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The Potential of Dynamic Filtration for Microalgae Harvesting

Martina Hladíková*, Radek Šulc

Czech Technical University in Prague, Faculty of Mechanical Engineering, Department of Process Engineering,
Technicka 4, 160 00, Prague 6, Czech Republic
Martina.Hladikova@fs.cvut.cz

Dynamic filtration is promising for microalgae harvesting and mitigation of fouling and has been used for various purposes, such as yeast separation, soy milk protein concentration, whey protein microfiltration, etc. This contribution reviews different designs of dynamic filtration systems. It aims to investigate and highlight the potential of dynamic filtration for microalgae harvesting. The performances of individual systems are compared. Dynamic filtration systems can yield permeate flux almost twice higher than systems using cross-flow filtration. Considering the filtration flux and power consumption, the optimal recommended disks for dynamic filtration are those with a gap between the disk and the membrane of 3 mm and disks with two vanes with a cross-sectional area that decreased in the outward direction from the disk center. Disks with two vanes or perforated disks are recommended to achieve a uniform distribution of shear stress along the membrane. Fluid velocity is 2-fold and shear stress 7-fold higher than those obtained for an unperforated disk. Due to the energy demand during dynamic filtration, it is not recommended to use the frequency of disk revolution higher than 1,000 rpm. The shear rate used to mitigate fouling during harvesting of microalgae typically varies between 5,000 to 90,000 s^{-1} and the shear stress varies between 0.6 to 29 Pa, depending on the design of the dynamic filtration system. In case of vibrating systems, a vibrating frequency of 5 Hz is capable of significantly reducing fouling.

1. Introduction

Autotrophic cultivation of microalgae produces microalgal suspensions of low concentrations, varying from 0.5 to 1 g L^{-1} in open pond cultivation systems and up to 5 g L^{-1} in photobioreactors. Due to low concentrations of microalgal suspensions, the cultivation must be followed by harvesting of microalgae which is applied to thicken the microalgal suspensions.

The harvesting process is energy-intensive and expensive. According to Christenson and Sims (2011), 20 to 30 % of total costs for biomass production are attributed to the harvesting process. The portfolio of harvesting technologies is very broad and these technologies are used in various fields of industry. The ideal technology for microalgae harvesting should have the ability to separate a large volume of culture medium in a short period of time and its energy consumption and costs of process equipment should be as low as possible. The harvesting technology also must be gentle enough to avoid degradation of the microalgae and the culture medium during harvesting. The technologies for microalgae harvesting were described in Hladíková and Šulc (2021).

A comprehensive comparison of various studies, which focus on dynamic filtration systems applied for microalgae harvesting and on the most important operating conditions and parameters, has not yet been published in the literature. Such a comparison is needed for efficient design and operation of apparatuses which involve microalgae processing. This contribution reviews operational parameters and performances and analyzes and compares them for different designs of dynamic filtration systems. The contribution also aims to investigate the potential of dynamic filtration for microalgae harvesting.

2. Filtration of microalgae and fouling formation

Membrane technologies are promising for microalgae harvesting. They are less sensitive to pH in comparison with coagulation and flocculation. Therefore, no pH adjustments of microalgal suspensions are required prior to harvesting. Harvesting using membrane separation does not require any chemicals and the final harvested

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biomass is free of any chemical contamination. Compared to centrifugation, which is nowadays the most applied technology for microalgae harvesting, membrane technologies are gentler to microalgae cells. High shear stress induced during centrifugation can cause a disruption of microalgae cells and a leakage of intracellular polymeric substances into microalgal suspensions. However, membrane technologies are prone to fouling. Fouling is affected by the age of microalgal suspensions (Rossi et al., 2004). The presence of intracellular polymeric substances released from microalgal cells increases with increasing age of microalgal suspensions.

The fouling formed by microalgae must be continuously removed from the membrane surface. When the accumulation of microalgae on the membrane surface prevents the smooth progress of separation, membranes must be cleaned (Rossi et al., 2004). It is often sufficient to do the cleaning simply by rinsing membranes (Rossi et al., 2004). Other options are relaxation or backwashing (Drexler and Yeh, 2014). Once fouling is based on adsorption, chemical cleaning has to be used. The chemical resistance of the membrane must be considered to avoid membrane damage due to the use of inappropriate chemicals. Sodium hypochlorite and citric acid are typically used for chemical cleaning of fouling (Bilad et al., 2013). Sodium hypochlorite is an oxidant that is suitable for removing inorganic fouling. Inorganic fouling can be indicated by the presence of crystals on the membrane surface which consist mainly of calcium released from calcium carbonate present in the culture medium (Bilad et al., 2012). Citric acid appears to be suitable for the removal of organic fouling (Bilad et al., 2013). However, cleaning of organic fouling is challenging because it is likely to involve the binding of organics to the membrane polymeric matrix by cationic bonds (Bilad et al., 2013). Antifouling strategies for microalgae harvesting are described by Mkpuma et al. (2022).

In general, membrane systems can be of four types, namely dead-end, cross-flow, submerged, and dynamic. In dead-end filtration, the fluid flow is perpendicular to the membrane surface, and a filter cake is formed on the membrane surface. Dead-end filtration is very prone to fouling. In the case of cross-flow filtration, the fluid flow is parallel to the membrane surface. Cross-flow filtration is recommended to be used to eliminate fouling. However, the feed is usually pumped by a pump which can cause damage to the cellular structure of microalgae and the release of intracellular substances into the culture medium. Submerged filtration is characterized by submerged membranes and aeration is used to eliminate fouling. For such purposes, a special system generating aeration must be installed within the equipment. During dynamic filtration, a rotating component is used which creates shear stress near the membrane surface. A disk rotating near a fixed membrane is usually used as the rotating component. Another option is to use rotating or vibrating membranes (Jaffrin, 2012). The resulting shear stress prevents the accumulation of separated particles on the membrane surface which limits the mass flux through the membrane. The application of dynamic filtration reduces the formation of fouling through a combination of high shear stress and low transmembrane pressure. Despite the good performance of dynamic filtration systems in controlling fouling and improving flux during filtration, increasing the filtration area for scaling-up can be difficult due to mechanical and hydrodynamic complexities (Cheng et al., 2021). Different types of membrane systems and their principles are shown in Figure 1 and Figure 2.

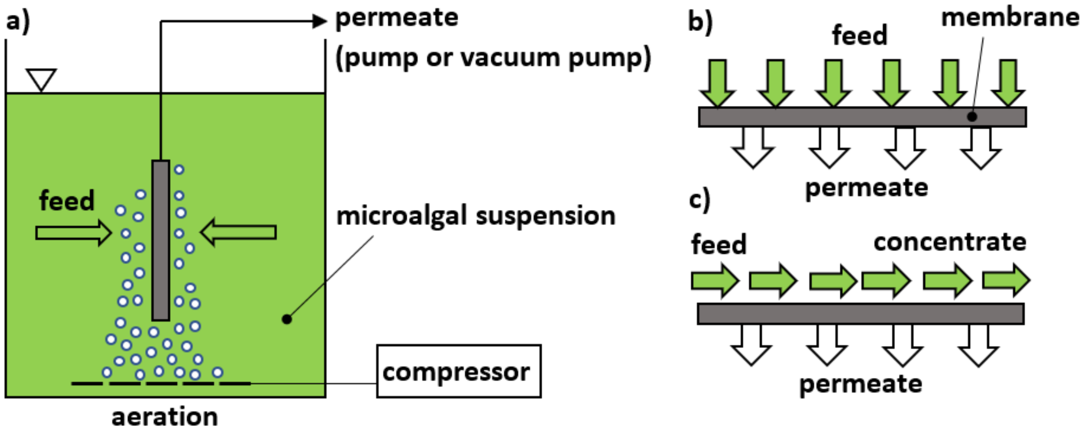

Figure 1: Different types of membrane systems: a) submerged filtration, b) dead-end filtration, and c) cross-flow filtration

Dynamic filtration using a rotating disk has been applied in the chemical and food industry and other industrial fields to effectively prevent fouling (Wu et al., 2019). An overview of different configurations used in dynamic filtration is provided by Jaffrin (2012), including systems with rotating disks and systems with rotating or vibrating membranes. Industrial and laboratory dynamic filtration systems are also reviewed by Cheng et al. (2021).

Mathematical modeling of vibratory shear-enhanced nanofiltration applied for the preconcentration of coffee extracts is described by Laurio et al. (2021). Dynamic filtration has also been applied for the following purposes: yeast separation using a rotating disk with blades of different heights (Brou et al., 2002), separation of whey proteins by microfiltration and ultrafiltration using rotating ceramic membranes (Espina et al., 2010), elimination of biofilm formed by *Candida krusei* (Brugnoni et al., 2011), purification of chicory juice by microfiltration and ultrafiltration using a rotating disk (Luo et al., 2013), purification of wine (Rayess et al., 2016), treatment of soy sauce wastewater (Wang et al., 2021), etc. Research on dynamic filtration applied for microalgae harvesting has focused mainly on designs with a rotating disk placed directly above a stationary membrane.

3. Dynamic filtration and microalgae harvesting

The work by Frappart et al. (2011) deals with the evaluation of hydrodynamic effects on ultrafiltration applied for the harvesting of microalgae *Cylindrotheca fusiformis*, the cell size of 4 to 10 μm, and *Skeletonema costatum*, the cell size of 8 to 15 μm. The initial concentrations of microalgal suspensions were 2.4 10^6 cells mL^{-1} and 0.5 10^6 cells mL^{-1}. Two harvesting systems were compared: i) cross-flow filtration system and ii) dynamic filtration system with a rotating disk placed near a stationary membrane. In both systems, a flat hydrophilic polyacrylonitrile membrane with an area of 100 cm^2 was used. Rossignol et al. (1999) recommend to employ hydrophilic membranes for microalgae harvesting because the adsorption of microalgae cells to their surface is low. Based on the results, the system with a rotating disk yielded permeate flux almost twice higher than the system using cross-flow filtration. A dynamic filtration system is shown in Figure 2.

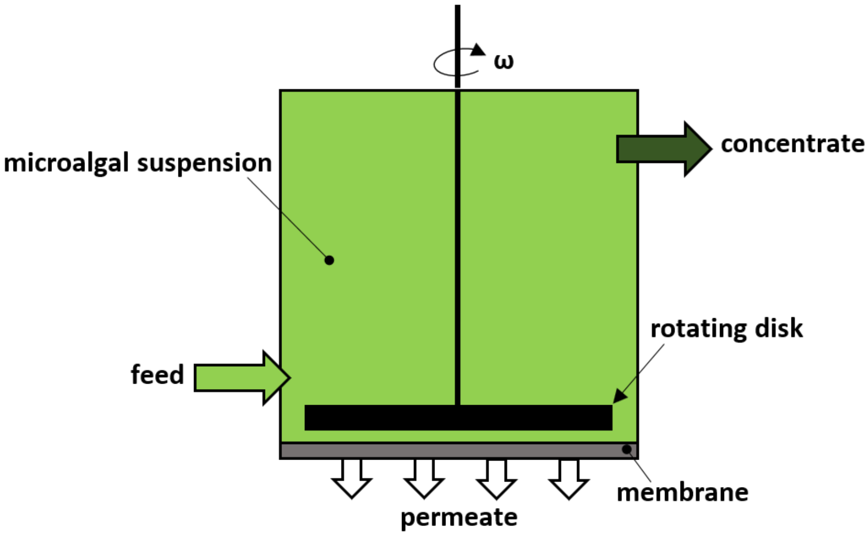

Figure 2: A scheme of a dynamic filtration system with a rotating disk

Hwang and Lin (2014) used rotating-disk dynamic microfiltration to harvest microalgae *Chlorella vulgaris*. The initial concentration of the microalgal suspension was 3.25 g L^{-1}, the cell size of 2 to 8 μm. A wide range of operating conditions were studied, namely disk rotation speed, suspension feed rate, and transmembrane pressure (TMP). The effect of operating conditions on the filtration flux and the cake properties was discussed. According to the conclusions, a high TMP yielded a high filtration flux at a low disk rotation speed. Software Ansys Fluent was used to numerically simulate the flow field in the harvesting system and the shear stress in the vicinity of the membrane surface.

Hwang and Wu (2015) studied the effect of the rotating disk structure on the distribution of fluid velocity and shear stress on the membrane surface during the harvesting of microalgae *Chlorella* sp. The initial concentration of the microalgal suspension was 3.25 g L^{-1}, the cell size of 2 to 8 μm. Software Ansys Fluent was used as a tool to determine the distributions. Six types of rotating disks were investigated and placed in a vessel above a membrane made out of cellulose acetate ester: i) a flat disk with the gap between the disk and the membrane of 10 mm, ii) a flat disk with the gap between the disk and the membrane of 3 mm, iii) a disk with two vanes, iv) a disk with four vanes, v) a disk equipped with two vanes with a cross-sectional area that decreased in the outward direction from the disk center, and vi) a disk with two vanes and two grooves. The highest flow velocity occurred near the rim of the rotating disk. The rotating disk equipped with more vanes was able to generate higher shear stress compared to the flat rotating disk. Energy consumption increased with the frequency of disk revolution. The authors do not recommend the frequency of disk revolution higher than 1,000 rpm. Considering the filtration flux and power consumption, the optimal recommended disks are: i) the circular disk with a gap between the disk and the membrane of 3 mm, and ii) the disk with two vanes with a cross-sectional area that decreased in the outward direction from the disk center, see Figure 3.

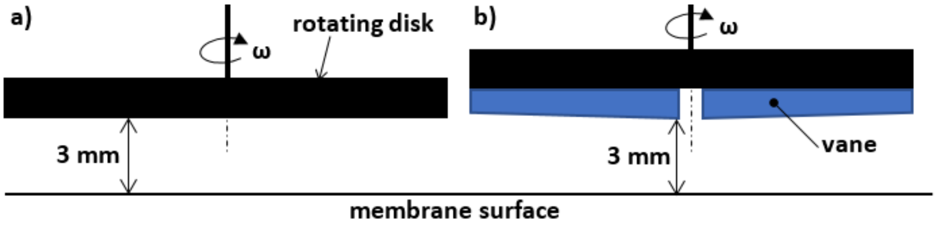

Figure 3: Optimal rotating disks recommended by Hwang and Wu (2015): a) a circular disk with a gap between the disk and the membrane of 3 mm, b) a disk with two vanes

Kim et al. (2016) applied perforated rotating-disk dynamic microfiltration to harvest microalgae *Scenedesmus obliquus*, the suspension initial concentration of 0.51 g L^{-1} and the cell size of 2 to 6 μm. The membrane was made of polyvinylidene fluoride. Fluid velocity near the membrane surface and shear stress acting on the membrane surface were numerically simulated in the SolidWorks software. Based on the results of the numerical simulations, fluid velocity was 2-fold and shear stress 7-fold higher than those obtained for an unperforated reference disk.

The different designs of dynamic filtration systems and their performances are compared in Table 1. In Table 1, the following abbreviations are used: (A1) a circular disk with a gap between the disk and the membrane of 10 mm, (CF) cross-flow filtration, (DF) dynamic filtration, (M) microfiltration, (PD) perforated disk, (U) ultrafiltration, and (UPD) unperforated disk.

Table 1: A comparison of the most important process parameters measured during microalgae harvesting using different dynamic filtration systems.

Microalgae	Filtration Type	$\dot{\gamma}$ (s^{-1})	τ (Pa)	Q_F (L h^{-1})	n (rpm)	TMP (kPa)	Q_P* (L h^{-1} m^{-2})	Reference
Cylindrotheca fusiformis	CF U	16,000	N/A	180	N/A	100	40	Frappart (2011)
Cylindrotheca fusiformis	DF U	16,000	N/A	30	360	100	75	Frappart (2011)
Skeletonema costatum	CF U	16,000	N/A	180	N/A	100	60	Frappart (2011)
Skeletonema costatum	DF U	16,000	N/A	30	360	100	100	Frappart (2011)
Chlorella vulgaris	DF M	N/A	< 1	10.8	150	10	18	Hwang and Lin (2014)
Chlorella vulgaris	DF M	N/A	< 5	10.8	350	10	64.8	Hwang and Lin (2014)
Chlorella vulgaris	DF M	N/A	< 5	10.8	500	10	72	Hwang and Lin (2014)
Chlorella sp.	DF M	5,000	N/A	30.819	1,000	100	N/A	Hwang and Wu (2015)
Chlorella sp.	DF M A1	40,000	N/A	30.819	2,000	100	N/A	Hwang and Wu (2015)
Chlorella sp.	DF M A1	90,000	N/A	180	3,000	100	N/A	Hwang and Wu (2015)
Chlorella vulgaris	DF PD	N/A	0.23	480	0	98	57	Kim et al. (2016)
Chlorella vulgaris	DF PD	N/A	2.46	480	200	98	149	Kim et al. (2016)
Chlorella vulgaris	DF PD	N/A	8.80	480	400	98	245	Kim et al. (2016)
Chlorella vulgaris	DF PD	N/A	16.9	480	600	98	323	Kim et al. (2016)
Chlorella vulgaris	DF PD	N/A	29.0	480	800	98	381	Kim et al. (2016)
Chlorella vulgaris	DF UPD	N/A	0.02	480	0	98	30	Kim et al. (2016)
Chlorella vulgaris	DF UPD	N/A	0.63	480	200	98	64	Kim et al. (2016)
Chlorella vulgaris	DF UPD	N/A	0.93	480	400	98	103	Kim et al. (2016)
Chlorella vulgaris	DF UPD	N/A	1.40	480	600	98	143	Kim et al. (2016)
Chlorella vulgaris	DF UPD	N/A	3.89	480	800	98	206	Kim et al. (2016)

*The Q_P plateau values listed in the table were obtained after the permeate volumetric flux became stabilized.

Vibrating separation units designed to harvest *Chlorella pyrenoidosa* microalgae were tested by Zhao et al. (2020). The concentration of the microalgae suspension was 0.7 g L^{-1}. The membrane pore size was 0.1 µm. According to the authors, at the vibration frequency of 5 Hz, fouling was significantly reduced and almost no microalgae were attached to the membrane surface. A scheme of the vibrating system is shown in Figure 4.

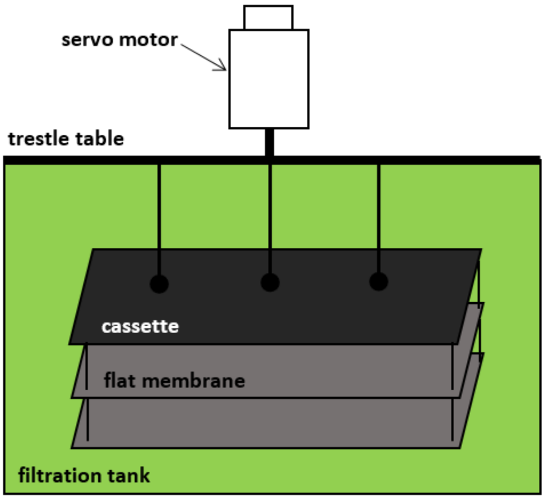

Figure 4: A scheme of the vibrating system for microalgae harvesting

4. Conclusions

Dynamic filtration is a suitable technology for microalgae harvesting and mitigation of fouling in comparison with other types of membrane filtration, such as dead-end, cross-flow, or submerged filtration. Dead-end filtration is very prone to fouling. Although cross-flow filtration is recommended to be used to eliminate fouling, the feed is usually pumped by a pump which can damage the cellular structure of microalgae. A release of intracellular substances into the culture medium can occur. Submerged filtration is characterized by submerged membranes and aeration is used to eliminate fouling. For such purposes, a special system generating aeration and built-in inside a filtration vessel must be installed which increases the costs of these systems.

The dynamic filtration systems using rotating disks are simple and consist mainly of a rotating disk placed above a stationary membrane. The rotating disk generates shear stress in the vicinity of a stationary membrane. Dynamic filtration is more effective in eliminating fouling and offers a higher permeate flux in comparison with cross-flow filtration. Due to energy consumption, it is not recommended to use the frequency of disk revolution higher than 1,000 rpm. Considering the shape of the rotating disk, disks with two vanes or perforated disks are recommended to achieve uniform distribution of shear stress along a membrane. The shear rate used to mitigate fouling during harvesting of microalgae varies between 5,000 to 90,000 s^{-1} and the shear stress varies between 0.6 to 29 Pa, depending on the dynamic filtration system. Vibration dynamic systems for microalgae harvesting were also considered. The vibration frequency of about 5 Hz is optimal to significantly reduce fouling. However, the energy demand is higher and the setup of vibrating systems is more complicated in comparison with dynamic filtration systems using rotating disks.

Nomenclature

$\dot{\gamma}$ – shear rate, s^{-1}
τ – shear stress, Pa
n – frequency of disk revolution, s^{-1}
Q_F – feed flow rate, $m^3\ s^{-1}$
Q_P – permeate flow rate, $m^3\ s^{-1}\ m^{-2}$
TMP – transmembrane pressure, Pa

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