Local hydrodynamic investigation by PIV and CFD within a Dynamic filtration unit under laminar flow

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ABSTRACT

Local hydrodynamics within a complex and confined dynamic filtration module named RVF (Rotating and Vibrating Filtration) was scrutinized under laminar flow with viscous Newtonian fluid. This module was designed to treat complex fluids such as fermentation broth or liquid food. Previous results reported global hydrodynamics (friction and power consumption curves) and RVF efficiency during filtration of fermentation broths. However, the access to local variables (shear rate, velocity) appeared as challenging in a confined volume. By associating Particle Image Velocimetry (PIV) and an optical trigger strategy, the instantaneous velocity fields were measured and analyzed. PIV experiments were carried out at 6 different planes in the 3 mm narrow gap between the membrane and the impeller, considering two feeding flowrates ($Q_f=25$ and 45 L/h) under mixing rates 2 Hz. In addition, a simulation approach by Computational Fluid Dynamics (CFD) was developed, confronted to PIV ($Q_f=45$ L/h, $N=2$ Hz) and compared to global parameters.

In this work, we showed the ability to measure local velocity in a complex, confined and rotating device. As expected, velocity in filtration cell was observed to be independent of flowrate. Magnitude of mean velocity fluctuation was quantified and discussed as a function of radial and axial position (constant impeller position). Moreover, velocity and shear rate profiles were introduced by simulation, they proved that simulations were in a good agreement with PIV measurements, and streamlines was also discussed combining Residence Time Distribution (RTD). Finally, local and global core velocity coefficients (issued from PIV and CFD), as an indicator of mechanical efficiency were calculated and compared to similar devices and alternative methodologies which were reported in the literature.

KEYWORDS

1 Introduction

The principle of dynamic filtration (DF) is to generate complex hydrodynamic perturbations (intensity, time dependent) by mechanical movement (rotation, vibration, oscillation) of membrane or external mechanical forces close to the membrane, to better control membrane fouling.

In the recent decades, many efforts and a great number of those studies have been done to develop novel DF module and hydrodynamic study, in lab scale or pilot scale. Reviewing the existing DF modules by our best of knowledge, they can be mainly classified by ‘*mobile membrane*’ and ‘*stationary membrane + dynamic device*’ in terms of membrane motion, the external force applied to the system can be longitudinal, transverse, torsional, or with a mix of these motions. Early in the 1967, Sherwood et al. [1] suggested a rotating cylinder filter in reverse osmosis for salt and water transport. Taking advantage from Taylor-Couette Flow in the annulus with a relatively low rotation speed, cells and macromolecules can avoid being destroyed. So this filter type was quickly applied to Pharmacy and Biological process such as *Biodruck-filter* (BDF-01, Sulzer AG, Winterthur, Switzerland)[2], *Biopurification System* [3], *RDF filter* (Rotary Dynamic Filtration) [4]. Lee. S et al. and Park et al.[5-7] also gave further studies with the similar systems. Rotating disk membrane module such as *Rotating Membrane Disk Filters (RMDFs)* [8], *Compact Rotating Disk (CRD filter)* [9], and *High shear rotary membrane system (HSR-MS)* [10] are typical modules equipped with one or more rotating disk membrane, other system like *Multi-shaft disk module (MSD, Westfalia Separator, Aalen, Germany)*, stacks of membrane disks were driven by two or more shafts rotate in the same direction, expected to have higher shear rate[11]. Similar rotating systems but installed with a

stationary membrane and a rotor close to it, were also widely studied. Main differences can be found in rotor configuration, for example, *Dynamic Membrane Filter (DMF, Pall Corp., Cortland, NY)* [12-14] and *RDM (Rotating Disk Module)* [15,16] have a rotating disk, *Cross Rotational Filters (CR-filters, Metso-Paper corp. Finland, ex: Raisio-Flootek, Finland, and ABB Flootek, Sweden)* [17] was designed with a two-blade impeller, the *DYNO (Bokela GmbH, Karlsruhe, Germany)* [18] and the *FMX (BKT United, Korea)* [19] filter installed with special rotors to promote turbulence. Vibrating disk membrane module well known as *Vibratory Shear Enhance Processing (VSEP, New Logic, USA) module* [20] and *Vibrating Membrane Filtration module (PallSep-VMF)* [21], consists of overlapping membranes or membrane-coated disks in series, mounted on a torsion bar driven by a motor transversely. Other popular module like vibrating hollow fiber membrane filter are well documented in the literature as well [22,23]. All these efforts contribute to high level of filtration quality, and enhanced efficiency. Compare with dead-end filtration (DE) and cross-flow (CF) filtration, DF filtration has been proved better (1) intensify filtration process and bioprocess, increase permeability and have higher biological productivity by achieving high cell concentration, (2) reduce environmental impact (low loop volume), (3) and reduce energetic consumption (uncoupling between retentate flowrate and wall shear rate, working under low transmembrane pressure, TMP).

Enhancements in DF filtration is considered mainly come from the complex hydrodynamics near the membrane surface, commonly known that the hydrodynamic flow field affects the particle-liquid distribution and mass transfer of the membrane filtration process. Global performances such as permeability, TMP, mean shear rate, fluid viscosity and power consumption were well studied, however, less concern was reported in local variables. To have access to local investigation, our attention was gravitated toward the field of visualization

measurement. One of the popular technique which has been widely used in this field is Particle Image velocimetry (PIV), this technique can provide the local velocity distribution (or vector map) by tracking the particle displacement in a given time interval. In DF filtration domain, PIV measurement has been first applied in rotating cylindrical filters, Wereley et al. [24-26] gave a detail of particles path and streamline spaced in different dimension and geometrical profile, help to explain the physical fouling mechanism due to the cylindrical Couette flow and the Taylor vortex flow. Figueredo-Cardero et al. [27] examined the flow field with in a thin gap between inner and outer cylinder, mainly focus on the radial behavior. Other PIV measurement also conducted with a rotating cone filter [28], a rotating flat-sheet (wing-like) membrane bioreactor [29,30], a vibrating hollow fiber filter [31], a folded plate membrane module[32] to better explain their filter performances by flow motion.

In this work, a local measurement using PIV technique had been carried out with an innovative DF device, called Rotating and Vibrating Filtration (RVF technology – patent no. FR-97-14825, RVF-filtration company, France). It consists of two identical filtration cells (Fig. 1a shows one filtration cell) in series (4 membranes in total, filtration area 0.048 m^2 , volume 0.2 L per cell, 1.5 L in total). And in each cell, as Fig. 1b shown, a three-blade impeller (flat blade, diameter = 138 mm, thickness = 8mm) is driven by a central shaft continuously rotating (up to 50 Hz) in a 14mm gap between two porous substrate plates (membrane support in metal) which drains the permeate, it gives a 3 mm gap between the impeller and the membrane surface. Feeding fluid flows into the system from the inlet at the bottom, and go through the filtration cells along the central shaft, then retentate flow out of the system from the outlet at the top.

This simple mechanical device runs continuously and generates a high shear rate as well as a hydrodynamic perturbation in the small gap TMP (up to 300 kPa) and rotation frequency can be adjusted to optimize the operating condition.

Fig. 1 Configuration of RVF module.

RVF module had been studied in previous papers [33-35]. In global point of view, Qualitative and quantitative performances with different membrane material (hydrophilic and hydrophobic properties), feeding fluid (water, clarified beer and rough beer, wine and crude wine) and operating conditions (feeding flowrate, rotation speed, TMP, volume reduction factor) have been reported. These papers proved that, RVF module could significantly intensify filtration process and increase permeability gain. In fact, both global (power consumption, pressure drop, heat dissipation, tracing) and local (radial pressure distribution at membrane surface, velocity fields) hydrodynamic approaches were necessary to gain insights into the complex hydrodynamic fields in the RVF and subsequently explain the better performances of Membrane Bioreactor (MBR). Global hydrodynamic analysis indicates that the local variables

(shear rate, velocity and pressure) could not be easily estimated in the RVF module, the scientific and technical challenge are inherent to the complex geometry of device (narrow gap, physical enhancement for perturbation, etc.) and the rheological flow behavior (potential fluid like multiphase fluid, high viscosity fluid, non-Newtonian etc.).

In this study, PIV experiments were performed within the RVF module in laminar flow regime with a viscous Newtonian fluid, at 6 different planes in the 3 mm gap between the membrane and the impeller (plus 2 additional planes in the gap between two impeller blades). In parallel, numerical simulations were performed to have access to more parameters in flow pattern. Our objective was to study and highlight the local hydrodynamics in a complex configuration (narrow gap with complex shape of flat impeller), to better realize the consequence of complex hydrodynamics on filtration and bioprocess performances, and also to give new additional information (both in experiment and simulation) for filtering viscous fluid while it is well known that high viscosity fluid is not easy to be filtered.

2 Material and methods

2.1 Experimental setup

A fully instrumented circulation loop combined with PIV system was developed for experimental measurement.

Fig. 2 Schematic diagram and apparatus used in the experiment (a) F: flowmeter; P1/P2: pressure sensor of inlet/outlet; T1/T2/T3: temperature sensor of inlet/outlet/bioreactor; P: pressure gauge; TM: Thermostat; (b) The PIV system synchronized with a CCD camera, double pulsed laser and

the RVF module with the transparent cell; (c-d) black-painted impeller in the transparent cell; (e)

An optical trigger synchronized with PIV system

2.1.1 Circulation loop

As the schematic Fig. 2 (a) shows, RVF module is integrated in a fully instrumented closed circulation loop: outlet and bypass of the RVF module are linked back to the feeding tank. In this loop, the feeding flow is pumped from a double-jacket feeding tank (2 L), which is connected with a thermostat to maintain a constant temperature. Flowrate is controlled by a volumetric pump (Head: TUTHILL CO., series A54739, Drive: GROSCHOFF CO., series PM8014, 3800rpm, DC motor control unit: DART 250G series) and measured by a flow meter (Altometer IFM 1080/6). Temperature and pressure are measured by thermal sensor (PT100) and pressure gauge (Endress Hauser Cerabar S PMC 731, $0-4 \times 10^3$ kPa), installed both at the inlet and outlet respectively. A third thermal sensor is fixed in the feeding tank. Power consumption of RVF module is calculated by measurement of current (Ammeter, LEM Co. AC current transducer AT-B10) and tension (Voltmeter, SINEAX U 504 31 LD). All the sensors are connected to a digital data acquisition system (AGILENT 34972A LXI) and convert to numerical data record by a PC.

2.1.2 PIV setup

Besides, as it displays in Fig. 2 (a) and (b), RVF module is also integrated with the PIV system which has traditional elements. In this study, measurements were focused at the horizontal plane (x - y plane). Due to the complex configuration of RVF, velocity field in vertical plane (y - z or x - z plane) was difficult to be obtained, this work will be included in the future. PIV system was supported and maintained by DANTEC DYNAMICS Co. (Denmark), basic elements are required as Fig. 2 (b) shown:

- The stainless steel filtration cell is replaced by a transparent cell as shown in (b);

- A fluorescent dye called Rhodamine B (powder) was used in this experiment, it has homogeneous distribution and good ability to present the flow motion and scatter the light from laser beams in our test fluid. Pretreatment was conducted with sonication (Elmasonic S 60 H, 50/60 Hz) for dissolving of particles in liquid, particle size ranged from 10 to 20 μm . Particle settling kinetics was carried out by TurbiscanLab (Fomulaction) with test fluid and has no significant decantation;
- A flat light source (pulsed laser, Model: LISTRON NANO L200-15 PIV, max trigger frequency 15 Hz) to illuminate the target plane and the florescent particles;
- A CCD (Charge Coupled Device) camera (DANTEC Dynamic, Flow sense EO, $2048 \times 2048 \text{ px}^2$, pixel size $7.4 \mu\text{m}$, max frequency 15 Hz) should focus on the target plane (perpendicular to the flat laser sheet);
- A processor and timer box is needed to communicate with the camera and the pulsed laser.
- Importantly, an optical trigger, as it shown in Fig. 2 (e), is also connected to the timer box. In this case, acquisition signal was sent by this trigger when it detected a marker on the shaft (which drives the impeller), images were always taken with the same impeller position.
- Moreover, it was assumed that no impact of permeate flux on the local velocity distribution, due to its low quantity compare with the feeding flow, thus permeate loop was closed and no membrane was used.

By using all the material and strategy above, the flat laser sheet beamed on the target area (x - y plane) between the upper wall (of the filtration cell) and the impeller surface, and could be adjusted to 6 slices as Fig. 2 (a) shown (step by 0.5 mm in z direction from the wall to the

impeller, $z_1=0.25$ mm, $z_2=0.75$ mm, $z_3=1.25$ mm, $z_4=1.75$ mm, $z_5=2.25$ mm, $z_6=2.75$ mm, with uncertainty ± 0.25 mm according to the thickness of laser sheet). Two additional slices were scrutinized at $z_7= 4.75$ mm and $z_8= 6.75$ mm in order to access to velocity fields between two blades. Since Rhodamine tracers were used in this case, a red filter is placed in front of the camera to allow only fluorescent light (reflected from particles) enter the camera, while reflection of the transparent cell is filtered out.

2.1.3 PIV Data Acquisition and Processing

The PIV measurement was performed in a field of 109×109 mm² view, focus on one third of the filtration cell in x - y (horizontal) plane, this area was capturing one leading edge and one trailing edge. Flow field was assumed to be periodic since it was agitated by a 3-blades impeller. This 1/3 area was considered to represent the whole filtration cell. The raw image processing was evaluated by using commercial software DynamicStudio.2015a (by DANTEC DYNAMIC, Denmark). A statistical adaptive cross-relation algorithm was used to find average particles displacement with a mask input to filter the non-interested area, and iteratively adjust and determine an appropriate Interrogation Area (IA) size and shape (specified criteria is needed) to local seeding density and flow gradient. An adaptive IA window was used to start with 32×32 px² to 16×16 px² window for the calculation, corresponding to 1.70×1.70 mm² and 0.85×0.85 mm², a 50% window overlapping was also applied to improve correlation. Therefore, each velocity map has theoretically 128×128 vectors, with about 9000 valid and 7389 disabled by the mask, while approximately 1% bad vectors had been rejected. The time interval between two images in each pair was controlled between 500-800 μ sec according to different operating conditions, it only allowed the particle displacement move approximately a quarter of the window size. Other parameters can be found in Tab. 1.

Parameters	Setting
Image size	2048×2048px ²
Interrogation window	adaptive PIV from 16×16 px ² to 32×32 px ² , step size 16×16 px ²
Particle density	5-10 particles per interrogation window (16px ×16px)
Particle size	Mean diameter of 10-20 μm
Calibration	Scale factor : 7.177 ; 1 pixel= 7.177×7.4=53 μm
Time interval between consecutive images, Δt	500-800 μsec
Frequency of acquiring/ trigger rate	Synchronized with impeller rotation speed
Number of samples	1000 of image pairs

237 Performed adaptive PIV processing, data was subsequently applied to MATLAB software
 238 (developed by MathWork) through a code for further analysis. Velocity profile at the given
 239 radius was calculated by Inverse Distance Weighting Interpolation (IDW) as the following
 240 equation:

$$U_m(x, y) = \frac{\sum_{j=1}^n [U_m(x_j, y_j) \cdot w_j]}{\sum_{j=1}^n w_j}, \quad \text{with } w_j = \frac{1}{h_j^p} \quad (1)$$

241 Where w_j is a weight factor assigned by the distances h_j between the reference points
 242 (value-known) and the interpolation point (value-unknown). $U_m(x, y)$ is the interpolation point
 243 and $U_m(x_j, y_j)$ is the neighbor vector as a reference input, n is the number of reference vectors
 244 and we put 4 in this case, p is an exponent value (power index, default value 2), determines how
 245 quickly the influence of neighboring points drops off, the higher value the closer vector influence
 246 more.

By this method, velocity profiles at any given radius and layer in the gap can be reported. It has to be highlighted that acquisition frequency was kept by the optical trigger and that the main purpose of this article was to study the flow field and velocity profile in different component.

2.2 Test fluid and operating conditions

A water soluble and viscous transparent Newtonian fluid (Breox® Polyalkylene Glycol 75 W 55000, BASF) was used. The thermo-physical properties including viscosity μ [Pa·s], density ρ [kg/m³], heat capacity C_p [J/(kg·°C)] versus temperature T [°C] and mass concentration C [%] were respectively measured with a rheometer (HAAKE Mars III, SN: 4201100100779, Thermo Scientific, Germany, torque range: $10^{-8} - 0.2$ N·m, rotation speed range: $10^{-7} - 4500$ RPM), a density meter (DE40, SN: MPK38384, Mettler Toledo, France, range: 10^{-4} to $3 \text{ g/cm}^3 \pm 10^{-4} \text{ g/cm}^3$, 4 to $90^\circ\text{C} \pm 0.05^\circ\text{C}$), and a differential scanning calorimeter (Micro DSC-III, SN: 60/50287.06.102, Setaram, France, temperature range: $-20 - +120^\circ\text{C}$, thermal kinetics: $10^{-3} - +1.2^\circ\text{C}$ and fluxmeter range: $0.2 \text{ } \mu\text{W} - 20 \text{ mW}$, resolution : 40nW). Density, viscosity and heat capacity are described as functions of Breox® mass concentration and temperature ($15 - 45^\circ\text{C}$) as follows:

$$\begin{cases} Cp = aT + b \\ a = -14.8C^2 + 16.3C - 1.46 \text{ (} R^2 = 0.974 \text{)} \\ b = -2.17 \times 10^3 C + 4.30 \times 10^3 \text{ (} R^2 = 0.972 \text{)} \end{cases} \quad (2)$$

$$\begin{cases} \rho = cT + d \\ c = 0.185C + 1.00 \text{ (} R^2 = 0.999 \text{)} \\ d = -9.74 \times 10^{-4} C - 2.58 \times 10^{-4} \text{ (} R^2 = 0.999 \text{)} \end{cases} \quad (3)$$

$$\begin{cases} \ln\mu = -\frac{Ea}{R} \left(\frac{1}{T} - \frac{1}{T_{20}} + \ln\mu_{20} \right) \\ Ea = -1.80 \times 10^4 C - 1.90 \times 10^4 \text{ (} R^2 = 0.964 \text{)} \\ \ln(\mu_{20}) = -7.88C^2 + 19.7C - 6.78 \text{ (} R^2 = 0.999 \text{)} \end{cases} \quad (4)$$

With these regression equations, fluid properties of BREOX solution can be easily estimated. A 40% (mass concentration) diluted BREOX solution was chosen as a test fluid (with $\mu = 0.81$ Pa·s, $C_p = 3274$ J/(kg·°C) and $\rho = 1067$ kg/m³ at $T=20^\circ\text{C}$). Temperature of the feeding tank was controlled at 20°C by adjusting the thermostat (room temperature was air controlled at 20°C). Rotation speed of the impeller (N) was fixed at 2 Hz, feeding flowrate (Q_f) controlled at 25 and 45 L/h. Additionally, during these measurements, the fluid properties and operating parameters were stable (permanent regime).

According to the previous study [33], Reynolds and mixing Reynolds can be estimated:

$$Re_{mixing} = \frac{\rho N d_m^2}{\mu} = 45 \quad (5)$$

Laminar regime: $Re_{mixing} < 400$, turbulent regime: $Re_{mixing} > 1 \times 10^6$;

$$Re_Q = \frac{\rho u_f d_h}{\mu} = \frac{2\rho Q}{\mu \pi d_h} = 0.01 \quad (6)$$

Laminar regime: $Re_Q < 3$, turbulent regime: $Re_Q > 50$.

With d_m is the diameter of the impeller, d_h (equal to 3 mm) is the equivalent hydraulic diameter of the RVF module. Therefore, at $N=2$ Hz, laminar regime is confirmed.

- Temperatures at inlet and outlet of RVF module exhibit only 0.2°C increase. Considering thermal dependency of physical properties, the variation of viscosity, density and heat capacity can be neglected and a permanent regime is assumed;
- Pressure difference between inlet and outlet was 49.2 ± 2 kPa at 45 L/h corresponding to 0.63 W;
- Mixing power was measured at 33.5 ± 0.6 W for 2Hz.

2.3 Statistical analysis for PIV

The amount of images on the flow statistics (mean values and standard deviation) was investigated to determine and to optimize PIV measurements. The reliability and stability of velocity fields were verified in order to access to the required number of image pairs. In Fig. 3, the mean value of velocity magnitude $\overline{U_m}$ (Eq. 7) and the standard deviation σ_I (Eq. 8) are calculated from velocity field in random points, and are plotted as a function of image number (I).

$$\overline{U_{m_I}} = \frac{1}{I} \sum_{i=1}^I [U_{m_i}], \quad I = 1, 2, \dots, 1000. \quad (7)$$

$$\sigma_I = \sqrt{\frac{1}{I} \sum_{i=1}^I (U_{m_i} - \overline{U_{m_I}})^2}, \quad I = 1, 2, \dots, 1000. \quad (8)$$

$\overline{U_{m_I}}$, it is defined as an accumulative moving average as well as σ_I is defined as an accumulative moving standard deviation,.

Fig. 3 Evolution of mean IDW velocity (a, b and c) and the associated standard deviation (d, e and f) as a function of the number of image pairs, I . Observations are reported for 3 radius (30, 45 and 65 mm) for 6 different slices within the gap ($z_I=0.25$ to $z_6=2.75$ mm) at $\theta=-50^\circ$.

From Fig 3a, b and c, an increase of mean velocity from the wall to the impeller (gap position) is observed whatever radius for position $\theta=-50^\circ$. Fig 3d, e and f indicate a large variation of standard deviation magnitude without correlation with gap position. For example, at $R=45\text{mm}$ for $z_I=0.25$, $z_3=1.75$ and $z_6=2.75$ mm, $\overline{U_{m_{100}}}$ values are respectively 0.1, 0.25 and 0.3 m/s whereas σ_{100} values are respectively 0.02, 0.04 and 0.035. Graphically, $\overline{U_{m_I}}$ and σ_I seems to converge to stable and constant values for $I > 50$ and $I > 100$ respectively. Some studies argued that large number of frames was needed, especially for turbulent flow characterization. Figueredo-Cardero et al. [27] proposed that 4000 image pairs had to be used, T. Li et al.[31] used a total of 300 image pairs for fouling investigation in a hollow fiber setup, while T.Jiang et al.[36] and N.Liu et al.[37] used only a small amount around 50 image pairs for their analysis, while

larger number of image pairs are required in other research fields like aeronautics and aerodynamics [38,39]. In our conditions, convergence criterion, $\left|\frac{d\overline{u_{mI}}}{dI}\right|$ and $\left|\frac{d\sigma_I}{dI}\right|$ are defined. A constant decreasing slope of $\log\left(\frac{d\overline{u_{mI}}}{dI}\right)$ and $\log\left(\frac{d\sigma_I}{dI}\right)$ vs $\log(I)$ is noticeable and absolute criterion, $<10^{-4}$, are used to estimate the minimum requested number of image pairs. For $\overline{U_{mI}}$ and σ_I , I superior to 200 is identified and $I=1000$ was retained, although it is overestimated.

2.4 Flow field analysis with CFD

To simulate numerically the flow field in this dynamic filtration module, a model based on the finite element method was developed using commercial CFD software COMSOL Multiphysics (version 4.3a, U.S).

2.4.1 Governing equations and boundary conditions

The geometrical domain was simplified to one filtration cell of RVF module. Assuming a periodic movement of the impeller, one third of the filtration cell is simulated and the governing equations are solved in a rotating reference frame. Considering a laminar and incompressible flow of a Newtonian fluid, mass and momentum balances were governed by the Navier Stokes equations expressed in a fixed reference frame as follows:

$$\nabla \mathbf{u} = 0 \quad (9)$$

$$\rho \cdot \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla \mathbf{u}) = -\nabla p + \mu \nabla^2 \mathbf{u} \quad (10)$$

where ρ is the fluid density in kg/m^3 , μ is the fluid dynamic viscosity in $\text{Pa}\cdot\text{s}$, P is the pressure in Pa, and $\mathbf{u}$ is the absolute velocity vector in m/s .

Navier Stokes equations were solved under boundary conditions related to fluid domain, wall and impeller which describe real working conditions:

- Simulation focused on one third of the filtration cell and flow fields were assumed to be periodic at $\theta = 0^\circ$ and 120° (Fig. 4 (a), section 1 and 2);
- A mean pressure gradient, as the driving force, was imposed to the entire volume of the filtration cell across the whole length from the bottom to the top (Fig. 4 (a), section 4);
- On the impeller surface (Fig. 4 (a), surface 5), radial velocity vector u_r and vertical velocity vector u_z were imposed to 0, angular velocity vector $u_\theta = 2\pi NR$, was expressed from rotation frequency of the impeller, with N, the rotation frequency [Hz] and R, radial coordinate [m];
- Velocity vectors on all the walls, including membrane surfaces (upper and lower wall) and the surrounding wall (Fig. 4 (a), surfaces 3 and 6) were imposed to 0 considering no-slip boundary conditions at fluid-solid interface;

Fig. 4 Geometry of the RVF filtration cell (a) and mesh (b) used with CFD software COMSOL 4.3a. For fluid, sections 1 and 2: vertical periodic cross sections and section 4: fluid inlet (bottom) and outlet (top) sections. For impeller, surface 5: rotating solid impeller. For wall, surfaces 3 and 6: horizontal membrane surfaces including upper and lower walls and surrounding wall.

2.4.2 Numerical method and calculation mesh

Eq. (9) and (10) were solved by the Rotating Machinery Model of COMSOL 4.3a, which was a time-dependent 3D problem. Selected mesh was a compromise between accuracy and reduction of the calculation time. For the simulations dealing purely with laminar flow, a physics controlled and refined mesh (automatically generated by COMSOL 4.3a) was chosen (Fig. 4b). Several element types were used, such as tetrahedral, pyramid, prism, triangular, quadrilateral, edge and vertex elements, with total number of 355362, total volume 55 mL. Large velocity gradient was carefully considered with local refined mesh.

For CFD simulation, a Newtonian fluid with a viscosity equal to 0.8 Pa·s was considered and assumed to be incompressible and independent of temperature in agreement with test fluid for PIV measurements. Simulated conditions were rotation frequencies equal to 2, 5 and 10 Hz, vertical mean pressure gradients, $\frac{(P_{inlet}-P_{outlet})}{L}$, equal to 1.17, 1.10 and 1.02 Pa/m corresponding to nominal flowrate equal to 45 L/h. One additional simulation was realized for Q=25 L/h, 2 Hz and a vertical mean pressure gradients equal to 0.76 Pa/m.

3 Results and discussions

3.1 From PIV measurement to velocity field analyses

By analyzing the PIV raw images, the instantaneous velocity fields (from single images pair) and time averaged mean velocity fields (from 1000 image pairs) in 6 horizontal plane (x-y plane) within membrane-impeller gap were computed. To acquire the mean velocity fields in this rotating system, the optical trigger plays a key role in these measurements because it synchronizes and governs the laser generator and the camera with the position of one specific blade. Image processing and statistical quantities ($\overline{U_m}$, σ_I) were detailed in Materials & Methods then velocity components in the angular and radial directions were calculated. Velocity fields (Fig. 5) and profiles (Fig. 6) are presented and compared to the CFD simulation (Fig 7 and 8).

Fig. 5 Illustration of PIV raw images (a, d), instantaneous velocity fields (b, e, issued from single image pair) and time-averaged velocity fields (c, f, averaged of 1000 image pairs) in RVF module. Slice positions: close to the wall, $z_I = 0.25$ mm (a, b and c) and close to the impeller, $z_I = 2.75$ mm (d, e and f); Operating conditions: $Q_f = 45$ L/h, $N = 2$ Hz; $\mu = 0.81$ Pa·s and $T = 20^\circ\text{C}$. Symbols: $\bigcirc$, leading edge and $\triangle$, trailing edge of blade.

Fig. 5 provides an overview of the magnitude of velocity fields. In our experimental conditions, maximal impeller velocity is equal to 0.87 m/s at $R=69$ mm ($d_m=138$ mm). Raw PIV images, Fig 5a and d show the constant position of impeller and the homogeneous surface density of florescent particles for $z_1=0.25$ (close to membrane) and $z_6=2.75$ (close to impeller) mm. In terms of flow pattern, instantaneous (Fig 5b and e) and mean (Fig 5c and f) velocity fields can be compared. As it stands, Fig 5b and c present the lowest velocity magnitudes whereas Fig 5e and f exhibit the highest values (close to the impeller velocity). As expected, mean velocity fields present a uniform and regular flow pattern. Jiang.T et al.[36,40] also introduced a PIV measurement by using pine pollen tracing in water (turbulent flow) with a rotating membrane bioreactor. This membrane module was consisted of 9 identical flat sheets vertically in a cylindrical reactor, with internal diameter of 240 mm and effective volume of 13 L. In their conditions, mean velocity fields show a clear and stable velocity gradient in radial direction with time-averaged velocity plot. In our study, similar observation can be established:

- It is found that velocity around the central shaft is regular and organized, and it is close to zero. As it described in Introduction part, feeding fluid goes through RVF module along the central shaft vertically (z direction) from the bottom to the top, governing velocity vector is at the z direction, so, velocity close to the central shaft in horizontal (x - y) plane is almost zero;
- Velocity gradient increases in radial direction from inner to outer diameters, but velocity remains nearly equal to zero at the maximum diameter $R=70$ mm (fluid is at rest close to the surrounding wall, no-slip boundary conditions at fluid-solid interface). This observation is verified for both position, $z_1=0.25$ and $z_6=2.75$ mm;

- Velocity magnitude close to the inner diameter, $R=25\text{mm}$, remains inferior to 0.1 m/s whereas shaft velocity is equal to 0.31 m/s;
- Velocity fields likely have periodic movements generated by the specific shape of impeller. Maximum fluid velocities (Fig 5c and f) were found near the leading edge of the blade. At $R=65\text{ mm}$, the maximum values were 0.15 and 0.45 m/s for $z_I=0.25$ and $z_6=2.75\text{ mm}$ respectively, while the impeller velocity was 0.82 m/s. However, maximum value in the velocity field $z_I=0.25$ and $z_6=2.75\text{ mm}$ are at $R=55\text{-}60\text{ mm}$, with 0.21 and 0.58 respectively;

Fig. 6 Evolution of mean velocity profiles, $\overline{U}_m$ and their radial and angular components, $\overline{U}_\theta$, $\overline{U}_r$ as a function of angular position for 6 horizontal planes (z) within the membrane-impeller gap. (a): interpolated mean velocity at $R=30, 45$ and 65 mm ; (b): mean, radial and angular velocity profiles, $\overline{U}_m$, $\overline{U}_\theta$ and $\overline{U}_r$, at $R=45\text{ mm}$. Operating conditions: $Q_f=45\text{ L/h}$, $N=2\text{ Hz}$; $\mu=0.81\text{ Pa}\cdot\text{s}$ and $T=20^\circ\text{C}$.

Symbols: $\bigcirc$, leading edge and $\triangle$, trailing edge of blade.

From velocity fields, several velocity profiles can be more specifically analyzed. Fig. 6a presents the evolution of IDW mean velocity magnitude $\overline{U}_m$ profiles at 3 given radius (30, 45 and 65 mm) for 6 axial positions ($z_I=0.25$ to $z_6=2.75\text{ mm}$). From this overview, However, the

unexpected velocity peaks (about 0.35 m/s) which locate at $R=30$ mm $z_0=2.75$ mm can be pointed out as they have the same magnitude as impeller velocity (0.38 m/s). An artifact most likely caused by the fluorescent particles accumulated on the blade edge is assumed and PIV system considers those particles in data treatment.

In Fig 6b, mean velocity profiles versus angular position ($-120^\circ < \theta < +10^\circ$) in one third of filtration cell are presented at $R=45$ mm within a reconstructed polar coordinate centered at the middle of RVF shaft. Both components were derived from the Cartesian velocity by decomposing the velocity vector into radial and tangential components, $\overline{U_m}^2 = \overline{U_\theta}^2 + \overline{U_r}^2$. Profiles were observed to be periodic and sustain previous observation with velocity fields. As expected, maximum velocity in RVF occurs close to the impeller ($z_0=2.75$ mm), and decrease gradually from the impeller to the wall without any disruption between the layers. It indicated that laminar flow within the gap was highly stable and well-organized. In addition, some noticeable waves appear around the leading edge and trailing edge (symbol O and Δ), probably due to the shape of three blades. It might imply that this impeller design could periodically generate a regular fluctuation along the angular direction, and tended to remove the membrane fouling even with highly viscous fluids. Specific remarks can be summarized from Fig. 6b:

- $\overline{U_m}$ and $\overline{U_\theta}$ are statistically similar. Since RVF module is an annulus mixing device with an impeller equipped with three flat blades, the dominant velocity component is $\overline{U_\theta}$.
- $\overline{U_r}$ has a negligible contribution in value but fluctuates with a highly organized ebbs and flows, probably due to the impeller design.
- Besides, velocity profiles were also compared with two feed flowrates (25 and 45 L/h). Results showed that no significant impact on velocity profiles was observed. It

corroborated one of the advantages of DF compare to the conventional filtration (DE, CF) with an internal flow pattern independent from feed flowrate.

3.2 Validation and analysis of CFD simulation

CFD simulation is a powerful tool to estimate and get access to the additional information in a flow field when experiment is hardly possible to perform. Therefore, in this second step, PIV experiments and CFD simulations ($\mu=0.81$ Pa·s, $Q_f=45$ L/h, $N=2$ Hz, $T=20$ °C) were compared to validate simulation model, and then to gain insight into local hydrodynamics.

3.2.1 Simulated velocity fields

CFD give access to velocity in x , y and z coordinate, results present in this part is velocity magnitude in the x - y plane associated with PIV measurements.

Fig. 7 Simulated velocity fields in 6 slices (a-f): z_1 to $z_6=2.75$ mm. Operating conditions: $Q_f=45$ L/h, $N=2$ Hz; $\mu=0.81$ Pa·s and $T=20^\circ\text{C}$.

In Fig. 7 (a), velocity fields at 6 slices are plotted to appreciate velocity magnitude and deviation. A first qualitative approach (Fig. 5 and Fig. 7) is aim to compare the simulated and experimental velocity fields :

- Velocities are nearly equal to zero when the flow layers are close to the wall (z_1), while the closest to the impeller present the highest values (z_6);
- Velocity is nearly zero close to the central shaft and the surrounding wall ($R=70$ mm) of the filtration cell;

- Maximum velocities occur at leading edge at $R=55-60$ mm of the impeller for (a) (b) (c) and (d) which has been found also in Fig. 5, but for (e) and (f), it is found above the blade body;
- Differences between PIV and CFD may come from the precision and uncertainty of measurement, as we described, adjusting the measuring plane may have ± 0.25 mm error due to the laser thickness.

3.2.2 Vertical velocity and shear rate profile

As mentioned, PIV measurements were performed in half of the filtration cell from z_1 to z_8 . Due to optical obstruction of laser beam, velocity field in z_7 and z_8 can only measure between 2 blades and provided very limited information, while CFD simulations were applied to the entire filtration cell (within 14 mm gap $-7 < z' < 7$ between both membranes, impeller thickness $-4 < z' < 4$).

Fig. 8 Evolution of mean velocity, $\overline{U}_m$ issued from PIV measurement and CFD simulations as a function of axial direction, z' for 3 points located between 2 blades at radius, $R=45$ mm (point 1: leading edge, point 2: between two blades, point 3: trailing edge). Operating conditions: $Q_f = 45$ L/h, $N=2$ Hz; $\mu=0.81$ Pa·s and $T=20^\circ\text{C}$. (Notice: $z'=-z+7$ is used, lead to: $-7 < z' < 7$ for the 14 mm gap between both walls where membranes are mounted, $-4 < z' < 4$ for the impeller thickness)

Fig. 8 compares velocity profiles at radius $R=45$ mm between PIV measurements and CFD simulation. All curves issued from CFD simulations present a typical parabolic laminar profile between two fixed walls for point 1 (leading edge at $\theta=0^\circ$), 2 (between two blades at $\theta=-30^\circ$) and 3 (trailing edge at $\theta=-60^\circ$). Between 2 blades, the maximum velocities were located at the

473 parabolic vertex corresponding to the middle of filtration cell ($z'=0$ mm). Between blade and
474 membrane, the maximum velocity can be observed at blade surface (Fig. 6b). Velocity at leading
475 edge (Point 1) is higher than the two others (point 2 and 3) with a maximum velocity of
476 0.757 ± 0.029 m/s in PIV and 0.778 m/s in CFD. For points 2 and 3, maximum velocities were
477 respectively 0.678 ± 0.027 m/s and 0.517 ± 0.046 m/s for PIV and 0.641 m/s and 0.556 m/s for
478 CFD. However, theoretical angular velocity of the impeller is 0.56 m/s at $R=45$ mm, a tentative
479 inference on this result is that special configuration (narrow gap, confined volume with rotating
480 three-blade impeller) have great influence in local velocity field and thus has complex
481 hydrodynamic in the filtration cell, according to author's limited knowledge. Regarding
482 maximum velocities, the consistency between PIV and CFD is well established. Considering
483 whole velocity profiles, the same trends could be observed even if the profile at trailing edge is
484 slightly overestimated with CFD. Slight deviations are justified by uncertainty of experimental
485 measurements regarding laser sheet location and velocity.

Fig. 9 Wall shear rate ($z'=\pm 7$ mm) calculated from CFD simulations with 3 points from radius $R=25$ to 70 mm. Operating conditions: $Q_f=45$ L/h, $N=2$ Hz; $\mu=0.81$ Pa·s and $T=20^\circ\text{C}$. (Notice: $z'=\pm 7$ mm is at the surface of the walls where membranes are mounted)

Velocity magnitudes and parabolic shapes sustain the accurate fitting between PIV and CFD, local shear rate can be estimated from CFD to introduce the hydrodynamic phenomena in the filtration cell. To this end, wall shear rate profiles at 3 angular position are plotted in Fig. 9 (shear rate profile are symmetrical at $z'=\pm 7$ mm, absolute values are almost the same). In our operating conditions ($Q_f=45$ L/h, $N=2$ Hz; $\mu=0.81$ Pa·s and $T=20^\circ\text{C}$), wall shear rate are equal to 229, 179 and 164 1/s for points 1, 2 and 3 respectively at radius $R=45$ mm. At this radius, it was found that wall shear rate at leading edge is higher than the others. Wall shear rate profile for $\theta=0^\circ$ increases from 150 1/s ($R=25$ mm) up to 230 1/s ($R=50$ mm) then decreases to 50 1/s at the surrounding wall ($R=70$ mm). Profiles at $\theta=-30^\circ$ and $\theta=-60^\circ$ are having a similar trend, both increase from 75 1/s ($R=25$ mm) and have a rapid decrease at $R=65$ mm. This information may

indicate a complex hydrodynamics at the membrane surface, and it is also intensified by the complex shape of impeller and its rotation.

3.2.3 Streamlines and RTD

So far, investigation of hydrodynamics in RVF module have occurred at different scales, ranging from filter efficiency at a global experiment point of view (in previous studies) up to local examination of velocity field (in this study). To complete this hydrodynamic, it requires the information of fluid residence time and the track of mixing, it fills the blank of information regarding how long the microbial cell can survive from such a complex filter, and also realize the mixing effect. Comparison between PIV experiments and CFD simulations has proved simulation approach was validated in laminar flow, which proved the access to additional flow patterns information is feasible, whereas experimental approaches is hardly possible. Therefore, in present case we pay attention to streamlines issued from CFD in order to access and discuss Residence Time Distribution (RTD) and the mixing effect within the RVF filtration cell.

Fig. 10 Illustration of streamlines in the filtration cell issued from CFD simulation, introduce streamlines in horizontal slices at 2 Hz with in the whole filtration cell. Operating conditions: $Q_f= 45$ L/h; $\mu=0.81$ Pa.s and $T=20^\circ\text{C}$.

Fig. 10 display the streamlines within the filtration cell between section 1 and 2 in Fig.4. The streamlines seem to be almost parallel to each other, indicating a well-organized flow motion in any horizontal plane around the shaft. As expected Streamlines velocity is found almost equal to zero close to the surrounding wall, it highly refers to an annular surrounding volume with low mixing, and a dead-zone can be assumed. However, a large magnitude of velocity between the streamlines is noticeable, velocity value corresponds to the velocity field in Fig. 7.

Fig. 11 Illustration of streamlines in the filtration cell issued from CFD simulation in 3D (a, b, c) and 2D (d, e, f) view, introduces the streamlines from inlet to outlet (Fig. 4, section 4), at rotation frequency $N=2$

Hz (a, d), $N=5$ Hz (b, e), $N=10$ Hz (c, f). Operating conditions: $Q_f=45$ L/h; $\mu=0.81$ Pa.s and $T=20^\circ\text{C}$. *

Notice each figure has 500 streamlines.

In addition, Fig 11 presents the streamlines corresponding to inlet and outlet section (Fig 4, section 4). CFD simulations were conducted in order to investigate the effect of mixing rate, to realize the contribution of the impeller to RTD in the system. It is clear that shortcut effect along the shaft is a dominant phenomenon. Graphically, from (a) to (c) with the increase of rotation speed, less streamlines pass over the entire filtration cell although each figure has 500 streamlines. It seems the flow has a shortcut straight from the inlet to the outlet. And it is further proved by the streamlines in the vertical view (d), (e) and (f): with the increase of rotation speed, vertical streamlines have higher velocity, it means that fluid left the system faster in this zone. And the flow in the rest of the cell hold steady and rotate in stable. To sum up, streamlines confirm that a dominant shortcut flux may exist along the shaft, consequently less flux flow into the filtration cell; the contribution of the shortcut in vertical direction became more prevalent with the increase of rotation speed, it may cause a risk of dead-zone in the filtration cell.

3.3 Identification of the core velocity coefficient

Core velocity coefficient K_θ is one of the key factors that present the mechanical efficiency of the RVF, to realize the device mechanical efficiency as an indicator. This coefficient can be raised by increasing surface roughness and changing device configuration. Among the early studies, Wilson et al.[41] found K_θ (ratio of fluid velocity to impeller velocity, $K_\theta = \frac{\langle \overline{U_\theta} \rangle}{\omega \cdot R}$) was close to 0.313 between a stationary and a rotating disk with suction. Bouzerar et al.[42] increased this coefficient up to 0.62 by modifying the rotating disk in a DF module via pressure measurement, and further increased up to 0.84 by Brou. et al.[15]. For the complex designed RVF module (three-blade and narrow-gap configuration), previous work [34] resulted a value of

0.71 by pressure measurement. However, these coefficients presented in the literature gave a global ratio between the impeller and the turbulent core fluid layer. By our experiment, local K_θ distribution can be identified. In the z direction, from the wall to the impeller, K_θ varies from 0.08 to 0.54 with a mean value of 0.31 in laminar flow, and slightly decreases from inner radius to the outer radius, affected by the surrounding wall. This result was in a good agreement with the simulation result which gives a mean value of 0.35.

4 Conclusions

Among the numerous filtration studies, including our past work, researchers developed a lot of application by using DF, research mainly apply to low viscosity filtration and have dealt with (a) fouling mechanisms, (b) the relationship between quantitative and qualitative performances, (c) the development of alternative membrane filtration such as membrane structure and dynamic filtration and (d) industrial applications. It is demonstrated that dynamic filtration can be an efficient substitute for some conventional filtration. Good performance has been proved in food engineering process such as beer, dairy, juice etc., and also used in biomedicine such as bovine serum albumin and cell harvest, as well as in drinking water/wastewater treatment plant, and fermentation industry. Less attention has been paid in the local flow field. Therefore, we suggested that, our earlier result of global hydrodynamic analysis should be strengthened by the determination of local variables (shear rate, velocity and pressure) which cannot be easily estimated in a confined volume, the RVF module. We have, however, obtained the access to the local hydrodynamics associated with high viscosity fluid, by using PIV, a powerful flow-visualization technique.

In this paper, PIV measurements were done in 6 horizontal planes (8 planes in Fig. 8) with an optical trigger, we show the ability to access to local velocity fields in a complex, confined

and rotating device by PIV technique, and compared to simulation. Firstly, results issued from PIV were discussed, such as velocity field and velocity profile in radial and vertical direction, and it had been proved that local velocity profile were highly organized and steady, moreover, it was independent of feeding flowrate. Furthermore, CFD simulation was performed in parallel, presented a good agreement with PIV measurements, enabled us to validate the numerical model and have the ability to estimate some more local variables precisely. Finally, local and global core velocity coefficients (issued from PIV and CFD) were deduced and compared to similar devices and alternative methodologies reported in the literature. These results lead to conclude that:

- velocity distribution in such a filter was strongly affected by complex physical configuration (three blades and narrow gap), it helped to generate a complex but periodic velocity variation;
- we believed that RVF may have high efficiency in fouling removal, since it had high wall shear rate even with very viscous fluid in pure laminar flow, and also proved by the high value of velocity coefficient;
- Less power would be consumed by RVF module compared to traditional filtration type, since it had been proved that velocity in the filtration cell was independent of feeding flowrate, high pressure of feeding pump was released;
- CFD model was validated, it can be used to scrutinized micro-hydrodynamics in the RVF module;

Overall, this work highlighted the local hydrodynamic phenomena in a DF module, and it was motivated by the lack of information in local aspect of this filter, to better understand the physical mechanism as an extended support for those good performances in the past work.

596 However, we had not discussed on the vortex that may possible occurred. It should be notice that
597 flow in the filtration device is a three-dimension phenomenon. Due to the technical limitation
598 like complexity of experimental setup and limitation of author's knowledge, the current study
599 was only focus on two-dimension measurement, which was parallel to the flat impeller surface.
600 Further studies may include PIV measurement in vertical plane, then it will be interesting for the
601 velocity decomposition by Proper Orthogonal Decomposition (POD) analysis in both horizontal
602 and vertical plane to further identify the flow pattern and velocity structure. More research on
603 RTD is also required to validate simulated streamline in this article, it is important to realize in
604 such dramatic hydrodynamics when work with biological fluid.

605 **Nomenclature:**

Latin Letter		
C_p	Specific heat capacity	[J/(kg·°C)]
d_h	$d_h = \frac{4S}{P}$, Equivalent diameter (P is the wetted perimeter)	[m]
d_m	Diameter of the impeller	[m]
h_i	Distance from reference points to the interpolation point	[mm]
I	Number of image pair	[/]
K_θ	Core velocity coefficient	[/]
n	Number of the reference points	[/]
N	Rotation frequency of the impeller	[Hz]
r	Radial coordinate	[mm]
R	Radius	[mm]
p	Power index	[/]

P_{in}	Inlet pressure	[Pa]
P_{out}	Outlet pressure	[Pa]
Q_f	Feeding flowrate	[L/h]
Re_{mixing}	$Re_{mixing} = \frac{\rho N d_m^2}{\mu}$, Reynolds number for a mixing system	[/]
Re_Q	$Re_Q = \frac{\rho u_f d_h}{\mu}$, Reynolds number for a system equivalent to a tube	[/]
T	Temperature	[°C]
TMP	Transmembrane Pressure	[Pa]
$\overline{U}_m$	Magnitude of the velocity vector	[m/s]
$\overline{U}_\theta$	Velocity of the vector at tangential direction	[m/s]
$\overline{U}_r$	Velocity of the vector at radial direction	[m/s]
w_i	Weight factor	[/]
x-y plane	Horizontal plane parallel to the impeller surface	[/]
x	x coordinate	[mm]
y	y coordinate	[mm]
z	z coordinate	[mm]
Greek symbol		
μ	Viscosity	[Pa·s]
ρ	Density	[kg/m]
ω	Angular velocity of the impeller	[rad/s]

θ	Angle, centered at the middle of the rotating shaft	[degree]
σ_I	Accumulative moving standard deviation of velocity magnitude, I stands for numbers of image pairs	[m/s]
Δ_t	Time interval between two image for one image pair	[μ s]
Other Symbol		
Δ	Trailing edge of the impeller	[/]
O	Leading edge of the impeller	[/]
Abbreviation		
CF	Cross-flow	
CFD	Computational Fluid Dynamic	
DF	Dynamic Filtration	
DE	Dead-end (filtration)	
IA	Interrogation Area	
IDW	Inverse Distance Weighting interpolation	
MBR	Membrane Bioreactor	
PIV	Particle Image Velocimetry	
RVF	Rotating and Vibrating Filtration module	

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List of caption:

Fig. 1 Configuration of RVF module.

Fig. 2 Schematic diagram and apparatus used in the experiment (a) F: flowmeter; P1/P2: pressure sensor of inlet/outlet; T1/T2/T3: temperature sensor of inlet/outlet/bioreactor; P: pressure gauge; TM: Thermostat; (b) The PIV system synchronized with a CCD camera, double pulsed laser and the RVF module with the transparent cell; (c-d) black-painted impeller in the transparent cell; (e) An optical trigger synchronized with PIV system

Fig. 3 Evolution of mean IDW velocity (a, b and c) and the associated standard deviation (d, e and f) as a function of the number of image pairs, I . Observations are reported for 3 radius (30, 45 and 65 mm) for 6 different slices within the gap ($z_I=0.25$ to $z_6=2.75$ mm) at $\theta=-50^\circ$.

Fig. 4 Geometry of the RVF filtration cell (a) and mesh (b) used with CFD software COMSOL 4.3a. For fluid, sections 1 and 2: vertical periodic cross sections and section 4: fluid inlet (bottom) and outlet (top) sections. For impeller, surface 5: rotating solid impeller. For wall, surfaces 3 and 6: horizontal membrane surfaces including upper and lower walls and surrounding wall.

Fig. 5 Illustration of PIV raw images (a, d), instantaneous velocity fields (b, e, issued from single image pair) and time-averaged velocity fields (c, f, averaged of 1000 image pairs) in RVF module. Slice positions: close to the wall, $z_I=0.25$ mm (a, b and c) and close to the impeller, $z_6=2.75$ mm (d, e and f); Operating conditions: $Q_f=45$ L/h, $N=2$ Hz; $\mu=0.81$ Pa·s and $T=20^\circ\text{C}$. Symbols: $\bigcirc$, leading edge and $\triangle$, trailing edge of blade.

Fig. 6 Evolution of mean velocity profiles, U_m and their radial and angular components, U_θ , U_r as a function of angular position for 6 horizontal planes (z) within the membrane-impeller

gap. (a): interpolated mean velocity at $R= 30, 45$ and 65 mm; (b): mean, radial and angular velocity profiles, U_m, U_θ and U_r , at $R=45$ mm. Operating conditions: $Q_f= 45$ L/h, $N=2$ Hz; $\mu=0.81$ Pa.s and $T=20^\circ\text{C}$. Symbols: $\bigcirc$, leading edge and $\triangle$, trailing edge of blade.

Fig. 7 Simulated velocity fields in 6 slices (a-f): z_1 to $z_6=2.75$ mm. Operating conditions: $Q_f= 45$ L/h, $N=2$ Hz; $\mu=0.81$ Pa.s and $T=20^\circ\text{C}$.

Fig. 8 Evolution of mean velocity, U_m issued from PIV measurement and CFD simulations as a function of axial direction, z' for 3 points located between 2 blades at radius, $R=45$ mm (point 1: leading edge, point 2: between two blades, point 3: trailing edge). Operating conditions: $Q_f= 45$ L/h, $N=2$ Hz; $\mu=0.81$ Pa.s and $T=20^\circ\text{C}$. (Notice: $z'=-z+7$ is used, lead to: $-7 < z' < 7$ for the 14 mm gap between both walls where membranes are mounted, $-4 < z' < 4$ for the impeller thickness)

Fig. 9 Wall shear rate ($z'=\pm 7$ mm) calculated from CFD simulations with 3 points from radius $R=25$ to 70 mm. Operating conditions: $Q_f= 45$ L/h, $N=2$ Hz; $\mu=0.81$ Pa.s and $T=20^\circ\text{C}$. (Notice: $z'=\pm 7$ mm is at the surface of the walls where membranes are mounted)

Fig. 10 Illustration of streamlines in the filtration cell issued from CFD simulation, introduce streamlines in horizontal slices at 2 Hz with in the whole filtration cell. Operating conditions: $Q_f= 45$ L/h; $\mu=0.81$ Pa.s and $T=20^\circ\text{C}$.

Fig. 11 Illustration of streamlines in the filtration cell issued from CFD simulation in 3D (a, b, c) and 2D (d, e, f) view, introduces the streamlines from inlet to outlet (Fig. 4, section 4), at rotation frequency $N=2$ Hz (a, d), $N=5$ Hz (b, e), $N=10$ Hz (c, f). Operating conditions: $Q_f= 45$ L/h; $\mu=0.81$ Pa.s and $T=20^\circ\text{C}$. * Notice each figure has 500 streamlines.

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Tab. 1 System acquisition parameters of PIV setup

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Properties of BREOX:

Fig. A.1

Fig. A.2

Fig. A.3 Comparison of velocity components with two flowrates (Measurement position: $R=45$ mm, $z=2.25$ mm)

Fig. A.4 Mean radial velocity profiles ($\overline{U}_m$) and their velocity components ($\overline{U}_\theta$, $\overline{U}_r$) for 6 horizontal planes. (a) Overview of interpolated mean velocity magnitude profiles at $R=30$, 45 and 65 mm, within the gap by 6 slices ($Q_f=45$ L/h, $N=2$ Hz); (b) Velocity profiles of $\overline{U}_m$, and their components $\overline{U}_\theta$, $\overline{U}_r$, at 65 mm radius.

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