

Design Methodology of Industrial Equipment for Microalgae Biomass Primary Harvesting and Dewatering

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Microalgae cultivation is considered as one of the promising technologies for CO₂ utilization and the biomass can be further used for the production of biofuels or high-value products. The processes of harvesting and dewatering of produced microalgae are complex since the microalgae cells are very small and the density is similar to the density of the culture medium. The separation has a major impact on the total biomass production cost. It is not possible to determine one separation system that is the most appropriate for specific microalgae species. In this paper, a methodology for the design of harvesting and dewatering equipment was developed based on the measured settling velocity and microalgae cell size. Sedimentation tests and distribution of particles were performed for different algal concentrations. This work describes the design methodology of the separation units for the primary harvesting and dewatering of microalgae mixture by gravitational and centrifugal forces. The basic design parameters of separation systems were selected according to the three demonstrative applications. The rest of the basic parameters were defined based on the developed design methodology and geometrically similar existing industrial equipment. Limitations of individual systems for the given configurations were emphasized. The disc centrifuge seems to be the most appropriate equipment for the selected demonstrative systems.

1. Introduction

In December 2019, the Copenhagen Climate Change Conference was held, and it was the first time that a consensus recognizing the global average temperature rise shall not be over 2 °C, was specified (Gao et al., 2017). According to the Climate Change Conference in Katowice in 2018, the limitation of the temperature decrease to 1.5 °C by 2050. The burning of fossil fuels releases an enormous amount of carbon dioxide CO₂ into the atmosphere and it can be the primary cause of global warming and environmental pollution. Various possibilities to prevent global warming have been developed in recent years, including Carbon Capture and Storage (CCS) and Carbon Capture and Utilization (CCU) (Cuéllar-Franca and Azapagic, 2015). The advantage of CCU is the ability to convert waste CO₂ into high-value products, which may affect overall economic evaluation compared to CCS technologies.

Microalgae cultivation is one of the promising methods that could be used to capture and subsequently utilize CO₂ from flue gases (Assis et al., 2019). Microalgae are able to process 1.8 to 2 kg of CO₂ to produce 1 kg of biomass (Chisti, 2007). Microalgae require for proper growth addition of CO₂ and a sufficient amount of light and nutrients at a certain temperature. As a source of nutrients for microalgae growth, it is possible to use sewage medium from wastewater treatment technologies. Microalgae can use nutrients contained in the medium for their growth, and at the same time, pollutants from sewage can be effectively eliminated (Wang et al., 2016). The produced microalgae biomass can be further used in a wide range of industries: chemical, food or pharmaceutical (Ruiz et al., 2016).

The microalgae are cultivated in open systems or closed photobioreactors (PBR). A large number of the various design configuration of cultivation systems on the industrial scale has been developed (Belohlav et al., 2018). Microalgae are treated in the cultivation systems in the form of highly diluted suspension of about 0.05 - 0.5 %

of dry solids (Moheimani et al., 2016). Microalgae cells are very small, and the density is similar to the density of the culture medium. Grima et al. (2003) reported a cell diameter in the range of 3 - 30 μm . Microalgae strains such as *Chlorella*, *Scenedesmus*, *Dunaliella* have a diameter less than 30 μm . *Spirulina* and *Coelastrum* can reach diameters greater than 70 μm (Brennan and Owende, 2010). The density of microalgae and culture medium suspension varies between 1,040 and 1,140 kg m^{-3} (Milledge and Heaven, 2013). All of these parameters make the process of dewatering and harvesting the produced microalgae from the culture medium more complicated. Due to this, harvesting and dewatering have a major impact on total biomass production cost. Mata et al. (2010) presented that the recovery from the culture medium accounts for 20 - 30 % of the total biomass production cost. Milledge and Heaven (2013) state that up to 90 % of equipment costs can be formed by harvesting and dewatering in open cultivation systems.

Grima et al. (2003) defined centrifugation as the best option for recovering high-value microalgae biomass from the culture medium. The process of centrifugation may be also preceded by adding flocculants in order to intensify the separation. If the microalgae cell structure is disturbed during separation in a centrifuge, microfiltration seems to be the most appropriate technique. Based on the predefined criteria, Singh and Patidar (2018) preferred coagulation/flocculation, centrifugation, and filtration for microalgae separation. Application of each technology depends on the specific requirements of the final product and cultivated microalgae species. It is not possible to determine the most suitable option due to the various operational and qualitative requirements for the harvesting and dewatering and in some specific cases, the combination of separation technologies is the most efficient. Japar et al. (2017) presented filtration, flocculation, bio-flocculation, and electro-coagulation-filtration as the best option. On the other hand, flotation and electrochemical harvesting techniques appear to be the least suitable for microalgae separation. Filtration can only be used for microalgae particles larger than 70 μm . For particles smaller than 30 μm , microfiltration or ultrafiltration is preferable. In general, filtration is more suitable for a smaller amount of processed culture medium. For volumes of less than 2 m^3 of processed culture medium, filtration may be more economically feasible than centrifugation (Brennan and Owende, 2010). Fasaie et al. (2018) describe the inappropriate application of spiral centrifuges for large scale cultivation. The lowest cost and energy consumption were achieved during harvesting by filtration and centrifugation. The costs of flocculation techniques are comparable to mechanical harvesting and dewatering methods. The use of flocculants is limited due to the quality requirements for the final microalgae biomass products.

According to previously mentioned studies, it is not possible to determine the most appropriate method for microalgae separation. Harvesting and dewatering processes are affected by several parameters. In addition to the physical properties of the microalgae strains, also the processing time, microalgae concentration in the culture medium, the density of the culture medium and the capacity of the cultivation system are crucial parameters. Investment and operational costs are crucial for overall evaluation as well. The aim of this work was to develop a design methodology of industrial equipment for harvesting and dewatering of microalgae biomass. Based on the basic physical and operational parameters of the culture medium, it is possible to determine the geometric arrangement of the main mechanical separation technologies. Furthermore, a demonstrative basic design of equipment was elaborated for its application on the industrial scale.

2. Design methodology

The separation of produced microalgae is dependent on parameters that are specific to each microalgae species. The methodology was developed based on these parameters in order to determine the most appropriate technology for harvesting and dewatering. The settling velocity and particles distribution of microalgae cells were measured for the selected algal culture. Based on the measurement, it is possible to determine the sedimentation velocity required for the design of gravitational sedimentation. The equivalent particles size for centrifugal sedimentation design can be also determined since the concentration of particles in the culture medium is low. This work describes the design methodology of the separation units for the primary harvesting and dewatering of microalgae mixture by gravitational and centrifugal forces. The basic design of the continuous and semi-continuous equipment (circular settler/thickener, lamella settler, decanter centrifuge, disc centrifuge) was developed, based on the sedimentation test and distribution of microalgae cells. The methodology is developed in order to remove all reference particles of microalgae. The density difference of culture medium and microalgae suspension can be determined pycnometrically. The mentioned parameters were experimentally verified in this work.

2.1 Settling velocity and microalgae particles distribution

The sedimentation test is described by a sedimentation curve, which is characterized by the dependence of height of the interface between the clear liquid and the settling suspension over time. The curve was elaborated according to the results of settling measurement in glass cylinders (250 mL). The interface between the clear liquid and settling suspension was measured over time (30 min intervals). The cylinders were covered in order

to avoid light irradiation of suspension, which could affect the activity of the microalgae and subsequently settlement rate as well (Milledge and Heaven, 2013). A mixture of culture medium (water with nutrients) and *Chlorella* was used for measurement. Subsequently, the settling velocity of the microalgae cells was determined. Laser particle sizer (Fritsch analysette 22 COMPACT) was used to determine the particle size distribution in microalgae suspension (measuring range 0.3 - 300 μm).

2.2 Gravitational separation

2.2.1 Circular settler/thickener

The suspension is fed through the center inlet (inner radius R_1) and the clarified culture medium is drained through overflow located in the top of the settler (Figure 1a). The settler is designed in order to ensure particle sedimentation at least on the outer radius R_2 . Between the inlet R_1 and outer radius R_2 , the settling particles track parabolic pathway. The outer radius of the circular settler can be determined.

$$R_2 = \sqrt{R_1^2 + \frac{V_{su}}{\pi u_s}} \quad (1)$$

where V_{su} ($\text{m}^3 \text{s}^{-1}$) is the suspension flow rate from cultivation system and u_s (m s^{-1}) is the settling velocity of the produced microalgae cells. The circular settler can be used also for primary thickening. The suspension with concentration c_{su} (kg m^{-3}) is continuously fed through the center inlet R_1 , and thickened sludge with concentration c_t (kg m^{-3}) is continuously removed from the bottom of the settler. The clarified culture medium is drained through the overflow and it can be recirculated in the cultivation system again. The settler cross-sectional area can be determined.

$$S = \frac{V_{su} c_{su}}{u_s} \left(\frac{1}{c_{su}} - \frac{1}{c_t} \right) \quad (2)$$

2.2.2 Lamella settler

The suspension is continuously fed to a lamella settler where the particles are separated between the inclined lamellae (Figure 1b). Separated sludge settling between the lamellae into the thickening area at the bottom of the settler. The purified culture medium flowing through the lamellae to the overflow placed at the top of the settler. For the selected basic design parameters, it is possible to determine the flow rate of the processed suspension.

$$V_{su} = i u_s L W \cos \alpha \quad (3)$$

where i (-) is the number of lamellae in the settler, L (m) is the length of the lamella, W (m) is the width of the lamella and α ($^\circ$) is the angle of lamella inclination.

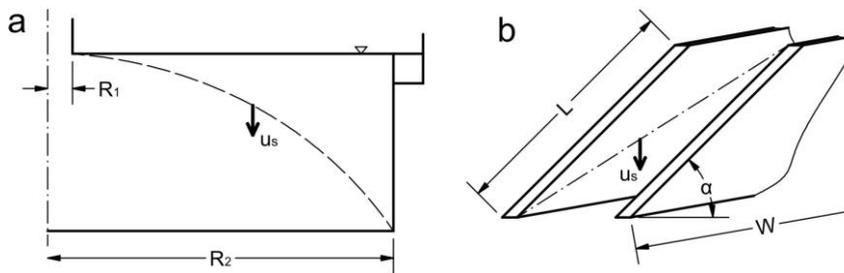


Figure 1: Scheme of gravitational separation equipment, a – circular settler, b – lamella settler

2.3 Centrifugal separation

2.3.1 Decanter centrifuge

The particles settling on the outer wall of the bowl due to the effect of centrifugal forces (Figure 2a). After separation of the particles, the clarified culture medium is drained away and particles are continuously removed by a screw conveyor. As already mentioned, the difference between the density of microalgae particles and the density of the culture medium is negligible. According to this, it can be assumed that the sedimentation process is very slow. Therefore, sedimentation can be described by Stokes's law (Milledge and Heaven, 2013). Consequently, it is possible to determine the settling time of the particles.

$$t_s = \frac{18 \mu}{D_p^2 (\rho_p - \rho_l) \left(2\pi \frac{n}{60}\right)^2} \ln \frac{r_2}{r_1} \quad (4)$$

where μ (Pa s) is the dynamic viscosity of the culture medium, D_p (m) is the diameter of separated microalgae particles, ρ_p (kg m^{-3}) is the density of particles, ρ_l (kg m^{-3}) is the density of culture medium, n (rpm) is the bowl speed, r_2 (m) is the outer radius of the bowl and r_1 (m) is the inner diameter of the rotating screw conveyor. Amount of processed suspension in the decanter centrifuge can be specified.

$$V_{su} = \frac{\pi(r_2^2 - r_1^2)H}{t_s} \quad (5)$$

where H (m) is the length of the bowl.

2.3.2 Disc centrifuge

The suspension is fed into the centrifuge through the central inlet. The particles are separated on the wall of the stator drum (Figure 2b). Centrifugal forces are ensured by the rotating discs, which are attached to the inlet tube. Discs with the inlet are placed inside the stator drum. The clarified culture medium is discharged through the disks out of the centrifuge. The settling velocity described by Stoke's law can be specified.

$$u_s = \frac{D_p^2 (\rho_p - \rho_l) \left(2\pi \frac{n}{60}\right)^2}{18 \mu} r_2 \quad (6)$$

where r_2 (m) is the outer radius of rotating discs. The radial component of peripheral velocity u_{sr} (m s^{-1}) can be determined from correlation.

$$\frac{u_{sr}}{u_s} = 0.27 \left(\frac{r_1}{r_2}\right)^{-0.397} \left(\frac{h}{r_2 \tan \varphi}\right)^{-0.957} \quad (7)$$

where r_1 (m) is the inner radius of rotating discs, h (m) is the axial distance between discs and φ ($^\circ$) is the angle of disc inclination. The flow rate of processed culture medium can be specified.

$$V_{su} = i 2 \pi r_2 h u_{sr} \quad (8)$$

where i (-) is the number of discs in the centrifuge.

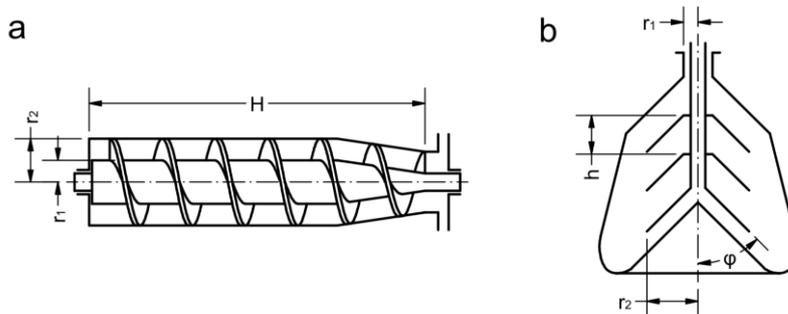


Figure 2: Scheme of centrifugal separation equipment, a – decanter centrifuge, b – disc centrifuge

3. Results and discussion

3.1 Settling velocity and particle distribution

Two sedimentation tests for different algal concentrations were performed. The first measurement (microalgae concentration 1.1 g L^{-1}) provided a settling velocity of 0.048 m d^{-1} . For the second measurement (2.7 g L^{-1}), settling velocity was 0.024 m d^{-1} . Measurement of particle distribution was performed for two microalgae suspension samples. Mean diameter was $5.12 \mu\text{m}$ and $5.19 \mu\text{m}$. Milledge and Heaven (2013) presented that settling velocity ranged from 0.1 to 3.6 m d^{-1} . The settling velocity varies according to the microalgae species properties and the suspension concentration. In general, the settling velocity of 0.1 m d^{-1} for green microalgae and $0 - 0.05 \text{ m d}^{-1}$ for cyanobacteria was presented. The diameter of *Chlorella* cells is in the range of $2 - 10 \mu\text{m}$ (Adamczyk et al., 2016). According to the measured values, the reference settling velocity and the particle diameter were selected for further design methodology 0.048 m d^{-1} and $5 \mu\text{m}$, respectively.

3.2 Design methodology

The basic design parameters of separation systems were selected according to three demonstrative applications. The calculation simulates the design for pilot and full-scale applications. Therefore, the following volumes of suspensions from cultivation systems were chosen for the design of the separation units: $0.3 \text{ m}^3 \text{ h}^{-1}$ for 0.2 ha cultivation system (García et al., 2018), $10 \text{ m}^3 \text{ h}^{-1}$ for 1 ha system (Deconinck et al., 2018), and $250 \text{ m}^3 \text{ h}^{-1}$ for 100 ha system (Fasaei et al., 2018). The basic design parameters were chosen according to the existing industrial equipment. The chosen design parameters and the corresponding performance of each system are shown in Table 1. Parameters that cannot be technically implemented or insufficient performance are marked with an asterisk. The circular settler can be used for a capacity of 0.3 and $10 \text{ m}^3 \text{ h}^{-1}$. For a suspension flow rate of $250 \text{ m}^3 \text{ h}^{-1}$, the outer radius of the settler is enormous. Therefore, it would be necessary to use several parallel circular settlers in order to process high productivity. A similar option is lamella settler as well. The amount of processed suspension can be increased by the addition of lamellas plates. For large scale capacities, it is necessary to install several lamella settlers in parallel.

Table 1: Design and process parameters, *Technically infeasible parameter or insufficient performance

Separation system	Parameter	Performance of cultivation system - Suspension flow rate		
		$0.3 \text{ m}^3 \text{ h}^{-1}$	$10 \text{ m}^3 \text{ h}^{-1}$	$250 \text{ m}^3 \text{ h}^{-1}$
Circular settler	R_1 (m)	0.05	0.05	0.05
	R_2 (m)	7.0	40.0	200.0*
	V_{su} ($\text{m}^3 \text{ h}^{-1}$)	0.31	10.05	251.40
Lamella settler	L (m)	2.4	2.4	2.4
	W (m)	3	5	5
	i (-)	30	120	500
	V_{su} ($\text{m}^3 \text{ h}^{-1}$)	0.31	2.04*	8.50*
Decanter centrifuge	r_1 (m)	0.05	0.12	0.175
	r_2 (m)	0.1	0.225	0.325
	H (m)	0.7	2.3	2.5
	n (rpm)	2,500	3,300	2,900
	V_{su} ($\text{m}^3 \text{ h}^{-1}$)	0.33	10.14	17.89*
Disc centrifuge	r_1 (m)	0.064	0.064	0.12
	r_2 (m)	0.125	0.125	0.4
	n (rpm)	1,500	3,900	3,000
	i (-)	20	82	87
	V_{su} ($\text{m}^3 \text{ h}^{-1}$)	0.33	10.39	251.47

For the separation of microalgae using centrifugal forces, a large number of configurations can be used. It is possible to vary the processed capacity of the suspension by choosing the design and operating parameters. The influence of productivity fluctuation of the cultivation system, and investment and operational costs are significant during the selection of appropriate configurations. The advantage is that it is possible to customize the separation units to seasonal production. For instance, during the winter season, when the production is lower, the centrifuges with lower performance can be used. On the other hand, during the summer season, the full capacity can be operated.

The application of disc centrifuge seems to be the most appropriate option for specified microalgae cultivation system configurations. The performance can be controlled by selecting the number of disks or the rotational speed. Disc centrifuge can process a wide range of suspension amount in a very small built-up area. At the same time, it is also important to assess the impact of economic aspects on overall evaluation. The elaboration of techno-economic analysis will be the aim of further work.

4. Conclusions

The settling velocity of *Chlorella* was measured in the range of $0.024 - 0.048 \text{ m d}^{-1}$ and the mean diameter of the microalgae cell was measured in the range of $5.12 - 5.19 \mu\text{m}$. Based on the measured values, the reference parameters of separation equipment were specified. According to the developed design methodology and geometrically similar existing industrial equipment, basic design parameters and theoretical performance were defined. Designed equipment were subsequently applied to the three demonstrative systems for microalgae cultivation of 0.3 , 10 and $250 \text{ m}^3 \text{ h}^{-1}$ of produced microalgae and culture medium mixture. The lamella settler is suitable only for a small quantity of processed suspension up to $0.3 \text{ m}^3 \text{ h}^{-1}$. The circular settler and the decanter centrifuge are applicable for performance up to $10 \text{ m}^3 \text{ h}^{-1}$. Due to this, for the system with $250 \text{ m}^3 \text{ h}^{-1}$ of produced

microalgae mixture, it is possible to use these devices only for primary treatment. Otherwise, it is necessary to install devices in a parallel configuration in order to increase the performance of the system. Application of the disc centrifuge seems to be the best option due to the wide range of performance since it can be easily controlled by changing the design and process parameters. The dimensions and number of the centrifuge discs can be selected according to the maximum flow rate of processed suspension in the cultivation system. The centrifuge performance can be regulated by the speed of rotation for the current suspension flow rate, which is variable throughout the year. This study can be used to design different scale cultivation systems. An important parameter will be also the economic evaluation of applied equipment. The aim of further work will be the elaboration of techno-economic analysis.

Acknowledgments

This work was supported by the Ministry of Education, Youth and Sports of the Czech Republic under OP RDE grant number CZ.02.1.01/0.0/0.0/16_019/0000753 "Research centre for low-carbon energy technologies". This work was supported by the Grant Agency of the Czech Republic University in Prague (grant no. SGS18/129/OHK2/2T/12).

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