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Local hydrodynamics investigation within a dynamic filtration unit under laminar flow

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ABSTRACT

A dynamic filtration module, called a Rotating and Vibrating Filtration (R.V.F.) module, was designed and dedicated to the treatment of highly viscous fluid, such as fermentation broth or liquid food. To this end, an experimental study was undertaken, using a laminar flow regime with a viscous Newtonian model fluid in a dynamic filtration module in order to quantify the effect of local hydrodynamics on filtration. Instantaneous velocity fields can be measured and analyzed within an R.V.F. by using Particle Image Velocimetry (P.I.V.). In this study, we applied P.I.V. to study the laminar local hydrodynamics in 3 different slices within the 3 mm gap between the membrane and the impeller and 3 vertical slices at different radial positions, with rotation speeds from 0 to 10 Hz. Radial and vertical profiles of tangential velocity were then plotted. Proper Orthogonal Decomposition (P.O.D.) was applied to the P.I.V. data to discriminate between mean flow and fluctuating velocities induced by the periodic motion of the impeller. Thus, viscous shear stress profiles were deduced in terms of both mean shear stress profile and root mean squared (r.m.s.) fluctuating shear stress profile; wall values were then deduced. With this approach, we were able to quantify the distribution of viscous shear stress at the wall (membrane), in terms of mean value and r.m.s. contribution. Dynamic filtration efficiency was thus enlightened by local hydrodynamics.

1. Introduction

Three phase reactors and, in particular, membrane bioreactors (MBR) appeared in the 1970s and have been largely applied in the biotechnology field: pharmaceutical and food industries, and white biotechnology. Increasing the cell density in bioreactors is useful to improve the overall productivity of fed-batch and continuous processes, particularly in biofuel production, which has to be competitive according to energy, economic and environmental criteria. The main constraints of membrane processes are related to material cost, energy consumption, fouling removal and permeate flux decline (Ersahin et al., 2012). Dynamic filtration, also named Shear Enhanced Filtration, appears to be a promising alternative to conventional filtration methods (dead-end filtration, cross-flow filtration), which are currently not efficient enough. What makes this system different from the conventional filtration type is that, in the filtration cells, the system creates and enhances the shear rate at the membrane surface by means of a mechanical part, such as a disk rotating near a fixed membrane, or rotating or vibrating membranes.

In recent decades, many efforts have been made and studies performed to develop novel DF modules to enhance the shear rate at the membrane surface by changing the configuration of the filtration cells. A review of the existing dynamic filtration modules (Xie, 2017) showed that they emanate from 30 companies and laboratories, exist at laboratory to industrial scales, and can be mainly classified according to the type of membrane (mobile or stationary) and the type of mechanical perturbation (rotating, vibrating, oscillating).

Rotating cylindrical membrane, rotating flat membrane and vibrating flat and cylindrical membrane modules have been applied in bioprocesses and can be mentioned to illustrate the technological diversity. However, DF modules with stationary membranes form the basis of the most popular configurations, in which a mechanical device (impeller, cone, smooth disk or with promoters welded onto disk surface) rotates close to the membrane. The shear rate at the disk surface

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is influenced by the gap between the rotor and the membrane, which has therefore become one of the most important points for researchers. Many rotating disk modules have been well documented in the literature, such as the Dynamic Membrane Filter (DMF, Pall Corp., Cortland, NY) (Frenander and Jönsson, 1996; Lee et al., 1995) and the RDM (Rotating Disk Module) (Akoum et al., 2006; Zhang and Ding, 2015). Applying a specially designed rotor was also very helpful in improving the system performance. Examples of such devices include: Cross Rotational Filters (CR-filters, Metso-Paper corp. Finland), (Huuhilo et al., 2001; Mänttäri et al., 1997), Rotating and Vibrating Filtration module (R.V.F. module, R.V.F. Filtration, Paris, France) (Fillaudeau et al., 2007; Rayess et al., 2016; Xie et al., 2017), the DYNO filter (Bokela GmbH, Karlsruhe, Germany) (Bott et al., 2000) and the FMX (BKT United, Korea) filter (Kim et al., 2015).

With such complex configurations, DF modules are able to generate high shear rates — up to approximately 1–3 × 10^5 s^{-1} on the membrane surface under low transmembrane pressure, TMP (Chang, 2008; Jaffrin et al., 2004). Shear rate is one of the crucial factors in the MBR process as it can control membrane fouling and enhance permeate flux. However, it also has a strong impact on biological media. Cell populations are known to be sensitive to the physicochemical environment, including local viscous dissipation and mechanical stresses (magnitude, fluctuation, duration), which may induce a metabolism switch to cell lysis. It is thus important to characterize the flow pattern and to quantify the velocity fields, pressure and parietal shear stresses at the membrane surface locally and instantaneously, as they are linked to the operating conditions and the evolution of the rheological behavior of the fermentation broth. The flow pattern results from the complexity of the geometrical configuration, the rheological behavior, and the operating conditions. It also depends on the time and length scales.

2. P.I.V. and P.O.D

P.I.V. is an efficient technique for investigating local and instantaneous velocity fields. It is based on the visualization of tracer particles displacement to estimate the flow velocity. P.I.V. provides instantaneous vector maps by tracking the particle displacement in a given time interval. In the DF filtration domain, P.I.V. measurement was first applied in rotating cylindrical filters (Rudolph et al., 1998; Wereley and Lueptow, 1999; Wereley et al., 2002), where it gave details of particle paths and streamlines in different dimensions and geometrical profiles. This helped to explain the physical fouling mechanism due to the cylindrical Couette flow and the Taylor vortex flow. Figueredo Cardero et al. (2012) examined the flow field in a thin gap between two cylinders, mainly focusing on the radial behavior. Other P.I.V. measurements have been made with a rotating cone filter (Francis et al., 2006), a rotating flat-sheet (wing-like) membrane bioreactor (Jiang et al., 2013a; Jiang et al., 2013b), a vibrating hollow fiber filter (Li et al., 2013), and a folded plate membrane module (Zhang et al., 2015) in order to better explain their filter performances by analyzing flow motion. In the present study, the P.I.V. technique was used to investigate local hydrodynamics.

Recently, the P.O.D. (Proper Orthogonal Decomposition) technique has been used to extract more and more information from such huge sources of experimental data (Moreau and Liné, 2006; Doulgerakis, 2010; Doulgerakis et al., 2011; Liné et al., 2013; Liné, 2016). P.O.D. is an efficient technique to process instantaneous velocity fields. It enables the velocity to be reconstructed in terms of summation of modes, each mode contributing to the total kinetic energy. P.O.D. is thus a modal decomposition of instantaneous velocity fields.

Based on statistics of instantaneous 2D velocity fields, P.O.D. can generate a series of eigenvalues and eigenvectors. In the following, $\lambda^{(I)}$ is the I^{th} eigenvalue and $\vec{\Phi}^{(I)}(x, y)$ is the I^{th} associated eigenfunction or eigenvector. Each instantaneous velocity field can be reconstructed as:

$$\vec{V}_k(x, y) = \sum_{I=1}^{N} a_k^{(I)} \vec{\Phi}^{(I)}(x, y)$$

where I is the I^{th} mode of P.O.D. (total mode number equal to N), while $a_k^{(I)}$ is the corresponding P.O.D. coefficient. The series of coefficients $a_k^{(I)}$ (or $a^{(I)}(t)$ in the case of resolved P.I.V.) is given by the projection of each instantaneous velocity field on the I^{th} eigenvector:

$$a_k^{(I)} = \left(\vec{V}_k, \vec{\Phi}^{(I)}\right)$$

It is possible to reconstruct the velocity field and, in particular, the mean flow and the organized motion.

P.I.V. measurements were performed in a 2-D plane here, x–y for example, on a regular mesh with L rows and C columns, leading to $L \times C$ points per plane. Each instantaneous velocity field measurement provided a snapshot of the flow. The statistical analysis was performed on N snapshots taken in the same plane (P.I.V. data). The number of grid points being $L \times C$, the matrix of instantaneous velocity vector data was obtained as:

$$\begin{bmatrix} \vec{U}_k(x_1, y_1) & \vec{U}_k(x_1, y_2) & \vec{U}_k(x_1, y_c) \\ \vec{U}_k(x_2, y_1) & \vec{U}_k(x_2, y_2) & \vec{U}_k(x_2, y_c) \\ & & \\ \vec{U}_k(x_L, y_1) & \vec{U}_k(x_L, y_2) & \vec{U}_k(x_L, y_c) \end{bmatrix}$$

where k is the index of the instantaneous event ($k = 1,N$). This matrix of vectors can be reshaped to build a vector $\vec{U_k}$ with 2 LxC rows as follows:

$$U_k = \begin{bmatrix} u_k(x_1, y_1) \\ u_k(x_2, y_1) \\ \\ u_k(x_L, y_c) \\ v_k(x_1, y_1) \\ v_k(x_2, y_2) \\ \\ v_k(x_L, y_c) \end{bmatrix}$$

The snapshot method adopted in this eigenvalue problem was proposed by Sirovich (1987). This method is based on the snapshot matrix M corresponding to the N instantaneous velocity fields. The matrix M can be expressed as

$$M = \begin{bmatrix} u_1(x_1, y_1) & u_2(x_1, y_1) & \dots & u_N(x_1, y_1) \\ u_1(x_2, y_1) & u_2(x_2, y_1) & \dots & u_N(x_2, y_1) \\ & & \dots & \\ u_1(x_L, y_C) & u_2(x_L, y_C) & \dots & u_N(x_L, y_C) \\ v_1(x_1, y_1) & v_2(x_1, y_1) & \dots & v_N(x_1, y_1) \\ v_1(x_2, y_1) & v_2(x_2, y_1) & \dots & v_N(x_2, y_1) \\ & & \dots & \\ v_1(x_L, y_C) & v_2(x_L, y_C) & \dots & v_N(x_L, y_C) \end{bmatrix}$$

The matrix M has $2LC$ rows and N columns, each column of the matrix M representing the k^{th} event of the instantaneous