

DESIGN OF FLAT LOOP REACTOR WITH BUBBLE COLUMN CIRCULATION, ALGAE GROWING EQUIPMENT

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Abstract: Based on the flow modeling and operational experience of the previous cylindrical loop reactor, we designed a sheet reactor combined with a loop reactor. The design with a cylindrical cross-section was applied to an equivalent cross-section (sheet) of several squares arranged next to each other. In accordance with the sedimentation processes experienced in the outlet branch, we created an algae trap, thereby reducing the flow to the level necessary for sedimentation. With this, I would like to achieve the already experienced, nearly 10-fold increase in algae concentration compared to the one in the mainstream.

KEYWORDS: Photobioreactor, flat panel reactor, loop reactor, bubble column, sedimentation

1 Introduction

The general problem of photobioreactor (PBR) systems used for artificial algae cultivation is that they develop zones with different light intensities. The light at full intensity only reaches the layer in the direction of the illumination, while the layers behind it receive less and less illumination due to the shading effect of the layers in front of them. This shading, depending on the algae concentration, can cause the algae to die beyond a layer thickness of a few centimeters.

The solution is the turbulence resulting from the flow, which is also necessary for material transfer. As a result, each cell is statistically exposed to the alternation of the dark-light zone. Several authors have investigated the effect of varying light intensity. Light fluctuations with a frequency lower than 1 Hz should be avoided because it already causes a significant reduction in yield [9]. This problem occurs especially in the case of large-scale reactors [13, 23]. In the case of frequencies of kHz or higher, metabolic processes do not stop during light-free periods. This phenomenon is called the "Flashing light effect" [32]. This, in turn, requires such intensive mixing that it can only be achieved with high frictional losses. Therefore, many experiment in the transition range between the two frequencies (1 Hz and 1 kHz) [31].

The light flux reaching the culture is a key parameter from the point of view of the operation of the photobioreactor [26], but the enhancement of the material flow is at least as important [3]. This avoids cell adhesion, which can cause harmful shielding and flow-limiting blockages. On the other hand, the input mechanical energy for maintaining the flow must be limited for two reasons. Due to the intense shearing effect, the cells can be damaged [10, 25, 30] or they can be in a state of increased stress. Higher energy consumption also reduces the economy of production. Based on these, hydrodynamics is directly related to photosynthetic activity and biomass production [26].

Dispersed flow itself promotes mixing in bubble-injection and air-stirred column reactors. This flow phenomenon can be characterized by the axial dispersion coefficient, mixing time, circulation time and the Bodenstein number [22]. Although in the case of bubble column reactors, a shorter mixing time is required, air-mixed systems are still more efficient in terms of productivity [4, 7, 22, 27]. The reason for this is that a less turbulent zone is formed in the ring surrounding the rising bubble in the insert tube, which allows better light penetration. In addition, the presence of the insert tube in the aerated PBR results in more effective mixing because the internal loop that allows the culture to circulate up through the insert tube and down through the annulus between it and the column casing [24]. In addition, air-entrained reactors have a distinct fluid flow and a relatively higher gas-liquid mass flow rate. A problem is that the bubble column can cause uneven cell density along the entire length of the reactor, which can cause starvation and death of the algae [7].

In our previous work [28], we investigated the algae cultivation process in a loop reactor under laboratory conditions. The operation of the equipment was also analyzed with computer modeling and kinematic simulations [29]. During modeling, **CFD** (Computational Fluid Dynamics) simulation, which provides a good approximation, should be used to predict the hydrodynamic and related properties of multiphase flow systems [8, 12, 18].

CFD is used to build a representative calculation model of a system or device. By applying the physics and chemistry of fluid flow to this virtual prototype, fluid dynamics and related physical phenomena can be predicted. The **CFD** technique numerically solves the Navier-Stokes equations in individual cells of the computational domain. **CFD** can be used to study factors that affect flow hydrodynamics, such as surface gas velocity, gas content, bubble diameter, column geometry, antifoam, and pressure.

Since the hydrodynamics of bubble columns are difficult to predict in laboratory experiments, fluid flows are difficult to predict. However, recent publications indicate that the hydrodynamics of bubble columns can be estimated using CFD simulations [14].

Many studies have predicted the dynamic behavior of a single bubble using other approaches, but they cannot accurately model how a bubble swarm or continuous chain in a bubble column behaves, which only the VOF (Volume of fluid) model can do [1]. In addition, the treatment of bubble-bubble interaction and higher-level turbulence becomes increasingly important for bubbles organized in a continuous chain, where models based on interphase forces by studying a single bubble cannot provide good results [1]. The VOF algorithm is designed to also track the position of interfaces between two or more immiscible fluids. This method proved to be more flexible and efficient than other methods for handling complicated independent boundary conditions, especially volume tracking, where the movement of all phases is solved with a group of transport equations, with appropriate boundary condition jumps at the phase boundary [5, 6, 11, 16]. The VOF approach for simulating the bubble motion is based on the Navier-Stokes equations given for the mixed phase. The continuity (continuity) as well as the singular equation of motion can be solved in the entire domain and distributed in all phases ("ANSYS Fluent 15 Users Guide," [2]). Turbulence and energy equations can also be solved in the liquid mixture. The surface tension, the effect of wall adhesion (adhesion) and the compressibility of the phases must also be taken into account. In a bubble column, the VOF simulation technique can be an effective tool for studying the rise speed of individual air bubbles and the serial interaction between bubbles with a hemispherical top. It can be particularly effective for studying the rise rate of individual air bubbles and for modeling the interaction between bubbles with hemispherical tops [1, 15]. Additional advantages of VOF methods are that bubble breakup and merger are handled in a transparent manner [19].

2 Design of a flat loop reactor

In our previous work ([28, 29]) we used a pipe loop reactor with a circular cross-section (Figure 1). During our modeling and experimental work, we developed the optimal operating conditions. blowing in between the two sides was exchanged from time to time.

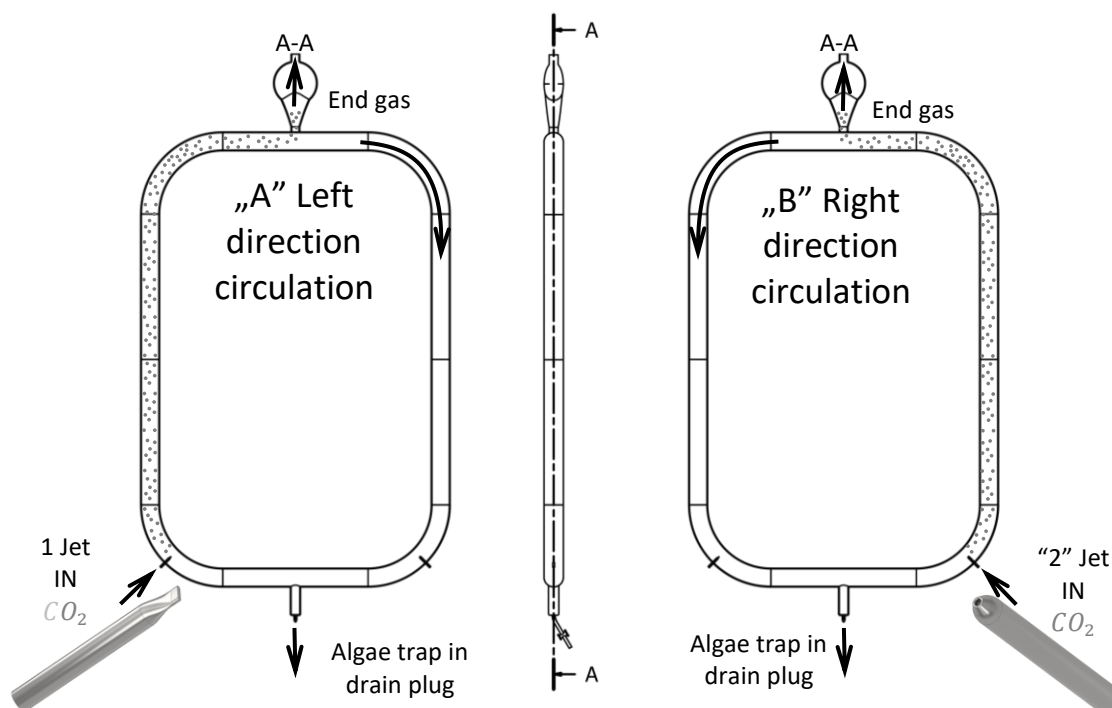


Fig. 1 Former tube bubble column loop reactor with a total volume of 14 liters

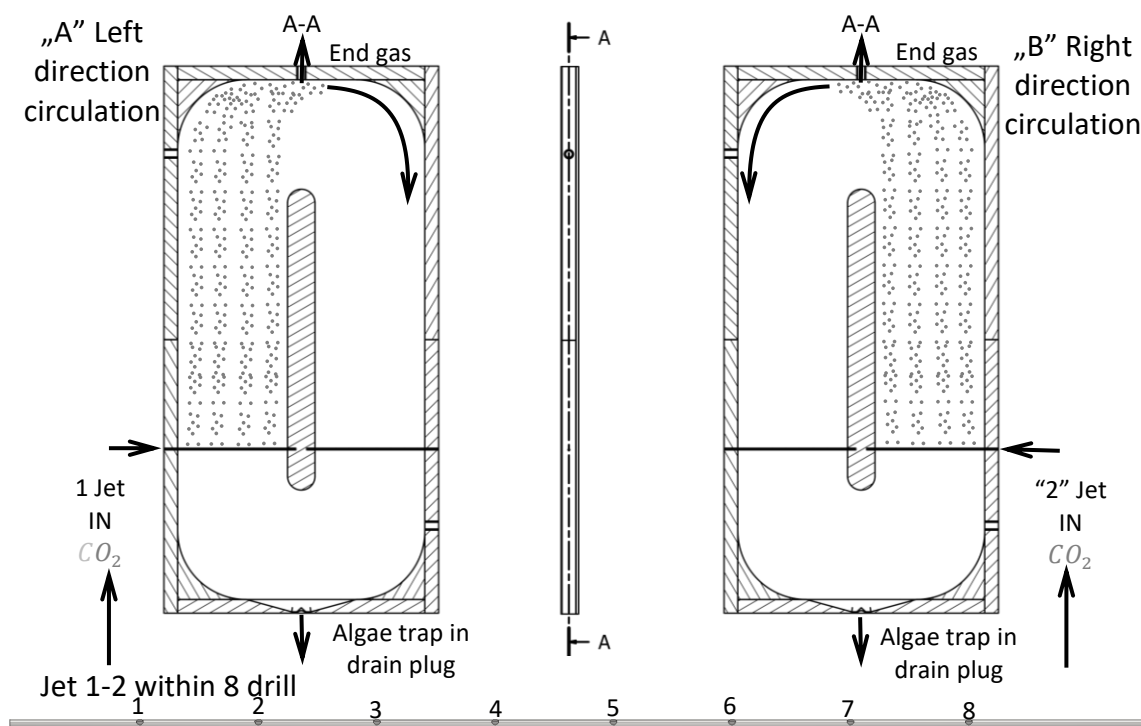


Fig. 2 The new Flat bubble column loop reactor with a total volume of liters (to be calculated).

In the design of the planned plate reactor (Figure 2), we create the possibility of gas injection in a similar direction.

The movement and behavior of bubble columns blown in at several points is similar to the behavior of a series of equivalent concentric loop reactors. Here, the principle loop reactors have a square cross-section. The size compatible with the tubular loop reactor was achieved by matching the diameter of the tube and the diagonal of the rectangle. Structural comparison of the new tubular loop reactor (Figure 3).

Based on our previous tests, the shape of the gas injection nozzles does not significantly affect the flow conditions, so the bubble column starting nozzles were formed by simple holes on the gas inlet pipe (Figure 4).

When designing the PBR, we experimented with several nozzle solutions affecting the incoming air flow, in order to produce the appropriate gas flow and mixing effect (Table 1).

Table 1. Comparison of different nozzles

IN-1 $A=3.14\text{mm}^2$		IN-2 $A=1.57\text{mm}^2$	
			
$Q = 10 \frac{l}{min}$	$Q = 4 \frac{l}{min}$	$Q = 9 \frac{l}{min}$	$Q = 4 \frac{l}{min}$
$v_{Gas} = 53,2 \frac{m}{s}$	$v_{Gas} = 21,3 \frac{m}{s}$	$v_{Gas} = 95,7 \frac{m}{s}$	$v_{Gas} = 42,5 \frac{m}{s}$
$v_{Water} \approx 1,2 \frac{m}{s}$	$v_{Water} \approx 0,39 \frac{m}{s}$	$v_{Water} \approx 1,1 \frac{m}{s}$	$v_{Water} \approx 0,4 \frac{m}{s}$

In the reactor, both nozzles performed well at high inlet air flow:

- Despite the high speed difference, the shearing effect is minimal, the algae cells just remained.
- The mixing effect is adequate, both in terms of the appropriate amount of light and gas exchange.
- The adhesion of algae to the wall is manageable and has remained minimal.

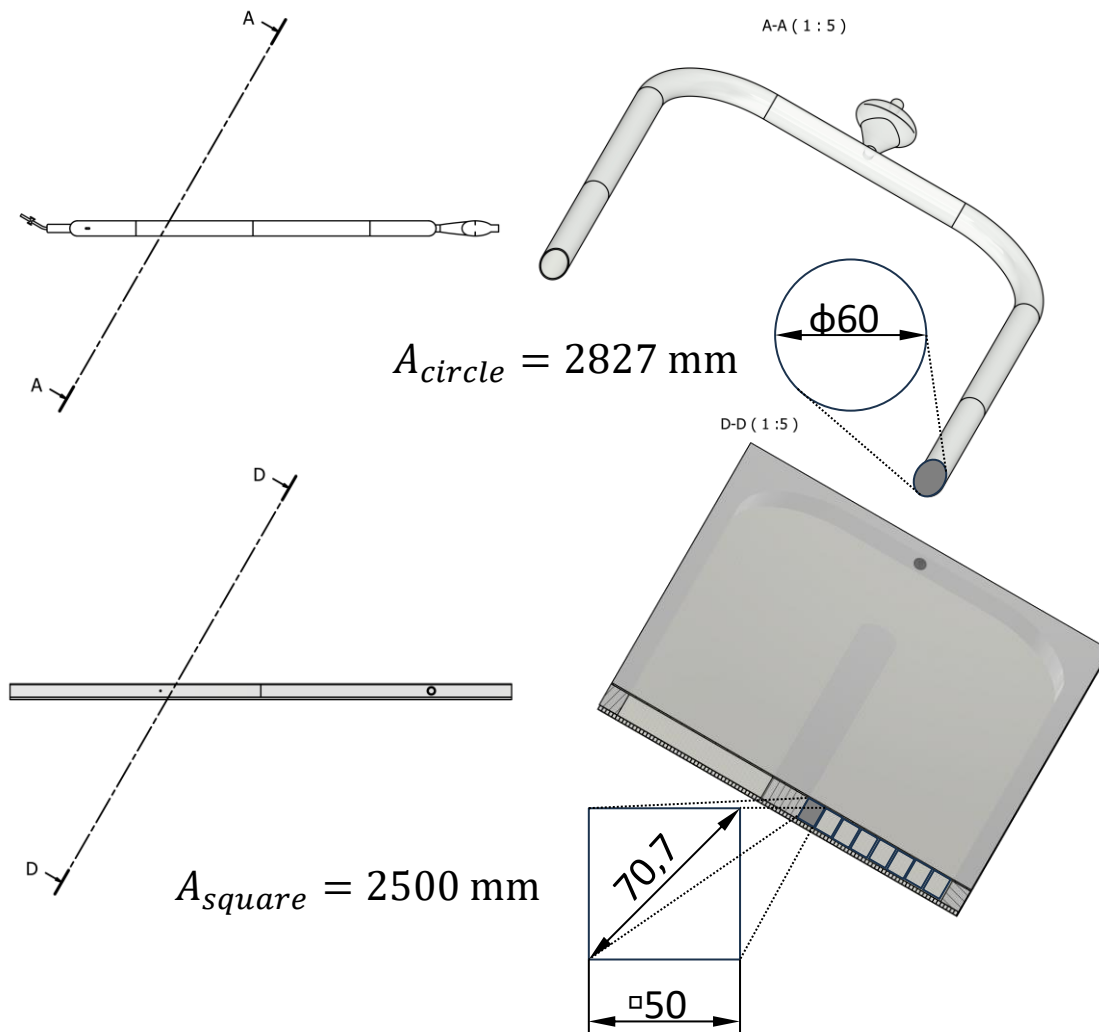


Fig. 3 Comparison of reactor structures based on the cross-section important from the point of view of light penetration

CONCLUSION

Based on the flow modeling and operating experience of a laboratory, cylindrical loop reactor, we designed a plate reactor suitable for semi-operational operation. In the planned sheet reactor, we used the working principle proven in the loop reactor, the circulation of the medium, which is created with the help of bubble columns. With the option of alternately injecting the gas, we can induce a flow of the growing medium in alternating directions, which reduces the chance of algae deposition. In addition to creating suitable flow conditions, the chance of deposition is further reduced by the use of the algae trap developed in the previous solution. Thus, due to the continuity of algae harvesting, the optimal algae concentration can be stabilized in the reactor.

REFERENCES

- [1] Akhtar, A., Pareek, V., Tadé, M. "CFD Simulations for Continuous Flow of Bubbles through Gas-Liquid Columns": Application of VOF Method. Chem. Prod. Process Model 2, pp. 1 – 19, **2007**. DOI: 10.2202/1934-2659.1011
- [2] "ANSYS Fluent 15 Users Guide", ANSYS Inc., pp. 1 – 2620, **2013**. <http://www.ansys.com>

- [3] Contreras, A., García, F., Molina, E., Merchuk, J.C. "Interaction between CO₂-mass transfer, light availability, and hydrodynamic stress in the growth of *Phaeodactylum tricornutum* in a concentric tube airlift photobioreactor", *Biotechnol. Bioeng* 60, pp. 317 – 325, **1998**. DOI: 10.1002/(SICI)1097-0290(19981105)60:3<317:AID-BIT7>3.0.CO;2-K
- [4] Degen, J., Uebele, A., Retze, A., Schmid-Staiger, U., Trösch, W. "A novel airlift photobioreactor with baffles for improved light utilization through the flashing light effect", *J. Biotechnol.* 92, pp. 89 – 94, **2001**. DOI: 10.1016/S0168-1656(01)00350-9
- [5] Delnoij, E., Kuipers, J.A.M., van Swaaij, W.P.M. "Computational fluid dynamics applied to gas-liquid contactors" *Chem. Eng. Sci.* 52, pp. 3623 – 3638, **1997**. DOI: 10.1016/S0009-2509(97)00268-6
- [6] Delnoij, E., Lammers, F.A., Kuipers, J.A.M., van Swaaij, W.P.M. "Dynamic simulation of dispersed gas-liquid two-phase flow using a discrete bubble model", *Chem. Eng. Sci.* 52, pp. 1429 – 1458, **1997**. DOI: 10.1016/S0009-2509(96)00515-5
- [7] Fan, L.-H., Zhang, Y.-T., Cheng, L.-H., Zhang, L., Tang, D.-S., Chen, H.-L., "Optimization of Carbon Dioxide Fixation by *Chlorella vulgaris* Cultivated in a Membrane-Photobioreactor", *Chem. Eng. Technol.* 30, pp. 1094 – 1099, **2007**. DOI: 10.1002/ceat.200700141
- [8] Grace, J. R., Taghipour, F. "Verification and validation of CFD models and dynamic similarity for fluidized beds", *Powder Technol.* 139, pp. 99 – 110, **2004**. DOI: 10.1016/j.powtec.2003.10.006
- [9] Grobbelaar, J. U., Nedbal, L., Tichý, V. "Influence of high frequency light/dark fluctuations on photosynthetic characteristics of microalgae photoacclimated to different light intensities and implications for mass algal cultivation", *J. Appl. Phycol.* 8, pp. 335 – 343, **1996**. DOI: 10.1007/BF02178576
- [10] Gudin, C., Chaumont, D. "Cell fragility - The key problem of microalgae mass production in closed photobioreactors", *Bioresour. Technol.* 38, pp. 145 – 151, **1991**. DOI: 10.1016/0960-8524(91)90146-B
- [11] Hirt, C. W., Nichols, B. D. "Volume of fluid (VOF) method for the dynamics of free boundaries", *J. Comput. Phys.* 39, pp. 201 – 225, **1981**. DOI: 10.1016/0021-9991(81)90145-5
- [12] Hutmacher, D. W., Singh, H. "Computational fluid dynamics for improved bioreactor design and 3D culture", *Trends Biotechnol.* 26, pp. 166 – 172, **2008**. DOI: 10.1016/j.tibtech.2007.11.012
- [13] Janssen, M., Slenders, P., Tramper, J., Mur, L.R., Wijffels, R.H. "Photosynthetic efficiency of *Dunaliella tertiolecta* under short light/dark cycles", *Enzyme Microb. Technol.* 29, pp. 298 – 305, **2001**. DOI: 10.1016/S0141-0229(01)00387-8
- [14] Kommareddy, A., Anderson, G. "Analysis of Currents and Mixing in a modified Bubble Column Reactor", *Pap. Number 043071 2004 ASAE Annu. Meet.* Published by the American Society of Agricultural and Biological Engineers, St. Joseph, Michigan, **2004**. DOI: 10.13031/2013.17681
- [15] Krishna, R., Van Baten, J. M. "Scaling up Bubble Column Reactors with the Aid of CFD", *Chem. Eng. Res. Des.* 79, pp. 283 – 309, **2001**. DOI: 10.1205/026387601750281815

- [16] Krishna, R., van Baten, J.M. "Rise characteristics of gas bubbles in a 2D rectangular column: VOF simulations vs experiments", *Int. Commun. Heat Mass Transf.* 26, pp. 965 – 974, **1999**. DOI: 10.1016/S0735-1933(99)00086-X
- [17] Launder, B.E., Spalding, D.B. "Lecture on Mathematical Models of Turbulence", London; New York: Academic Press, London, **1972**.
- [18] Leib, T.M., Pereira, C.J., Villadsen, J. "Bioreactors: a chemical engineering perspective", *Chem. Eng. Sci.* 56, pp. 5485 – 5497, **2001**. DOI: 10.1016/S0009-2509(01)00173-7
- [19] Lörstad, D., Fuchs, L. "High-order surface tension VOF-model for 3D bubble flows with high density ratio", *J. Comput. Phys.* 200, pp. 153 – 176, **2004**. DOI: 10.1016/j.jcp.2004.04.001
- [20] Macleave, H., Cézanne, P. "A festő és a hegy. (A man and his mountain) ", Cézanne élete. (Ford. G. Beke Margit, Falvay Mihály). Gondolat, Budapest, **1986**.
- [21] Merchuk, J.C., Gluz, M., Mukmenev, I. "Comparison of photobioreactors for cultivation of the red microalga *Porphyridium* sp", *J. Chem. Technol. Biotechnol.* 75, pp. 1119 – 1126, **2000**. DOI: 10.1002/1097-4660(200012)75:12<1119:AID-JCTB329>3.0.CO;2-G
- [22] Mirón, A. S., Gómez, A. C., García Camacho, F., Molina Grima, E., Chisti, Y. "Mixing in Bubble Column and Airlift Reactors", *Chem. Eng. Res. Des.* 82, pp. 1367–1374, **2004**. DOI: 10.1205/cerd.82.10.1367.46742
- [23] Molina, E., Fernández, J., Acién, F. G., Chisti, Y. "Tubular photobioreactor design for algal cultures", *J. Biotechnol.* 92, pp. 113 – 131, **2001**. DOI: 10.1016/S0168-1656(01)00353-4
- [24] Oncel, S., Sukan, F. V. "Comparison of two different pneumatically mixed column photobioreactors for the cultivation of *Arthrospira platensis* (*Spirulina platensis*) ", *Bioresour. Technol.* 99, pp. 4755 – 4760, **2008**. DOI: 10.1016/j.biortech.2007.09.068
- [25] Panda, A. K., Mishra, S., Bisaria, V. S., Bhojwani, S. S. "Plant cell reactors - A perspective. *Enzyme Microb*", *Technol.* 11, pp. 386 – 397, **1989**. DOI: 10.1016/0141-0229(89)90132-4
- [26] Pruvost, J., Pottier, L., Legrand, J. "Numerical investigation of hydrodynamic and mixing conditions in a torus photobioreactor", *Chem. Eng. Sci.* 61, pp. 4476 – 4489, **2006**. DOI: 10.1016/j.ces.2006.02.027
- [27] Ranjbar, R., Inoue, R., Katsuda, T., Yamaji, H., Katoh, S. "High efficiency production of astaxanthin in an airlift photobioreactor", *J. Biosci. Bioeng.* 106, pp. 204 – 207, **2008**. DOI: 10.1263/
- [28] Tolner, I.T. "Kinematikai szimulációk, mérések egy modell csöves algatermesztő berendezésben (PhD Dolgozat) ", Széchenyi István Egyetem, Wittmann Antal Növény-, Állat- és Élelmiszer-tudományi Multidiszciplináris Doktori Iskola, 2019. (in Hungarian)
- [29] Tolner, I.T., Neményi, M., Jančo, R. "Flow Simulation in an Alga Photobioreactor Tested Under Laboratory Conditions", *Strojnícky Časopis – Journal of Mechanical Engineering* 74, pp. 35 – 44, **2024**. DOI: 10.2478/scjme-2024-0004
- [30] Thomas, W.H., Gibson, C.H. "Effects of small-scale turbulence on microalgae", *J. Appl. Phycol.* 2, pp. 71 – 77, **1990**. DOI: 10.1007/BF02179771
- [31] Yoshimoto, N., Sato, T., Kondo, Y. "Dynamic discrete model of flashing light effect in photosynthesis of microalgae", *J. Appl. Phycol.* 17, pp. 207 – 214, **2005**. DOI: 10.1007/s10811-005-7908-y

- [32] Zou, N., Richmond, A. "Light-path length and population density in photoacclimation of *Nannochloropsis* sp. (Eustigmatophyceae) ", J. Appl. Phycol. 12, pp. 349 – 354, **2000**. DOI: 10.1023/A:1008151004317