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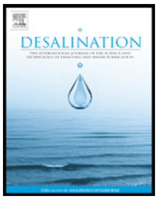

Influence of hydrodynamics in tangential and dynamic ultrafiltration systems for microalgae separation

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ABSTRACT

The present work deals with the evaluation of hydrodynamic effects on the ultrafiltration of microalgae suspensions for harvesting or metabolite production by coupling photobioreactors with membrane separation processes. Two ultrafiltration systems were compared: the first was a cross flow ultrafiltration unit equipped with a flat sheet membrane and the second was a dynamic filtration module, consisting of a disk rotating close to a stationary membrane in order to reduce fouling. *Cylindrotheca fusiformis* and *Skeletonema costatum* microalgal suspensions have been ultrafiltered at 1 bar with a 40,000 Da polyacrilonitrile (PAN) membrane with a shear rate equal to 16,000 s^{-1}. First results have shown that the dynamic filtration module yielded permeate flux almost twice higher than the cross flow filtration system both at constant concentration and in concentration mode for the two microalgae species. Further work will be required to better evaluate the potential of the dynamic module, its maximum concentration, treatment capacity, investment cost, energy consumption and impact of shear on microorganisms.

1. Introduction

During the last decade, the interest in photosynthetic microorganisms (microalgae and cyanobacteria) has increased for many applications, like therapeutics, dermocosmetics, aquaculture, food and feed industries, and more recently, energy production and environment.

Membrane separation can find many applications in photobiotechnology. Rossi et al. [1,2] have studied the harvesting of *Arthrospira platensis* both with ceramic and organic membranes and Rossignol et al. [3], the continuous recovery of *Haslea ostrearia* and *Skeletonema costatum*. In both cases, experimental studies have shown that ultrafiltration was satisfactory, provided that a low transmembrane pressure (less than 1 bar) and low fluid velocity to reduce shear rate to less than 40,000 s^{-1} were used in order to preserve microorganisms and avoid exopolysaccharide (EPS) synthesis causing severe fouling [4–6]. Permeate fluxes were about 30–50 $L\ h^{-1}\ m^{-2}$. Generally, membrane processes are cheaper in terms of investment and energy costs than other kinds of harvesting processes like centrifugation or decantation [7].

Membrane processes have also been successful for concentration and/or pre-purification of metabolites issued from microalgae. Jaouen et al. [8] have clarified suspension containing a phycobiliprotein, the C-phycocyanin (C-PC), a natural blue pigment, from disintegrated *Spirulina platensis* cells with 0.2 µm ceramic microfiltration membrane and a permeation flux of 50 $L\ h^{-1}\ m^{-2}$. Concentration of this pigment was carried out with ultrafiltration and nanofiltration membranes. Permeate fluxes were close to 80 $L\ h^{-1}\ m^{-2}$ for and C-PC retention ranged from 96 up to 100%. Denis et al. [9] have used ultrafiltration membranes in order to concentrate R-phycoerythrin (another phycobiliprotein) extracted from algae. Best results were obtained with the 30,000 Da ultrafiltration PES membrane. Mean fluxes, in concentration mode, were 10.1 $L\ h^{-1}\ m^{-2}$.

Photobioreactor technology is nowadays more and more commonly used for producing specific metabolites since it allows biomass production under controlled conditions [10–12]. Coupling photobioreactors and membrane processes permit to improve both biomass and metabolite concentration or purity [13–15].

However, in cross flow filtration of microalgae suspensions, fast fouling is observed and frequent washing is needed. Controlled hydrodynamic conditions, such as low transmembrane pressure and low shear rate, are required in order to limit fouling and cell damage [16–19].

Modified flows or geometries such as swirling annular flow [20–22], pulsed feed flow [23,24], Dean vortices [25,26], and gas–liquid two-phase flow [27–29] have shown their interest to increase membrane performance in bioprocess applications.

More recently, the development of dynamic filtration systems has shown the possibility to reduce membrane fouling by generating high shear rates independent of the feed flow [30,31]. A wide range of applications have been investigated, such as purification of oligosaccharides [32,33], concentration of soy milk proteins [34] or fractionation of milk proteins [35] where both fluxes and selectivity were

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higher than that obtained with tangential filtration. As a consequence, this kind of membrane process fitted with the ultrafiltration membrane could be an interesting alternative for continuous operations allowing biomass respect and minimizing cleaning products.

In this study, cross flow and dynamic ultrafiltration systems have been compared with the same operating conditions (temperature, pressure, cells concentration, shear rate) in terms of permeation fluxes and impact of shear rate on cells.

2. Materials and methods

2.1. Filtration bench

The cross flow filtration system was a flat membrane system Rayflow 100 (Orelis, Miribel, France) (Fig. 1). The width of the retentate side was 7.5 cm and its length 14.5 cm. It was equipped with a rectangular membrane of 100 cm^2 area. For a tangential flow velocity $v = 1\ ms^{-1}$, the Reynolds number was equal to 1000 and flow regime was laminar. In consequence, the shear rate is obtained from Poiseuille's law as:

$$\dot{\gamma} = \frac{8}{e} v_{flow} \qquad (1)$$

where, e is the chamber thickness (e = 0.5 mm) and v_{flow}, the tangential flow velocity obtained in the chamber (flow rate divided by the cross area). The transmembrane pressure (TMP) in this module is defined by the following equation where p_i, p_o and p_p are respectively the inlet, outlet and permeate pressure:

$$TMP = \frac{p_i + p_o}{2} - p_p. \qquad (2)$$

The rotating disk module, shown in Fig. 2, has been already described by Bouzerar et al. [36]. The module was equipped with a single circular membrane of 188 cm² area (outer radius = 7.75 cm; inner radius = 0.5 cm). The membrane is mounted on the cover of the cylindrical housing in front of the disk. The axial gap between the membrane and the disk was about 8 mm. The disk is fixed on a rotating shaft which is linked by a belt to an electrical motor. The shaft can rotate at adjustable speeds, ranging from 100 to 2500 rpm. The disk can be smooth or equipped with eight 6 mm vanes in order to increase the velocity factor (k) of the disk defined below.

The shear rate on the fixed membrane in the turbulent flow with a wide gap is given by [37]:

$$\dot{\gamma} = 0.0296 r^{8/5} (k\omega)^{9/5} \upsilon^{-4/5}. \qquad (3)$$

Here, ω is the disk angular velocity (rad s^{-1}), $k\omega$, the angular velocity of inviscid fluid in the gap, where k is the velocity factor, ν, the kinematic viscosity ($m^2\ s^{-1}$) and r the distance from the center (m). In the case of dynamic filtration, the maximum membrane shear rate, assumed to be the representative shear rate, is given at the disk rim ($r = R_d = 7.25$ cm) [38].

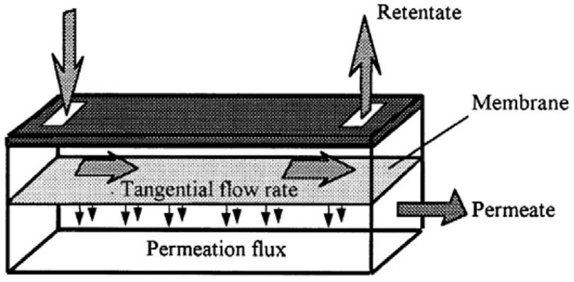

Fig. 1. Schematic of the tangential membrane system Rayflow.

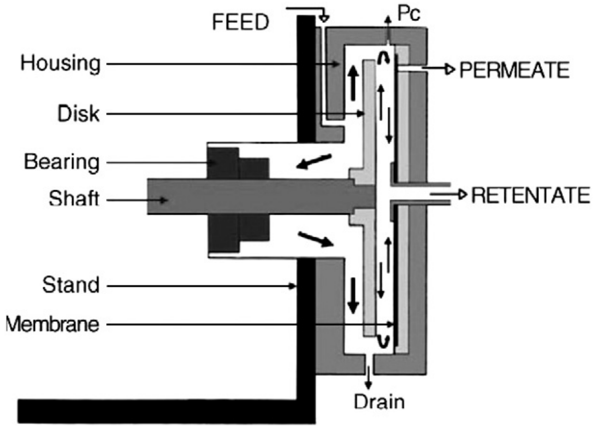

Fig. 2. Schematic of the rotating disk module.

The values of velocity factor k were obtained from measurements of peripheral pressure p_c at different speeds and found to be 0.42 for a smooth disk and 0.89 for a disk equipped with 6 mm vanes [31].

The pressure is adjusted by acting a throttling valve on the outlet tubing. The transmembrane pressure (TMP) is then determined by [31] as:

$$TMP = p_c - \frac{1}{4} \rho k^2 \omega^2 R^2 \qquad (4)$$

where R is the housing inner diameter, and p_c the peripheral pressure.

2.2. Biological suspensions

Two kinds of microalgae species were ultrafiltrated. *Cylindrotheca fusiformis* is a unicellular marine diatom (Fig. 3). Cell length is about 95 µm for a thickness between 4 and 10 µm. Cultures, conducted in a photobioreactor, were produced in our laboratory.

S. costatum is a cell-chain marine diatom consisting of 3 to 15 cells connected by silica links (Fig. 3). These silica links make the diatom breakable under shear stress. Its dimensions are highly variable since they depend on the number of cells linked together. Its length varies from 50 to 70 µm and its diameter from 8 to 15 µm [3].

2.3. Membrane

The ultrafiltration membrane used in this study was an IRIS 3038 (Orelis, Miribel, France) made in polyacrylonitrile (PAN). This membrane is highly hydrophilic, with a molecular weight cut-off of 40,000 Da [3].

Rossignol et al. [3] and Rossi et al. [1] have shown that this type of membrane is well suited to microalgae suspensions as it presents less adsorption of cells or cell compounds.

2.4. Operating conditions

To compare both systems, experiments were conducted simultaneously under same operating conditions. Each system was fed by microalgae suspensions at a temperature of 25 °C with peristaltic pumps known to induce low shear stress in order to preserve microorganisms in the modules [39,40]. The temperature was regulated by a heat exchanger. In both cases, a low shear rate was fixed at 16,000 s^{-1} by adjusting feed flow rate to about 180 L h^{-1} for the Rayflow system or by rotating a disk with vanes at 360 rpm on the rotating disk module, fed with only 30 L h^{-1}. TMP was then increased