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Ming Cheng, Claude Le Men, Alain Line, Philippe Schmitz, Luc Fillaudeau. Investigation of instantaneous and local transmembrane pressure in rotating and vibrating filtration (RVF) module: Comparison of three impellers. Separation and Purification Technology, 2022, 280, 10.1016/j.seppur.2021.119827 . hal-03450507

HAL Id: hal-03450507

<https://hal.inrae.fr/hal-03450507>

Submitted on 16 Oct 2023

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1 Investigation of instantaneous and local transmembrane pressure in 2 Rotating and Vibrating Filtration (RVF) module: comparison of three 3 impellers

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9 **Abstract:** The instantaneous and local pressure at membrane surface was
10 experimentally investigated in a dynamic filtration module, named Rotating and
11 Vibrating Filtration (RVF) module. The present paper focuses mainly on the pressure
12 fluctuations in turbulent regime. To this end, the instantaneous pressure is
13 decomposed into its time-averaged and fluctuating quantities using Statistical
14 Analysis (SA), Probability Distribution Function (PDF) and Fast Fourier Transform
15 (FFT). The effects of back pressure, flowrate, rotation frequency and radial position at
16 the membrane on the magnitude of the pressure fluctuations are studied for three
17 different impellers (Imp 1, 2 and 3). For mixing pressure, Imp 2 (6 blades) exhibits a
18 larger core velocity coefficient than Imp 1 and Imp 3 (3 blades). For pressure
19 fluctuation, the extracted variables from SA (standard deviations), PDF (peak-to-peak
20 values) and FFT (amplitudes) confirm that the magnitude of Imp 1 > Imp 3 > Imp 2.
21 Considering SA at 20 Hz, standard deviation of Imp 1 exceeds 100 mbar (up to 25%
22 of TMP), while these values are negligible (<10%) for Imp 2 and 3. After FFT, the
23 dominant frequency identified with Imp 1 is equal to 3 times the rotation frequency
24 ($3N$). Conversely, different frequencies ($6N$, $3N$ and N) exhibiting low amplitude are
25 observed for Imp 2 and 3. Based on the PDF modelling, periodic and random
26 contributions are extracted by deconvolution. Then, the empirical correlations are
27 established to estimate their intensities as a function of rotation frequency and radial
28 position. A “resonance frequency” of 21.1 Hz is clearly identified with Imp 1.

29 **Keywords:** Instantaneous pressure; impeller configurations; core velocity
30 coefficient; pressure fluctuation; resonance frequency; signal reconstruction.

31 **Highlights:**

- 32 1. Comparison of local pressure at membrane surface for three impellers;
- 33 2. Determination of local core velocity coefficient;
- 34 3. Decomposition of signal with periodic and random contributions;
- 35 4. Analysis of peak amplitudes and dominant frequencies;
- 36 5. Signal reconstruction with established empirical correlations.

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Table of content

1	Introduction	4
2	Materials and methods.....	5
2.1	Experimental set-up and instrumentation.....	5
2.1.1	RVF module.....	5
2.1.2	Experimental set-up.....	6
2.1.3	Operating conditions and data acquisition	7
2.2	Data treatment	7
2.2.1	Time domain analysis.....	7
2.2.2	Frequency domain analysis	8
2.2.3	Modelling	8
3	Results and discussion.....	9
3.1	Raw data	9
3.2	Continuous components	10
3.2.1	Mixing pressure.....	10
3.2.2	Core velocity coefficient	10
3.3	Fluctuating components	11
3.3.1	SA.....	11
3.3.2	PDF.....	14
3.3.3	FFT	15
3.3.4	Modelling	17
3.4	Signal reconstruction	19
4	Conclusions	19
	Nomenclature.....	21
	Acknowledgments.....	21
	References.....	21

66 1 Introduction

67 Dynamic filtration (DF) is defined as the mechanical movement of devices or
68 membranes to generate a high stress (shear rate and pressure) at the membrane surface.
69 The external forces induced by rotation, oscillation and/or vibration show great
70 promise for controlling fouling, cake formation and mitigating concentration
71 polarization. This results in uncoupling between local shear rate and transmembrane
72 pressure (TMP) from feeding flowrate [1]. In consequence, DF is considered to be
73 energy-saving (power/flux) compared to the conventional dead-end and cross-flow
74 filtration [2, 3]. However, due to the complex geometries and configurations of DF,
75 the study of its internal hydrodynamics remains a great challenge.

76 Based on the hydrodynamic approaches, the technologies to create instabilities of
77 flow may contribute to reducing concentration polarization and fouling at the
78 membrane surface [4], and shear-based studies have been reported extensively [1,
79 5-8]. In rotating system, the shear rate has been enhanced by changing the shape of
80 the rotor [9-11], or by adding the insert [12] in the filtration cell. Some studies have
81 achieved a higher shear rate via overlapping membrane discs on one or more shafts
82 [13]. For cylindrical filters, the Taylor vortices generated between the annular gap
83 greatly increase the mixing effect in laminar flow; increasing the rotation speed,
84 Taylor vortices degenerate into turbulent flow [2, 14]. In oscillating system, flat disk,
85 rectangular, cylinder or hollow fibre membranes were mounted on the fixed shaft for
86 transverse, longitudinal or azimuthal vibration [15-19]. Wu et al. [20] reported the
87 installation of a vibrating spacer close to the submerged flat sheet membranes for
88 fouling control. It suggested that the turbulence promoter contributes to the
89 enhancement of turbulent kinetic energy and membrane surface shear rate.

90 The hydrodynamics in the DF modules have been carried out in order to evaluate
91 and estimate the filtration performances. Global approaches associated with
92 dimensionless correlations, such as Reynolds number versus Darcy's and power
93 number were established to model the power consumption [1, 21]. Semi-local
94 approaches include the additional pressure and local shear rate. In rotating systems,
95 the mixing pressure caused by the rotating disk or impeller is related to the core
96 velocity coefficient, but this theory has not been reported in vibrating systems. The
97 empirical correlations to estimate local shear rate were promoted according to the
98 operating conditions and specific cell geometrics [1]. For local approaches, the
99 experimental measurement allows the visualization of velocity, pressure and shear
100 fields, followed by the comparison to computational fluid dynamics (CFD)
101 technology [22-24].

102 Some researchers have found the empirical relations between steady-state
103 permeate flux and local shear rate [5, 25, 26]. The average shear rate is commonly
104 used as a primary indicator for evaluating filtration systems. In spite of the fact that an
105 increase in shear implies a higher permeate flux, it is also essential to account for the
106 unit energy consumption, irreversible fouling and fluid sensitivity. The theory of
107 critical and threshold flux was promoted in order to limit the increase of foulant, with

108 the relevant TMP usually being a time-mean value [27, 28]. In rotating disk module,
109 the disk with vans yields higher permeate flux than smooth discs at the same shear
110 rate [29], the explanation of which may be attributed to the stress (shear and pressure)
111 fluctuation. In microfiltration, transmembrane pressure can be maintained at very low
112 values (~ 100 mbar), and then high-pressure fluctuation (same order of magnitude than
113 TMP) could contribute to surface cake layer and internal reversible fouling
114 destabilization.

115 In a previous study [30], the instantaneous and local pressures at the membrane
116 surface were investigated during the rotation with a three-blade impeller. The time
117 series pressures were treated to extract the fluctuating information (intensity and
118 frequency), which showed to be affected by the radius and rotation frequency. In the
119 present study, the effects of back pressure, flowrate and impeller configurations
120 (number and shape of blades) on pressure fluctuations were investigated on time and
121 frequency domain. According to the Probability Distribution Function (PDF), the
122 fluctuating signals were decomposed into the representative of periodic and random
123 components. Thus, the dominant frequencies, intensities of periodical and random
124 contributions constitute the pressure fluctuation; the core velocity coefficient allows
125 to estimate of the mixing pressure. Finally, the reconstructed instantaneous pressures
126 were achieved by the sum of steady pressure and fluctuating components and then
127 compared with the experimental data.

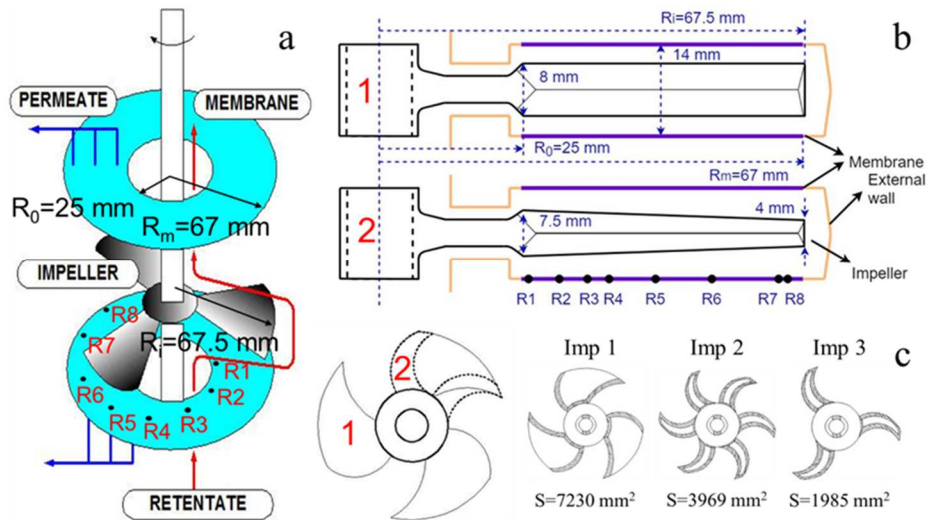
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129 **2 Materials and methods**

130 **2.1 Experimental set-up and instrumentation**

131 **2.1.1 RVF module**

132 The lab-scale RVF module [22, 31] consists of two filtration cells (0.2 L per cell,
133 1.5 L in total), both of which equips with an impeller rotate with the central shaft. The
134 rotation frequency N refers to the central shaft (impeller), with a maximum value of 50
135 Hz. Fig. 1a shows the schematic diagram of one filtration cell. Two crown membranes
136 ($R_0=25$ mm, $R_m=67$ mm) can be mounted on the porous substrates that allow the
137 collection of permeate to the lateral ducts. In order to achieve an accurate measurement
138 of the instantaneous pressure on the membrane surface, the 8 pressure taps with 2 mm
139 diameter are distributed over a radius ranging from R1 to R8. Three impellers with two
140 shapes of blades (shape 1 has increased surface area and 8 mm thickness; shape 2 has
141 decreased surface area and thickness) are applied in the tests, as shown in Fig. 1b and c.
142 Imp 1 equips with three blades (shape 1); Imp 2 and 3 have six and three blades (shape
143 2), respectively.



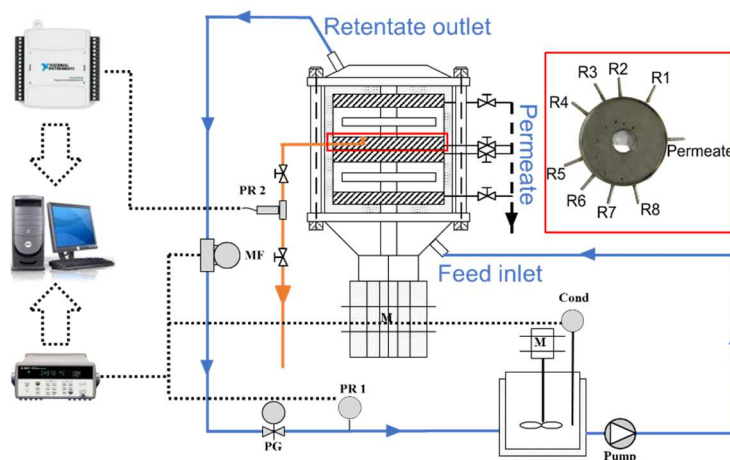
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Fig. 1 Schematic diagram of Rotating and Vibrating Filtration module. (a) one filtration cell; (b) rotating impellers in the filtration cell; (c) three types of the impeller.

2.1.2 Experimental set-up

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In Fig. 2, the experimental set-up constitutes the feeding tank, circulation loop and RVF module. During the experiments, the fluid is pumped from a double-jacket tank (8 L) into the RVF module. The permeate is closed, and retentate is fed back to the tank. The feeding flowrate is controlled by a volumetric pump (Pump) and acquired with a mass flowmeter (MF) in the outlet. It enables the measurement of flowrate (Q_F), density (ρ) and outlet temperature (T_{outlet}). The inlet temperature is recorded from the conductivity sensor Cond (T_{inlet}) in the feeding tank, to be maintained at 20 ± 5 °C with thermal regulation. The back pressure is measured by a relative pressure sensor (PR1, Bourdon-Haenni Y913, 0/6 bar, $\pm 0.2\%$ full scale) and adjusted by a counter-pressure valve coupled with a pressure gauge (PG, 0/4 bar). Another relative pressure sensor (PR2, Killer, -1/+1 bar, $\pm 0.2\%$ full scale, maximum acquisition frequency 5 kHz) locates at the distributed stainless tubes of a home-designed porous substrate, which permits the instantaneous pressure measurements without membrane.



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Fig. 2 Experimental set-up and data acquisition systems (dash line: permeate outlet, closed during the measurement; dotted lines: data acquisition channels. red frame: home-designed porous substrate;

165 *orange line: instantaneous pressure measurement).*

166 2.1.3 Operating conditions and data acquisition

167 In cross-flow microfiltration, the ratio between the average feed rate and
168 permeability under turbulent conditions is higher than 10,000 [32]. This phenomenon
169 also occurs in the applications of RVF module in wine making and brewing [31, 33].
170 Therefore, the suction effect can be neglected. Then, the experiments were carried out
171 without permeate (no membrane was used) and back pressure at 300 mbar to avoid
172 cavitation caused by the high rotation frequency. Tap water was used as feed fluid
173 with flowrates up to 300 L/h. The instantaneous and local pressure at 8 radii from R1
174 to R8 (26.2-64.9 mm), different rotation frequencies (0-50 Hz) and rotating impellers
175 were achieved.

176 In the tests, the operating conditions include the feeding flowrates, back pressure
177 and temperature along the circulation loop were recorded by Agilent 34972A (Agilent
178 Technologies, Loveland, USA) with the 3 s time interval. In contrast to these global
179 measurements, local pressure was measured with PR2 and access to the NI USB-6009
180 (National Instruments, USA, 1 kHz) with a sampling frequency of 1000 Hz for more
181 than 40 s.

182 2.2 Data treatment

183 Instantaneous pressure at the membrane surface can be classically decomposed
184 into the sum of the steady pressure $\bar{P}(r)$ and the pressure fluctuations $\tilde{P}(r, t)$, as
185 shown in Eq. (1). The evolution of the pressure field depends on the operating
186 conditions. By considering another variable rotation frequency (N) in the experiments,
187 the steady pressure and pressure fluctuation are given as $\bar{P}(N, r)$ and $\tilde{P}(N, r, t)$ in
188 the following analysis, respectively.

$$189 P(r, t) = \bar{P}(r) + \tilde{P}(r, t) \quad (1)$$

189 2.2.1 Time domain analysis

190 The mean local pressure or steady pressure $\bar{P}(N, r)$ at the membrane surface is
191 given in Eq. (2). Based on Navier Stokes equation, in cylindrical coordinates, and
192 considering inviscid fluid and angular velocity is the main component, mean local
193 pressure can be represented by Bernoulli's equation (Eq. (3)) [9]. Its value is equal to
194 the sum of P_0 and ΔP_{mixing} . P_0 is the local pressure of the steady flow without rotation.
195 ΔP_{mixing} is the mixing pressure given by the rotation of the impeller, the value of
196 which is determined by the mean velocity \bar{u} in the main fluid. In turbulent regime,
197 the angular velocity $2\pi Nr$ generated by the rotating disk is much higher than radial
198 and vertical velocity. The mean velocity in the flow can be represented as \bar{u} equal to
199 $k \cdot 2\pi Nr$, where k is the core velocity coefficient and inferior to 1 [30, 31, 33], ρ is
200 the density. With the mean steady pressure, the experimental k value can be
201 determined.

$$\bar{P}(N, r) = \frac{1}{m} \sum_{i=1}^m P(N, r, t_i) \quad (2)$$

$$\bar{P}(N, r) = P_0 + \Delta P_{mixing} = P_0 + \frac{1}{2} \rho \bar{u}^2 = P_0 + \frac{1}{2} \rho (k \cdot 2\pi N r)^2 \quad (3)$$

202 The standard deviation of instantaneous pressure σ_p has been used to describe
 203 the intensity of the fluctuations [30], where m represents the sampling number. The
 204 coefficient, β is defined as the ratio between σ_p and $\bar{P}(N, r)$, and give the relative
 205 standard deviation.

$$\sigma_p^2 = \frac{1}{m} \sum_{i=1}^m (P(N, r, t_i) - \bar{P}(N, r))^2 \quad (4)$$

$$\beta = \frac{\sigma_p}{\bar{P}(N, r)} \times 100\% \quad (5)$$

206 Higher-order moments are useful to better characterize the Probability
 207 Distribution Function of the signal. Among them, skewness (S) is known as the
 208 normalized central moment of the third order, associate with the symmetry of the
 209 signal in PDF.

$$S = \frac{1}{m\sigma_p^3} \sum_{i=1}^m (P(N, r, t_i) - \bar{P}(N, r))^3 \quad (6)$$

210 Flatness (F) is the normalised central moment of the fourth order. It indicates the
 211 sharpness of the distribution.

$$F = \frac{1}{m\sigma_p^4} \sum_{i=1}^m (P(N, r, t_i) - \bar{P}(N, r))^4 \quad (7)$$

212 2.2.2 Frequency domain analysis

213 For frequency domain analysis, the dominant frequencies and their respective
 214 amplitudes are found using the Fast Fourier Transform (FFT). As shown in Eq. (8),
 215 the discrete function of Fourier Transform is displayed as a complex, where f is the
 216 frequency and m is the number of sampling points. The amplitude at the given
 217 frequency A_f is calculated as Eq. (9).

$$P(f) = \sum_{i=0}^{m-1} \tilde{P}(N, r, t_i) e^{-\frac{2\pi j f i}{m}}, \quad f = 0, 1, \dots, m-1 \quad (8)$$

$$A_f = \frac{2}{m} \sqrt{P(f)^2} \quad (9)$$

218 2.2.3 Modelling

219 Based on the PDF, the pressure fluctuations are decomposed into periodic and
 220 random contributions. Both terms have been identified in the methodology paper
 221 previously [30]. The periodic component is simplified as a single sinusoidal wave,
 222 whereas the random component follows the normal distribution, shown as:

$$\widetilde{P}_P(t) = A \sin(2\pi f t + \varphi) \quad (10)$$

$$\widetilde{P}_R(t) \sim \text{Norm}(\bar{x}, \sigma^2) \quad (11)$$

223 where A is the amplitude, f is the frequency, φ is the phase; \bar{x} is the mean value of
 224 random signal equal to 0, σ means the standard deviation.

225 From the simulated functions, the model PDF is built by the convolution of PDF
 226 for both terms, as described below:

$$PDF_{model} = \frac{1}{\pi\sqrt{A^2 - x^2}} * \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\bar{x}}{\sigma}\right)^2} \quad (12)$$

227 By comparing the experimental data and model in PDF, two constants A and σ
 228 are obtained by minimising the cumulative error function Δ . It is defined as:

$$\Delta = \text{Min} \left(\sum_{i=0}^{100} \sqrt{(PDF_{exp} - PDF_{model})^2} \right) \quad (13)$$

229 The fluctuating intensities of periodic (I_P) and random (I_R) components can be
 230 represented as $A/\sqrt{2}$ and σ , respectively. Thus, the sum of both contributions
 231 indicates the total energy input, or as the total fluctuation intensity.

232

233 3 Results and discussion

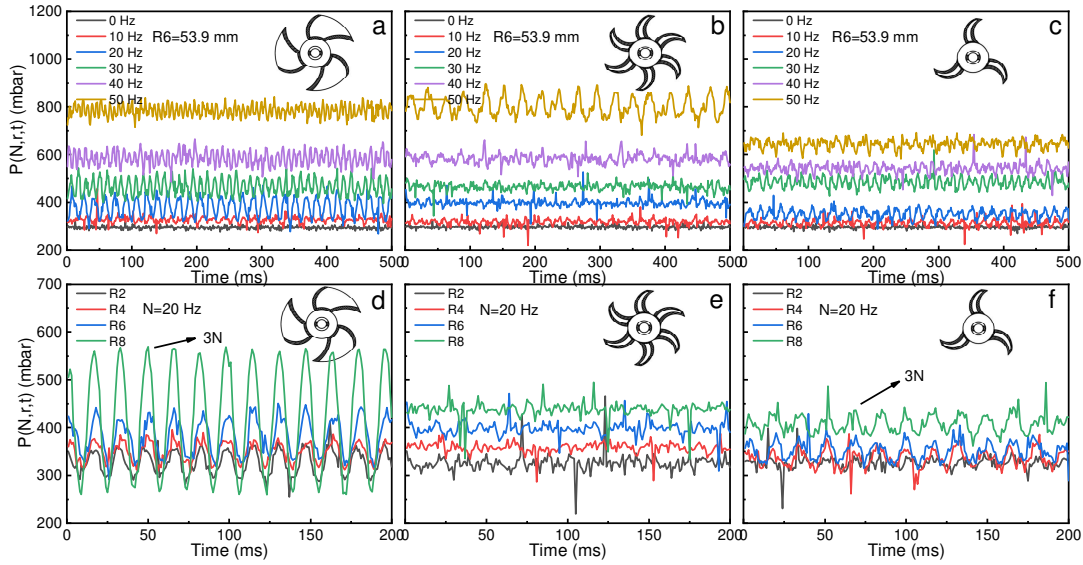
234 As demonstrated previously, the evolution of moment of the first order, the
 235 centre moment of second order, the nominalized centre moments of third and fourth
 236 order tend to converge with respect to the number of sampling points m superior to
 237 1000 [30]. The following analyses include Statistical Analysis (SA), PDF and FFT,
 238 based on the raw data length equal to 2^{15} points. In order to establish the empirical
 239 model to estimate the local pressure, the raw signal is decomposed into continuous
 240 and fluctuating components.

241

242 3.1 Raw data

243 Instantaneous pressures were locally measured at eight radii (R1 to R8) and
 244 different rotation frequencies from 0 to 50 Hz. They are shown in Fig. 3, indicating
 245 the increase of steady pressure versus N and r . Interestingly, Imp 1 and 2 have similar
 246 steady pressure values, both higher than Imp 3. In addition, the magnitudes of
 247 pressure fluctuations for Imp 1 are more remarkable compared to Imp 2 and 3. In Fig.
 248 3d, it can be observed that the instantaneous pressure for Imp 1 varies with a period
 249 around 60 Hz, which is consistent with three times the rotation frequency. This can be
 250 attributed to the number of blades. Whereas in Fig. 3f, the periodic amplitude of Imp 3
 251 at 20 Hz is relatively small, its period is also in accordance with $3N$. For Imp 2 at 20
 252 Hz, the periodic variation cannot be achieved from Fig. 3e, and the pressure
 253 fluctuations are much weaker. Further analysis is associated with the continuous
 254 component of the signal (steady pressure) and the pressure fluctuations defined in Eq.

255 (1).
 256



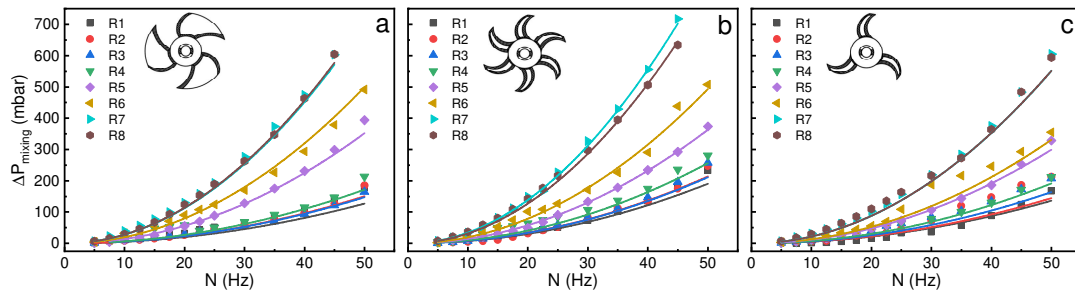
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 258 Fig. 3 Raw data analysis. (a), (b) and (c) are the evolution of instantaneous pressure versus rotation
 259 frequency for three impellers at R6; (d), (e) and (f) are the evolution of instantaneous pressure versus
 260 local radius for three impellers at 20 Hz.

261 **3.2 Continuous components**

262 The continuous pressures compose of P_0 and ΔP_{mixing} . The former is dependent
 263 on the back pressure and feeding flowrate, while the latter varies with rotation
 264 frequency and radius.

265 **3.2.1 Mixing pressure**

266 The mixing pressures as a function of rotation frequency and radius are presented
 267 in Fig. 4. In the global overview, it can be seen that Imp 1 and 2 generate the same
 268 level of additional pressure, and superior to Imp 3.



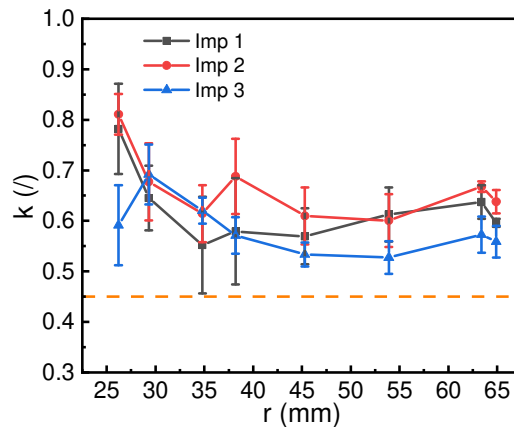
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 270 Fig. 4 Mixing pressures as a function of rotation frequency and radius. (a) Imp 1; (b) Imp 2; (c) Imp 3.

271 **3.2.2 Core velocity coefficient**

272 In rotating systems, the angular velocity in the main fluid can be written as $k \cdot$
 273 $2\pi N$. As the tangential velocity is considered as the dominant component of the
 274 velocity vector, the additional pressure due to mixing can be approximated as
 275 proportional to $N^2 r^2$, i.e., the square of the tangential velocity component. Therefore,

276 it appears that the value of k larger than the actual value [30]. Fig. 5 shows the
 277 calculated k values as a function of the radius for the three different impellers. An
 278 increase of k can be observed at a lower radius, it might be explained by the highest
 279 contribution of radial velocity at the entrance of the cell (close to the shaft). Another
 280 decrease is found at the highest radius, which can be attributed to the reduction of
 281 local velocity close to the external wall [34]. By the regression of mixing pressure at
 282 all the conditions (rotation frequencies and radii), the core velocity coefficient follows
 283 the order: Imp 2>Imp 1>Imp 3 (0.63>0.59>0.54). It can be concluded that more
 284 blades and a larger surface area seem to increase k value. Similar results can be found
 285 in the rotating disk with vans [6, 29].

286 As reported in the literature, k value for the rotating flat disk is inferior to 0.45,
 287 above which occurs with rotating impeller or disk with vans [1]. In comparison to the
 288 full disk, the additional force generated by the rotating impeller includes the push
 289 force at the leading edge and the differential pressure force between the leading and
 290 trailing edge of the blade, apart from the shear force on the plate [29, 30]. Therefore,
 291 the complex geometry of the impeller may be hard to estimate the local shear stress at
 292 the membrane surface.



293

294 Fig. 5 Core velocity coefficient at the various radius. The dashed line indicates the k value at the
 295 boundary between the rotating flat disk ($0.31 < k < 0.45$) and the rotating disk with vans or impeller
 296 ($0.45 \leq k < 0.9$).

297

298 3.3 Fluctuating components

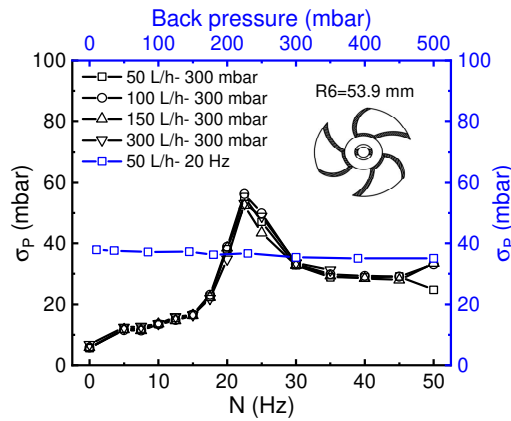
299 Previously, the pressure fluctuations have been analysed with SA, PDF, FFT and
 300 modelled [30]. Similar treatments are carried out to compare the fluctuations in terms
 301 of amplitudes and frequencies with three different impellers.

302 3.3.1 SA

303 3.3.1.1 Standard deviation

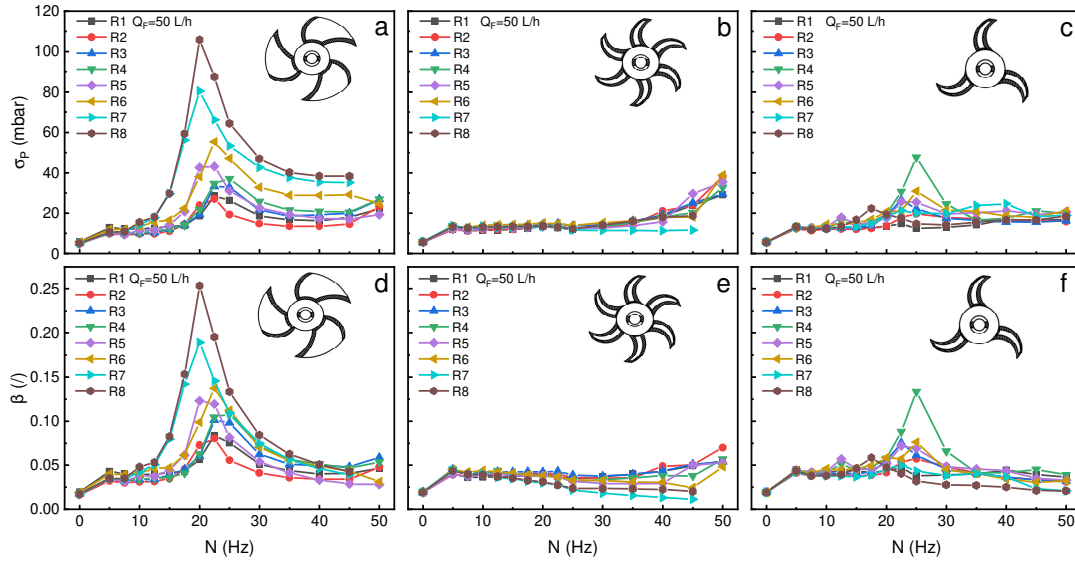
304 The standard deviation σ_P has been used to describe the fluctuation intensity of
 305 the signal. As shown in Fig. 6, pressure fluctuations are independent of back pressure
 306 and flowrate, but influenced by rotation frequency. On the contrary, the local pressure

307 P_0 is influenced by these parameters.



308
 309 *Fig. 6 Standard deviation of instantaneous pressure for Imp 1 at different conditions (flowrates, rotation*
 310 *frequencies and back pressures).*

311 Fig. 7a, b and c present the evolution of the standard deviation at different
 312 conditions. For Imp 1, a large increase of σ_P with N can be observed below 20 Hz, and
 313 followed by a decrease until 50 Hz. The maximum σ_P fluctuates in the range of
 314 rotation frequency between 20 and 25 Hz. It increases with local radius, even reaches
 315 more than 100 mbar at R8. For Imp 2, σ_P exhibits a constant value below 20 mbar,
 316 and then slightly increases with a rotation frequency from 40 to 50 Hz. While the
 317 increase of σ_P occurs at 20 Hz with Imp 3, it is relatively lower than Imp 1. With the
 318 same shape of blades, the highest deviations for Imp 2 and 3 are limited to a value
 319 below 50 mbar, almost negligible when compared with Imp 1. It can be concluded
 320 that more blades contribute positively to a higher mixing pressure but negatively to
 321 the generation of pressure fluctuations. Comparing the standard deviation of
 322 instantaneous pressure relative to steady pressure, the coefficients of variation β are
 323 shown in Fig. 7d, e and f. It can be noticed that the β value of Imp 2 is limited to less
 324 than 7%; Imp 3 shows an increase, reaching 13% at R4. However, these values are
 325 inferior to Imp 1, which achieved 25.3% of local pressure at R8. It indicates that the
 326 pressure fluctuations cannot be neglected with Imp 1. An intensive fluctuating area
 327 with high-pressure fluctuations at the membrane surface is promoted as the range of
 328 rotation frequency from 15 to 30 Hz.



329

330 *Fig. 7 Statistical Analysis. (a), (b) and (c) are the evolution of standard deviation versus rotation*
 331 *frequency for three impellers; (d), (e) and (f) are the coefficient of variation versus rotation frequency for*
 332 *three impellers.*

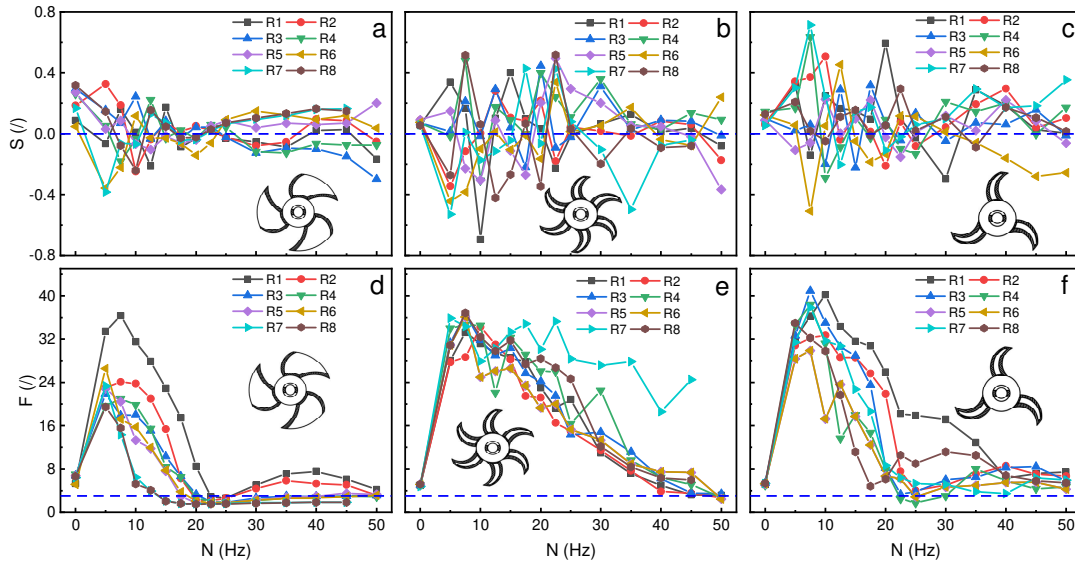
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3.3.1.2 Skewness and Flatness

334

The high order moment distributions from 0 to 50 Hz and R1 to R8 are shown in Fig. 9. Fig. 9a, b and c present the skewness under different conditions, with values fluctuating from -0.8 to 0.8 and show disorder for rotation frequency and local radius. The flatness indicates the degree of peakedness of PDF, as shown in Fig. 9 d, e and f. Compared with F in a normal distribution ($F=3$, dashed blue lines), the value of F superior to 3 informs that a sharp distribution with a narrow fluctuation intensity, while $F<3$ indicates the extension of PDF and results in a large deviation. For Imp 2, F shows a decrease with the rotation frequency, and its value is consistent with a normal distribution when the maximum speed of 50 Hz is reached. That can be explained by the increase in pressure fluctuations. The same results are also achieved from Imp 1 and 3. Comparison with the normal distribution gives an indication of the fluctuations in the data to some extent, but the magnitude of the fluctuations still needs further analysis.

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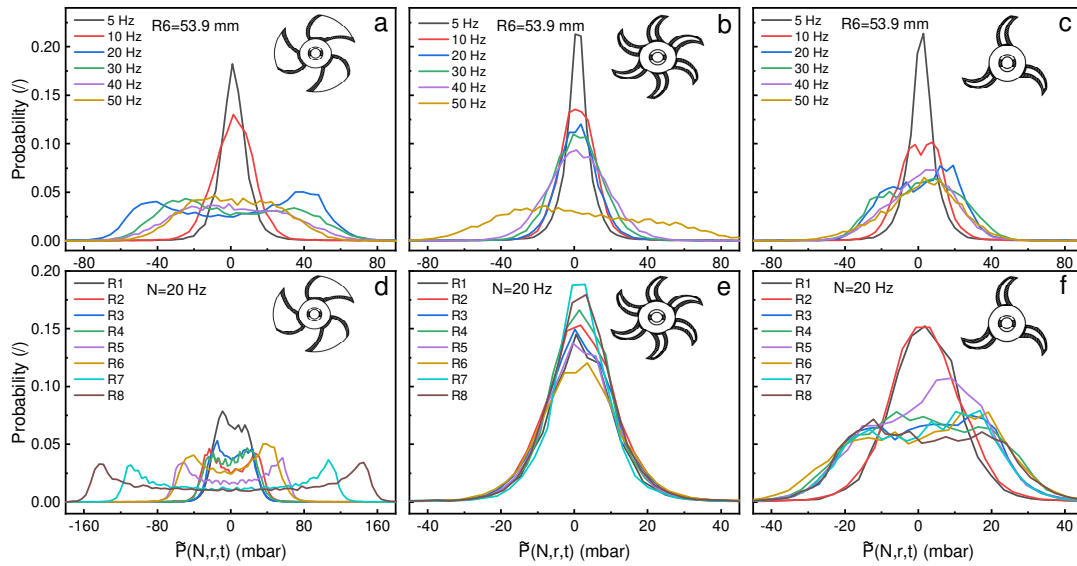


346

347 *Fig. 8 High order items distribution. (a), (b) and (c) are the skewness distribution for three impellers; (d),*
 348 *(e) and (f) are the flatness distribution for three impellers. The dashed line indicates the S and F for*
 349 *normal distribution.*

350 3.3.2 PDF

351 PDF provides a more explicit profile of pressure fluctuations. Fig. 9 presents the
 352 PDF of three impellers at different conditions. At R6, a strong fluctuation occurs at a
 353 rotation frequency around 20 Hz for Imp 1. The same observation can be found for
 354 Imp 3, but with lower fluctuation intensity. While the large extension of PDF for Imp
 355 2 only finds at 50 Hz. At the same rotation frequency (20 Hz), Imp 1 shows two peaks
 356 in the PDF, with an increase of fluctuations from 40 to 160 mbar with radius. The
 357 pressure fluctuations are limited below 40 mbar for Imp 2 and 3, only one peak is
 358 found for Imp 2 at all the radius, while two peaks can be observed for Imp 3 at a
 359 rotation frequency ≥ 20 Hz. These results are consistent with the fluctuation intensity
 360 represented by standard deviation. Previously, the peak-to-peak value was extracted to
 361 inform the fluctuating intensity [30], but this method is inappropriate for Imp 2 and 3.



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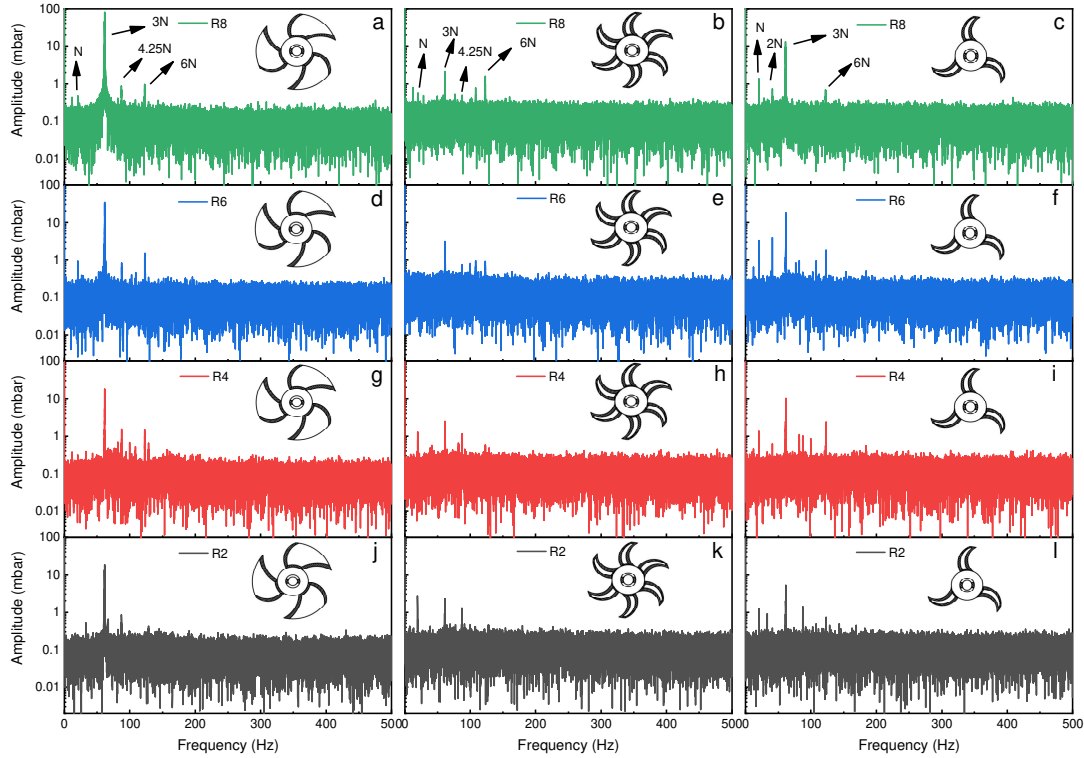
363 *Fig. 9 PDF at different conditions. (a), (b) and (c) are the PDF versus rotation frequency for three*
 364 *impellers; (d), (e) and (f) are the PDF versus radius for three impellers.*

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3.3.3 FFT

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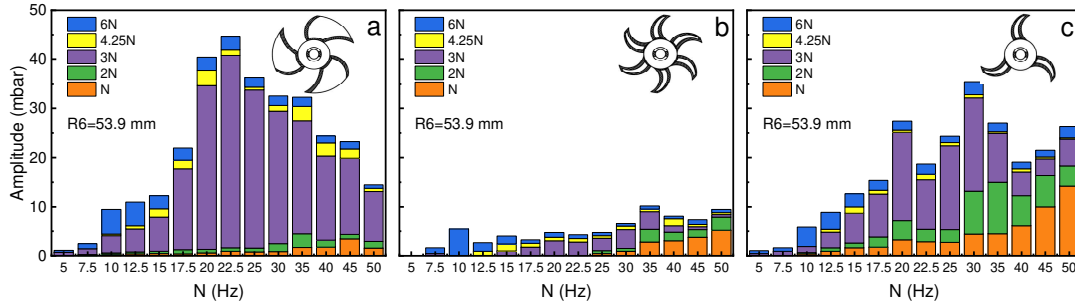
367 With FFT, the time variations of pressure are presented on frequency domain. A
 368 rotation frequency of 20 Hz is selected as the representative displayed in Fig. 10. For
 369 three blades impellers (Imp 1 and 3), the significant peak amplitudes are found at N ,
 370 $2N$, $3N$, $4.25N$ and $6N$, where N is the rotation frequency. The value of $3N$
 371 demonstrates that the main frequency can be associated with the rotation frequency
 372 and the number of blades. N and $2N$ indicate the effects of one and two blades, while
 373 $6N$ is linked to twice the number of blades. The same peaks can be observed with six
 374 blades impeller, but $12N$ amplitude is almost negligible in the spectrum. In addition,
 375 another peak amplitude can be found at $4.25N$ for the three different impellers, with
 376 intensities around 1 mbar. It remains unclear for the pressure fluctuations during
 377 mixing. Compared to the amplitude at $3N$, there is an increase with the radius for Imp
 378 1, even reaching up to 100 mbar at R8. Imp 3 also shows the same behaviour but with
 lower amplitude. Whereas the amplitude for Imp 2 is almost constant at all the radius.



379

380 *Fig. 10 Frequency domain analysis with FFT at 20 Hz. (a), (d), (g) and (j) are Imp 1; (b), (e), (h) and (k)*
 381 *are Imp 2; (c), (f), (i) and (l) are Imp 3.*

382 Fig. 11 shows the cumulative amplitude of pressure fluctuations for N , $2N$, $3N$,
 383 $4.25N$ and $6N$ at R6 for the three impellers. This type of representation appears to be
 384 very useful to enhance the dominant frequencies, i.e., the frequencies associated with
 385 the higher amplitudes in FFT analysis plotted in Fig. 10. It can be seen in Fig. 11a that
 386 the cumulative amplitude increases significantly with the rotation frequency until 22.5
 387 Hz, and then decreases for Imp 1. This behaviour is similar to one of the standard
 388 deviations plotted in Fig. 7a. The dominant frequencies are $6N$ below 10 Hz and $3N$
 389 above 10 Hz. For Imp 2 (Fig. 11b), the cumulative amplitude is very weak, below 10
 390 mbar. We find that the dominant frequencies are $6N$ from 5 to 15 Hz, change to $3N$
 391 from 17.5 to 35 Hz, finally to be N from 40 to 50 Hz. It indicates that there is an
 392 increase of the contribution of the frequency N (one-blade effect) at higher rotation
 393 frequency. Furthermore, it should be noted that the cumulative amplitude does not
 394 increase at 50 Hz as it appears in σ_P , which means that this increase of pressure
 395 fluctuations is generated by a random component instead of a periodic signal. For Imp
 396 3 (Fig. 11c), with the increase of rotation frequency, the dominant frequencies evolve
 397 from $6N$ (5-10 Hz) to $3N$ (12.5-30 Hz) and $2N$ (35 Hz), finally by N (40-50 Hz). The
 398 cumulative amplitudes also differ somewhat from σ_P , especially for the value of N
 399 associated with the maximum fluctuations (cumulative amplitude at 30 Hz, σ_P at 25
 400 Hz). It can be concluded that the random signal is not so important in the pressure
 401 fluctuations of Imp 1, while it has a greater effect in the case of Imp 2 and 3.



402

403 Fig. 11 Cumulative amplitudes at R6. (a) Imp 1; (b) Imp 2; (c) Imp 3.

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3.3.4 Modelling

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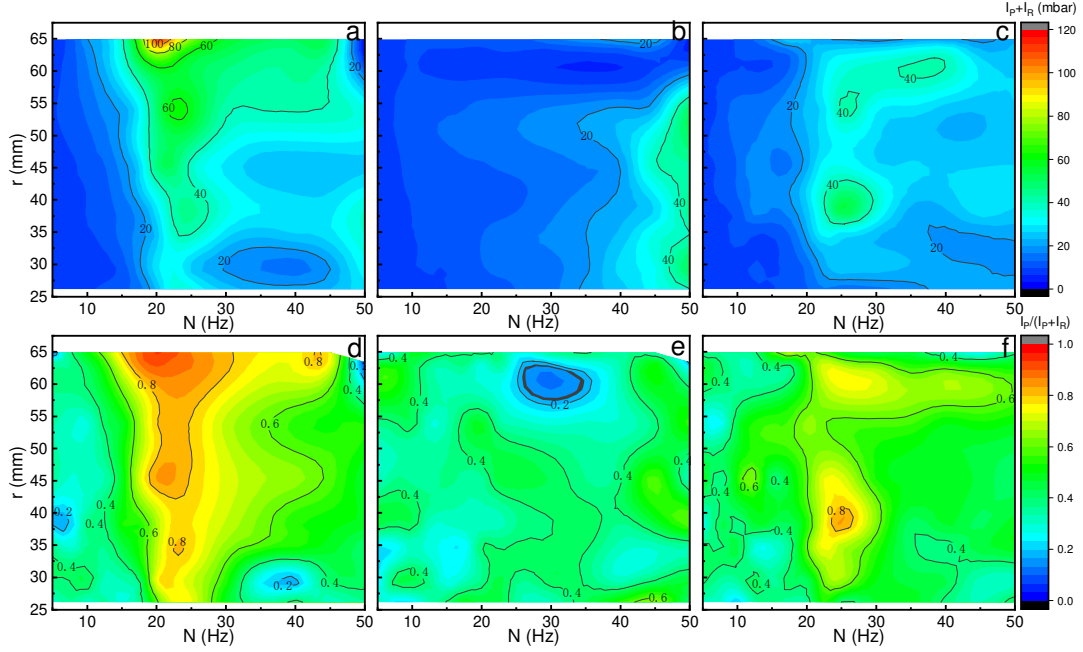
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As explained in section 2.2.3, a model is proposed to reconstruct the PDF of pressure fluctuations from the convolution of a periodic and a random signal. The model parameters are determined from the minimisation of the cumulative error function: $\Delta \leq 0.3$. The plots of Fig. 12a, b and c show the phase diagram of total intensities versus rotation frequency and radius at the membrane surface. With the same legend, the total energy input for Imp 1 can reach up to 100 mbar at 20 Hz, which is much higher than the maximum value from Imp 2 and 3. The more intensive fluctuations occur at a high rotation frequency ($N > 40$ Hz) for Imp 2, and from 20 to 40 Hz for Imp 3. These total energy inputs are consistent with σ_P , indicating a high degree of model validity. For random signal, the I_R is limited below 30 mbar for the three impellers. The relative periodic contribution $I_P/(I_P+I_R)$ are presented in Fig. 12d, e and f. It is found that the periodic fluctuations for Imp 1 dominate for most conditions (15-40 Hz), while they only appear at 20 to 30 Hz for Imp 3. Due to the weak amplitude observed in Fig. 11b for Imp 2, the periodic contribution remains below 50%. Thus, the use of Imp 1 is more appropriate than Imp 2 and 3 to intensify the pressure fluctuations at the membrane surface.



421

422 *Fig. 12 Total energy input $I_P + I_R$ (a, b, c) and periodic contribution $I_P / (I_P + I_R)$ (d, e, f) as a function of*
 423 *rotation frequency and radius for Imp 1, Imp 2 and Imp 3, respectively.*

424 The regression of intensity versus rotation frequency (N , Hz) and radius (r , m)
 425 can be a useful way to estimate the pressure fluctuations. It is plotted in Fig. 13. For
 426 periodic fluctuations (I_P , mbar), the fluid flow resonates under the periodic rotation of
 427 the impeller. On the membrane surface, the periodic pressure fluctuations evolve
 428 similarly to the response amplitude $U(\omega)$ of a second-order linear system to a periodic
 429 input force $F = F_0 \sin(\omega t)$ [35], which follows the equation:

$$U(\omega) = \frac{GF_0}{\sqrt{(1-s^2)^2 + (2\epsilon s)^2}} \quad (14)$$

430 where $s = \omega / \omega_0$ is the pulsation ratio. Here, we recognise the three parameters of
 431 the second order system: G is the gain, ω_0 is the intrinsic pulsation and ϵ the
 432 damping coefficient. However, the input signal $F' = F_0 \omega r \sin(\omega t)$ varies as a
 433 function of ω and r in our system, Eq.(14) was then modified to obtain a new
 434 function $U'(\omega)$. It can be written as:

$$U'(\omega) = \frac{GF_0 r^2 s^2}{\sqrt{(1-s^2)^2 + (2\epsilon s)^2}} \quad (15)$$

435 With slight modifications, a new model based on rotation frequency and local
 436 radius is proposed as in Eq.(16); the corresponding resonance frequency (N_r) of the
 437 system is calculated using Eq. (17).

$$I_p(N, r) = \frac{K}{\sqrt{(1-s^2)^2 + (2\epsilon s)^2}} \times \rho N^2 r^2 \quad (16)$$

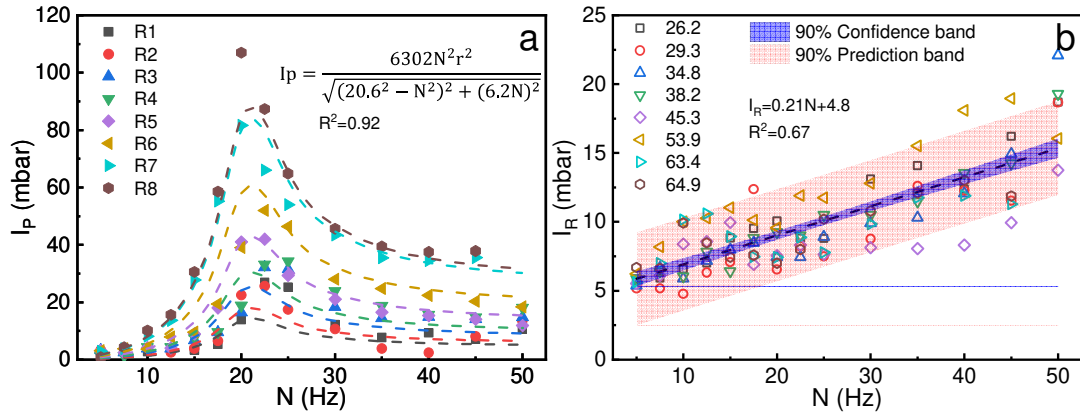
$$= \frac{KN_0^2}{\sqrt{(N_0^2 - N^2)^2 + (2\epsilon N_0 N)^2}} \times \rho N^2 r^2$$

$$N_r = \frac{N_0}{\sqrt{1-2\epsilon^2}} \quad (17)$$

438 where $K = \frac{GF_0}{\rho N_0^2}$ and ϵ are constants, N_0 is the intrinsic frequency of the fluid in the
 439 cell. After regression, N_0 is equal to 20.6 Hz, which is slightly lower than the
 440 resonance frequency (21.1 Hz). Meanwhile, the values of K and ϵ are solved as 1.5
 441 and 0.15, respectively.

442 For the random signal, I_R is found to be independent of the radius and to slightly
 443 increase with the rotation frequency. Then a linear regression is used to approximate
 444 the variations of random intensity as a function of N , which give a 90% prediction
 445 band with $I_R \pm 3.4$ mbar.

$$I_R = 0.21N + 4.8 \quad (16)$$



446
 447 Fig. 13 Fluctuating intensities for Imp 1 as a function of rotation frequency and radius. (a) periodic
 448 intensity; (b) random intensity.

449

450 3.4 Signal reconstruction

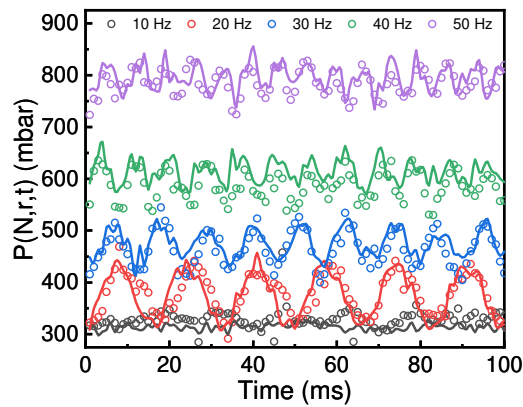
451 Table. 1 Signal reconstruction for Imp 1 at R6, with the value of the two parameters to estimate the
 452 instantaneous pressure. A and σ are calculated from Eq. (14) and (15).

N (Hz)	P_0	ΔP_{mixing}	$\widetilde{P}_P(t)$		$\widetilde{P}_R(t)$
	Constant (mbar)	k (/)	A (mbar)	f (Hz)	σ (mbar)
10	294.5	0.59	5.5	3N	6.9
20			58	3N	9

30	32.3	3N	11.1
40	24.4	3N	13.2
50	21.8	3N	15.3

453

454 At different rotation frequencies, the local pressure of the steady flow without
455 rotation (P_0) is almost constant with the same back pressure (300 mbar) and flowrate
456 (50 L/h). ΔP_{mixing} is calculated with the mean k value equal to 0.59 obtained in section
457 3.2.2. The model parameters A and σ are determined from experimental data as
458 explained in section 3.3.4. The dominant frequency is chosen equal to $3N$. φ does not
459 affect the signal fluctuations and can be ignored. The time variations of pressure
460 calculated from the model are compared with the experimental data and shown in Fig.
461 14. It can be noticed that the reconstructed signal provides a good description of the
462 instantaneous pressure. Thus, this indicates that we can make use of this simplified
463 model or estimate the time variations of the local pressure.



464

465 *Fig. 14 Signal reconstruction of instantaneous pressure with empirical correlations (continuous and*
466 *fluctuating components at R6) for Imp 1. Dots and lines correspond to the experimental and*
467 *reconstructed signal, respectively.*

468

469 4 Conclusions

470 DF has shown promise in reducing filter cake layer build-up, fouling
471 accumulation and concentration polarisation. The enhanced filtration performance is
472 attributed to the local shear as well as the pressure-driven force at the membrane
473 surface in the RVF modules. The local shear rate has been widely discussed in the
474 literature. In contrast, the present study exhibits new insight on the local pressure and
475 in particular on the pressure fluctuations.

476 By the regression of ΔP_{mixing} curves, it is found that the core velocity coefficient,
477 k values are higher at filtration cell entrance close to the shaft (lower radius, R1) due
478 to the small cross-section and the low contribution of angular velocity. The mean
479 values of k follow the order: Imp 2 > Imp 1 > Imp 3. It is concluded that the mixing
480 pressure can be affected by the number of blades, then the impeller surface area.

481 The analysis of pressure fluctuations (SA, PDF, FFT) confirm that the magnitude

482 following the same trends: Imp 1 > Imp 3 > Imp 2. At 20 Hz, σ_P (SA) of Imp 1 can
483 reach up to 25% of TMP, while these values are negligible (<10%) for Imp 2 and 3.
484 Considering FFT, the dominant frequency identified with Imp 1 is equal to 3 times the
485 rotation frequency ($3N$). On the contrary, different frequencies ($6N$, $3N$ and N)
486 exhibiting low amplitude are observed for Imp 2 and 3.

487 Based on the PDF modelling, periodic and random contributions are extracted by
488 deconvolution of the time signal. Then, the empirical correlations are established to
489 estimate their intensities as a function of rotation frequency and radial position. The
490 intensity of the random pressure fluctuations is limited to 30 mbar for all impellers.
491 The periodic contribution is dominant for Imp 1, and a “resonance frequency” of 21.1
492 Hz is clearly identified. Considering fluctuating pressure analysis and modelling, Imp
493 1 appears as the best candidate for microfiltration applications. However, other
494 criteria such as local shear rate and filtration performances (instantaneous and local
495 permeate flux or hydraulic resistance) could also be used to select optimal impeller
496 and operating conditions.

497 This work provides a better fundamental knowledge for the characterization and
498 the modelling of instantaneous pressure at the membrane surface in a dynamic
499 filtration module; it highlights the potential of pressure fluctuations as an additional
500 driving force to intensify microfiltration and also to better optimise the impeller
501 configuration. Nevertheless, for better performance in DF (enhanced permeate flux
502 and reduced fouling), the optimal impeller configuration requires further simulation
503 and verification based on shear fluctuation include pressure as well as shear stress. A
504 theoretical explanation for the time variations of pressure (resonance phenomenon)
505 also deserves further development.

506
507

Nomenclature

A	Amplitude, mbar
A_f	Amplitude at frequency f , mbar
F	Flatness, /
f	Frequency, Hz
G	Gain of the system, /
I_P	Periodic intensity, mbar
I_R	Random intensity, mbar
K	Numerical coefficient, /
k	Core velocity coefficient, /
m	Sampling number, /
N	Rotation frequency of the impeller, Hz
N_0	Intrinsic frequency, Hz
N_r	Resonance frequency, Hz
$P(f)$	Pressure at frequency f , mbar
P_0	Pressure without the rotation of impeller, mbar
$P(r;t)$	Instantaneous pressure, mbar
$\widetilde{P}_P(t)$	Periodic signal, mbar
$\widetilde{P}_R(t)$	Random signal, mbar
$\bar{P}(N, r)$	Mean time pressure, mbar
$\tilde{P}(N, r, t)$	Fluctuating pressure, mbar
Q_F	Feeding flowrate, m ³ /s
r	Radius at membrane surface, m
R_0	Inner radius of the membrane, m
R_m	Outer radius of the membrane, m
S	Skewness, /
T_{inlet}	Inlet temperature, °C
T_{outlet}	Outlet temperature, °C
\bar{u}	Mean velocity of fluid, m/s
β	Coefficient of variation, /
ϵ	Dumping factor, /
ρ	Fluid density, kg/m ³
σ	Standard deviation of random signal, mbar
σ_P	Standard deviation of fluctuating pressure, mbar
φ	Phase, °
Δ	Minimum cumulative error, /
ΔP_{mixing}	Additional pressure generated by the rotating impeller, mbar

Acknowledgments

511 Financial support from the China Scholarship Council is gratefully acknowledged
 512 (grant No. 201801810069). Thanks to Pascal DEBREYNE and Jacky SIX (INRAE,

513 Lille) for the realisation of the experimental device about the instantaneous and local
514 pressure measurement.

515

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