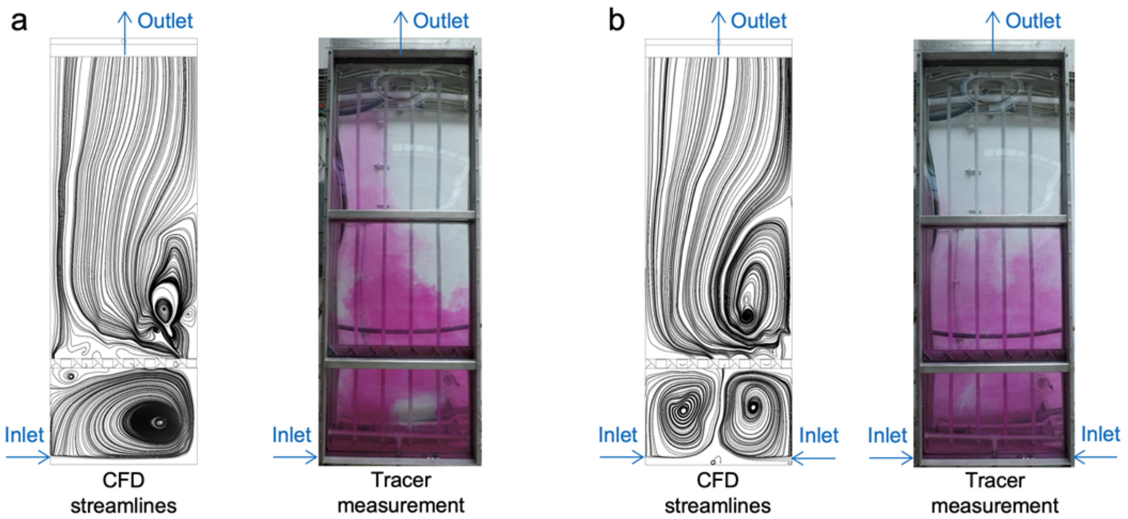

Figure 2: CFD simulation and indicator measurement in FP PBR chamber, flowrate: 45 L min^{-1}, a – single inlet configuration, b – double inlet configuration

Based on the measurement, it can be determined that the measured and simulated streamlines were in a good agreement and the CFD model can be used to simulate various operating conditions in FP PBR with an installed static mixer. From the distribution of the tracer shown in Figure 2a, it is possible to observe an uneven flow of the processed medium in a single inlet configuration. It is evident that dead zones are formed in the upper right part of the chamber. From the distribution of the tracer in the double inlet configuration (Figure 2b), it can be seen that in the lower part of the chamber below the static mixer, the inlet streams disperse with each other, resulting in a more even inflow to the static mixer. The process medium is therefore mixed more efficiently in a static mixer, which results in a more homogenous flow distribution over the entire cross-section of the chamber. The formation of dead zones in the upper right part of the chamber is thus eliminated.

3.3 Hydrodynamics analysis based on CFD simulation

The single inlet configuration (Figure 3a) creates a circulation loop in the lower part of the chamber below the static mixer, which prevents the medium from flowing homogeneously through the segments of the static mixer. On the left side of the static mixer was a minimum flow of medium and, conversely, most of the medium was directed to the right side of the mixer. This causes a local increase in flowrate on the right side of the static mixer. Due to the inflow of only one side of the static mixer, a circulation loop was formed in the upper part of the FP PBR chamber. The medium stream was then returned to the static mixer on the right side of the chamber. A dead zone was formed on the right side of the chamber above the static mixer, where the mixing intensity was very low. At a flowrate of 45 L min^{-1}, the majority of the medium above the static mixer flows on the left side of the chamber. As the flowrate increases to 63 L min^{-1}, more intensive mixing above the static mixer occurs, which results in a partial disturbance of the dead zone. However, the flow was not homogeneous in the cross-section of the FP PBR chamber and the residence time of the processed medium in the chamber was unstable (Table 1).

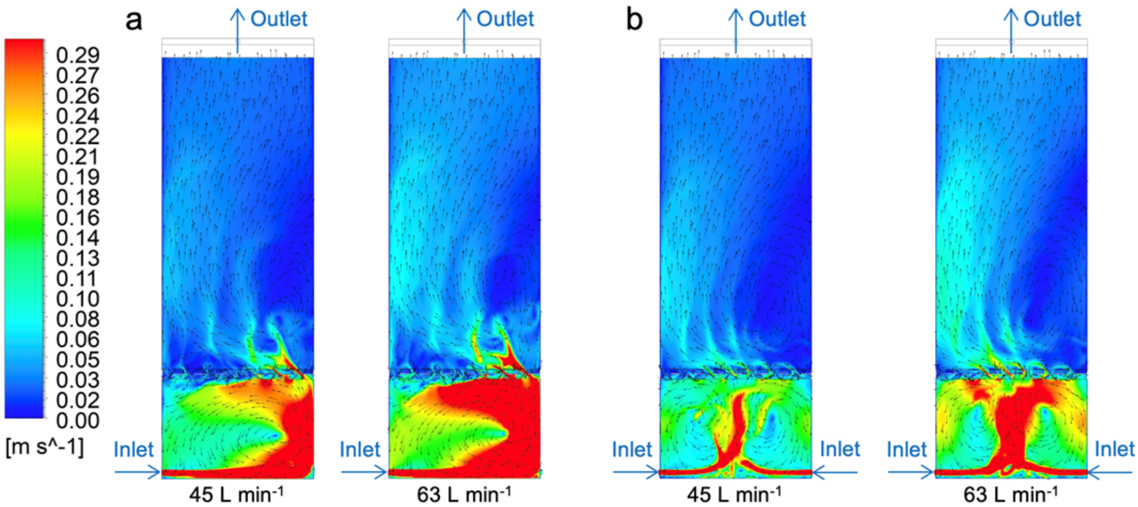

Figure 3: Velocity distribution in FP PBR chamber for various flowrates, a – single inlet configuration, b – double inlet configuration

The double inlet configuration ensures a more uniform flow of medium to the center of the static mixer. The flow behind the static mixer was significantly more stable and homogeneous. The flow distribution for the double inlet in Figure 3b shows a significantly more homogeneous flow distribution in the FP PBR chamber compared to the single inlet configuration. It can be observed that also in the case of the double inlet configuration, the medium reaches higher velocities in the left part of the chamber. However, the formation of dead zones in the right part of the chamber was not so noticeable in comparison with the single inlet configuration. The flow in the left part was caused by the inclination of the blades of the static mixer, which are perpendicular to the transparent surface of the FP PBR (Figure 1b). When the medium flows out of the static mixer, the flow was directed to the left side of the chamber. By installing another static mixer with the inverted rotation of the blades, it would be possible to eliminate the flow on the side of the chamber and further intensify the process of mixing the processed medium. Compared to an empty chamber of FP PBR, the use of a static mixer generally stabilizes the flow in the PBR chamber, which was more homogeneous throughout its cross-section. Moreover, as the flowrate increases, no circulation loop was formed in the center of the chamber.

4. Conclusions

In a single inlet configuration, the flow above the static mixer was directed to the left side of the chamber, which consequently leads to the formation of dead zones. When the flowrate was increased from 45 L min^{-1} to 63 L min^{-1}, the dead zones were partially eliminated, but they were not completely removed. In the double inlet configuration, a more stable inlet to the static mixer was ensured. This makes the flow of medium behind the static mixer more uniform and homogeneous in the cross-section of the FP PBR chamber. Compared to the empty FP PBR chamber, the homogenization time was extended by 17 % in a single configuration using a static mixer at a flowrate of 45 L min^{-1}. By increasing the flowrate to 63 L min^{-1}, the ratio between the empty chamber and the static mixer chamber was reduced to 4 %. The extension of the homogenization time was caused by the formation of dead zones. Conversely, at a flowrate of 45 L min^{-1}, the homogenization time was reduced by 17 % in a double inlet configuration using a static mixer. At a flowrate of 63 L min^{-1}, the homogenization time in the static mixer chamber was reduced by 34 % in the double inlet configuration compared to the empty FP PBR chamber. The double inlet configuration with the static mixer ensures homogeneous flow in the FP PBR chamber and thus eliminates dead zones. At the same time, it reaches the lowest values of the homogenization time.

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References

Acién Fernández, F.G., Fernández Sevilla, J.M., Sánchez Pérez, J.A., Grima, E.M., Chisti Y., 2001, Airlift-driven external-loop tubular photobioreactors for outdoor production of microalgae: Assessment of design and performance, Chemical Engineering Science, 56(8), 2721-2732.

Belohlav, V., Jirout, T., Kratky, L., Uggetti, E., Díez-Montero, R., 2019, Numerical analysis of hydrodynamic conditions in pilot flat-panel photobioreactor: operating and design parameters influence on the microalgae cultivation. European Biomass Conference and Exhibition Proceedings, 255-260.

Belohlav, V., Zakova, T., Jirout, T., Kratky, L., 2020, Effect of hydrodynamics on the formation and removal of microalgal biofilm in photobioreactors, Biosystems Engineering, 200, 315-327.

Bitog, J.P., Lee, I.B., Lee, C.G., Kim, K.S., Hwang, H.S., Hong, S.W., Seo, I.H., Kwon, K.S., Mostafa, E., 2011, Application of computational fluid dynamics for modelling and designing photobioreactors for microalgae production: A review, Computers and Electronics in Agriculture, 76(2), 131-147.

Cicci, A., Stoller, M., Bravi, M., 2014, Analysis of microalgae growth in residual light: A diagnostics tool for low-cost alternative cultural media. Chemical Engineering Transactions, 38, 79-84.

Degen, J., Uebele, A., Retze, A., Schmid-Staiger, U., Trösch, W., 2001, A novel airlift photobioreactor with baffles for improved light utilization through the flashing light effect, Journal of Biotechnology, 92(2), 89-94.

Gómez-Pérez, C.A., Espinosa, J., Montenegro Ruiz, L.C., van Boxtel, A.J.B., 2015, CFD simulation for reduced energy costs in tubular photobioreactors using wall turbulence promoters, Algal Research, 12, 1-9.

Huang, J., Li, Y., Wan, M., Yan, Y., Feng, F., Qu, X., Wang, J., Shen, G., Li, W., Fan, J., Wang, W., 2014, Novel flat-plate photobioreactors for microalgae cultivation with special mixers to promote mixing along the light gradient, Bioresource Technology, 159, 8-16.

Janssen, M., Tramper, J., Mur, L.R., Wijffels, R.H., 2003, Enclosed outdoor photobioreactors: Light regime, photosynthetic efficiency, scale-up, and future prospects, Biotechnology and Bioengineering, 81(2), 193-210.

Pires, J.C.M., Alvim-Ferraz, M.C.M., Martins, F.G., 2017, Photobioreactor design for microalgae production through computational fluid dynamics: A review. Renewable and Sustainable Energy Reviews, 79, 248-254.

Schreiber, C., Behrendt, D., Huber, G., Pfaff, C., Widzgowski, J., Ackermann, B., Müller, A., Zachleder, V., Moudříková, Š., Mejzeš, P., Schurr, U., Grobbelaar, J., Nedbal, L., 2017, Growth of algal biomass in laboratory and in large-scale algal photobioreactors in the temperate climate of western Germany, Bioresource Technology, 234, 140-149.

Wang, L.L., Tao, Y., Mao, X.Z., 2014, A novel flat plate algal bioreactor with horizontal baffles: Structural optimization and cultivation performance, Bioresource Technology, 164, 20-27.

Zhang, Q., Wu, X., Xue, S., Liang, K., Cong, W., 2013, Study of hydrodynamic characteristics in tubular photobioreactors. Bioprocess and Biosystems Engineering, 36(2), 143-150.

Zhu, J., Rong, J., Zong, B., 2013, Factors in mass cultivation of microalgae for biodiesel, Chinese Journal of Catalysis, 34(1), 80-100.