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## Flow investigation in an innovating dynamic filtration module using tracing methods

Xiaomin Xie, Christophe Andre, Nicolas Dietrich, Philippe Schmitz, Luc Fillaudeau

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1 **FLOW INVESTIGATION IN AN INNOVATING DYNAMIC**  
2 **FILTRATION MODULE USING TRACING METHODS**  
3

4 Xiaomin XIE<sup>a,e</sup>, Christophe ANDRE<sup>b,c,d\*</sup>, Nicolas DIETRICH<sup>a,e</sup>, Philippe SCHMITZ<sup>a,e</sup>, Luc  
5 FILLAUDEAU<sup>a,e</sup>  
6

7 <sup>a</sup> LISBP, Université de Toulouse, CNRS UMR5504, INRA UMR792, INSA, Toulouse, France

8 <sup>b</sup> UC Lille, HEI, Laboratoire de Génie des procédés, 59046 Lille, France

9 <sup>c</sup> INRA, UR638, PIHM, Villeneuve d'Ascq, France

10 <sup>d</sup> UMET, CNRS-UMR8207, Université de Lille 1, Villeneuve d'Ascq, France

11 <sup>e</sup> FERMAT, INP Toulouse, CNRS, INSA Toulouse, UPS, France.

12 \*corresponding author:

13 UC Lille, HEI, Laboratoire de Génie des procédés, 59046 Lille, France

14 INRA, UR 638, PIHM, BP 20039,369 rue Jules Guesde, 59651 Villeneuve d'Ascq, France

15 E-mail: [christophe.andre@yncrea.fr](mailto:christophe.andre@yncrea.fr)  
16  
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## ABSTRACT

Residence Time Distribution (RTD) experiments were carried out under laminar and turbulent regimes in a complex dynamic filtration module, named Rotating and Vibrating Filtration (RVF). This filtration module, dedicated to bioprocess intensification and downstream processing, consists of two filtration cells in series in which a three-blade impeller rotates between two flat membranes.

Our objectives are to improve filtration and overall industrial bioprocess performances by (i) deeply understanding the flow behaviour within RVF modules and (ii) characterizing and modelling the RTD through a systemic analysis and (iii) identifying critical operating conditions with microbial cells.

Analytical study of distribution functions was conducted and statistical moments were calculated and discussed. This study provides useful recommendations, guidelines by identifying efficient volume (functioning area), dead zone volume (dysfunctioning area). The influence of operating parameters (mixing rate  $N$  and flow rate  $Q_f$ ) on the mean residence time,  $t_s$  were highlighted. The systemic analysis led to compare three models with analytical solutions. Finally, a simple model allowing the description of the evolution of the RTD of the studied filtration module was proposed.

### Keywords:

Dynamic filtration; thermal balance, Residence time distribution; modelling; systemic approach.

## 63 Nomenclature:

Latin Letters		
$C$	Concentration (salt)	[g/L]
$C_p$	Specific heat capacity	[J/(kg·°C)]
$d_m$	Impeller diameter	[m]
$E_a$	Activation energy	[kJ/mol]
$E(t)$	Residence time distribution function	[1/s]
$F(t)$	Cumulative distribution function	[/]
$J$	Number of reactors	[/]
$N$	Mixing rate	[Hz]
$N_p$	Power consumption number	[/]
$Pe_L$	Peclet number	[/]
$Q_f$	Feeding flowrate	[L/h]
$R$	Universal gas constant, 8.314 J/(mol °C)	[J/(mol °C)]
$Re_{mixing}$	Reynolds number of a mixing system	[/]
$Re_Q$	Reynolds number of a system equivalent to a tube	[/]
$t_s$	Mean residence time	[s]
$T$	Temperature	[°C]

TMP	Transmembrane pressure	[bar]
$V_1, V_2$	Used volume and dead-zone volume, $V_1+V_2=V_{RVF}$	[L]
$V_{RVF}$	Total volume of RVF module, 1.47 L	[L]
$x(t), y(t)$	Experimental inlet and outlet reduced and normalized signals	[1/s]
$X(t), Y(t)$	Cumulative function of $x(t)$ and $y(t)$	[/]
$X(s), Y(s), G(s)$	Laplace transform function of $x(t)$ , $y(t)$ and $E(t)$	[/]
<b>Greek symbols</b>		
$\mu$	Viscosity	[Pa·s]
$\rho$	Density	[kg/m <sup>3</sup> ]
$\beta^2$	Reduced variance (centred moment of 2 <sup>nd</sup> order)	[/]
$\tau$	Holding time	[s]
$\Gamma$	Centred moment of the given order	
$\alpha$	Slope (regression coefficient)	
$\sigma$	Electric conductivity	[S/m]
<b>Abbreviations</b>		
CF	Cross-flow	
CFD	Computational Fluid Dynamic	
CSTR	Continuous stirred-tank reactor	

DF	Dynamic Filtration	
DE	Dead-end (filtration)	
OVL	Overlapping coefficient,	
PF	Plug flow reactor	
RVF	Rotating and Vibrating Filtration module	

64

65

## 66 **1 Introduction**

67 The principle of Dynamic Filtration (DF) is to generate complex hydrodynamic  
68 perturbations (magnitude of velocity and shear stress, time dependent) by mechanical movement  
69 (rotation, vibration, oscillation) of membrane or external mechanical forces close to the  
70 membrane, to better control membrane fouling. The external force applied to the system can be  
71 longitudinal, transverse, torsional, or with a mix of these motions. In the recent decades, many  
72 efforts have been done to study hydrodynamics and to develop novel DF modules at lab scale or  
73 pilot scale. In each device, the controls of local and global performances (permeability, fouling,  
74 limitations) are closely related to our knowledge of local and global hydrodynamic. The existing  
75 DF modules can be classified in terms of mechanical movement as cylindrical rotating filter  
76 (such as *Biodruck-filter*[1], *Biopurification System*[2], *RDF filter*[3]), rotating flat membrane  
77 filter (such as *CRD filter*[4], *MSD filter*[5], *RDM module*[6-8], *DYNO filter*[9], *RVF module*[10-  
78 12]), and vibrating filter (such as *VSEP filter*[13], *VMF filter*[14] and *hollow fibber filter*[15,16]).  
79 Compare with dead-end (DE) and cross-flow (CF) filtration, DF has been proved (1) by reducing  
80 environmental impact (low loop volume), (2) by reducing energy consumption, uncoupling  
81 between the conventional driving force (from feeding flowrate) and wall shear stress, working  
82 under low transmembrane pressure (TMP). Enhancements in DF are mainly attributed to  
83 complex hydrodynamics near the membrane surface due to the various motions (rotation,  
84 vibration, oscillation) of the external driving forces.

85 Recent development in the processing and technology of dynamic filtration have motivated  
86 numerous of researches in the evaluation of membranes filters quantitatively and qualitatively, in  
87 the domain of drinking/waste water treatment, food engineering, pharmacy and biological  
88 processing and so on. Basically, the accumulation of material rejected and remained on or near

89 the membrane surface always leads to a decline of permeate flux over time. Many efforts have  
90 been done to recover or maintain a high efficiency and quality of permeate by using plenty of  
91 low viscosity feeding fluid. However, less attention has been paid to the fluid transport and flow  
92 behaviour in the system, less is known about the homogeneity which might be affected by the  
93 flow perturbation and mixing, both in laminar and turbulent regime. To provide systemic  
94 information, Residence Time Distribution (RTD) is a crucial approach to diagnose the flow  
95 performance associated with degree of mixing and shearing which play an important role in the  
96 final product quality[17].

97 Therefore, in this paper, investigation of RTD was performed in a pilot plant with a  
98 dynamic filtration module integrated in an instrumented open loop. As a response variable,  
99 thermal balance and RTD are crucial parameters that has been commonly used to investigate the  
100 performance of fluid mixing and to diagnose the defect of a system design. Our objective was:  
101 (1) to study the impact of processing conditions (flowrate, rotation speed) on RTD in an  
102 industrial pilot-plant (RVF); (2) to compare through distribution functions the RVF  
103 hydrodynamic behaviours in laminar and turbulent regimes; (3) to evaluate the homogeneity  
104 within the device and (4) to validate a reactor model to predict RTD. In the first step, tracer  
105 experiments were performed and scrutinized with different process conditions (flowrate, mixing  
106 rate) with Newtonian fluids, embracing laminar and turbulent regimes. Experimental data were  
107 interpreted thru the sets of moment and centred moments deduced from distribution functions.  
108 Their statistical deviation and evolution were discussed as a function of the process parameters.  
109 In a second step, a systemic analysis led to the identification of a suitable model thanks to the  
110 comparison of three different models.

## 111 2 Materials and methods

### 112 2.1 Filtration module

113

114 The DF module, shown in fig. 1, is called Rotating and Vibrating Filtration (RVF  
115 technology – patent no. FR-97-14825) [18]. It is designed for biological or food liquids. RVF  
116 module has been studied in the previous studies [10-12,19], it consists of two filtration cells in  
117 series (4 membranes, filtration area = 0.048 m<sup>2</sup>, cell volume = 0.2 L and RVF volume 1.48 L),  
118 and in each cell, a three-blade impeller (flat blade, d<sub>m</sub> = 138 mm, thickness = 8 mm) is driven by  
119 a central shaft continuously rotating (up to 50 Hz) in a 14 mm gap between two porous flat  
120 support (membrane support) which drains the permeate. It gives a 3 mm gap between the  
121 impeller and the membrane surface. This simple mechanical device runs continuously and  
122 generates a high shear rate as well as a hydrodynamic perturbation in the small gap, TMP (up to  
123 300 kPa) and rotation frequency can be adjusted to optimize the operating conditions.

124

(figure 1)

125 Friction and power consumption curves of RVF module were established previously [10],  
126 aimed to identify the flow regime of given operating conditions. The critical Reynolds numbers  
127 can be obtained to define flow regime as follows: laminar regime:  $Re_{mixing} < 1 \times 10^3$ ; transition  
128 regime:  $1 \times 10^3 < Re_{mixing} < 3 \times 10^4$ ; and turbulent regime:  $Re_{mixing} > 3 \times 10^4$ .

### 129 2.2 Experimental setup for RTD

130 Figure 2 shows the experimental set-up which was implemented with: (1) an open loop  
131 configuration including a pump (TUTHILL CO., series A54739, Drive: GROSCHOPP CO.,  
132 series PM8014, 3800RPM, DC motor control unit: DART 250G series, Q<sub>f</sub> = 0 to 400 L/h), a  
133 flowmeter (Flowmeter Altometer IFM 1080/6 DN 15mm, precision 5%), a manometer (0-6bar)

134 and a counter-pressure valves, (2) an injection unit for tracer include a septum for syringe  
135 injection followed by a static mixer to achieve homogenous concentration and (3) temperature  
136 (Pt1000, -20°C/+150°C, precision:  $\pm 0.15^\circ\text{C}$ ) and conductivity measurements (Conducell 4USF-  
137 PG325, range: 1-500000  $\mu\text{S}/\text{cm}$ , precision:  $\pm 1\%$ /decade and KEMOTRON type 9147 Integral  
138 flow, range: 5-2000000  $\mu\text{S}/\text{cm}$ , precision:  $\pm 3\%$ /decade) were located before connecting ducts  
139 (Diameter = 12 mm, Length= 125 mm) at inlet and outlet of RVF module. The total  
140 experimental volume between the conductivity meters is equal to VRVF=1.61 L.

141 **(figure 2)**

142 In laminar regime, the fluid was stored at room temperature in a 50 L feeding tank and  
143 collected into a recycling tank. In turbulent regime, the fluid was not recycled (open loop).

### 144 *2.3 Experimental fluids and tracers*

145 The tracer must have several properties as: (1) non-reactive (2) easily detectable (3)  
146 properties similar to the fluid in the system (4) completely soluble (5) should not adsorb [20].  
147 The concentration of the tracer is adjusted considering temperature and fluid according to a  
148 known function [21]. The selected tracer should not modify the physical properties of the fluid  
149 and the hydrodynamic condition in the system. In present work, saline tracer solutions ( $[\text{NaCl}] =$   
150 100 g/L) were injected with a 5 mL syringe within a short time ( $< 5\text{s}$ ) (close to an ideal pulse  
151 injection). The inlet and outlet response signals are obtained by measuring electric conductivity  
152 and by calculating the equivalent tracer concentration.

153 The RTD experiments were restricted to two Newtonian fluids (BREOX solution and water)  
154 for laminar and turbulent regime respectively. A water soluble and viscous transparent  
155 Newtonian fluid (BREOX® Polyalkylene Glycol 75 W 55000, BASF) was used to achieve

156 laminar regime, and water was used for the turbulent regime. For BREOX solution, thermo-  
157 physical properties including viscosity  $\mu$  [Pa·s], density  $\rho$  [kg/m<sup>3</sup>], heat capacity  $C_p$  [J/(kg·°C)]  
158 were respectively measured with a rheometer (HAAKE Mars III, SN: 4201100100779, Thermo  
159 Scientific, Germany, torque range: 10<sup>-8</sup> to 0.2 N·m, mixing rate range: 10<sup>-7</sup> to 4500 RPM), a  
160 density meter (DE40, SN: MPK38384, Mettler Toledo, France, range: 10<sup>-4</sup> to 3 g/cm<sup>3</sup>  $\pm$  10<sup>-4</sup>  
161 g/cm<sup>3</sup>, 4 to 90°C  $\pm$  0.05°C), and a differential scanning calorimeter (Micro DSC-III, SN:  
162 60/50287.06.102, Setaram, France, temperature range: -20 to +120°C, thermal kinetics: 10<sup>-3</sup> to  
163 +1.2°C and fluxmeter range: 0.2  $\mu$ W to 20 mW, resolution : 40nW). These three properties  $\mu$ ,  $\rho$   
164 and  $C_p$  are described as functions of temperature  $T$  [°C] and mass concentration  $C$  [%] (15 to  
165 45°C) as follows:

$$\begin{cases} Cp = aT + b \\ a = -14.8C^2 + 16.3C - 1.46 (R^2 = 0.974) \\ b = -2.17 \times 10^3 C + 4.30 \times 10^3 (R^2 = 0.972) \end{cases} \quad (1)$$

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

$$\begin{cases} \ln\mu = -\frac{Ea}{R} \left( \frac{1}{T + 273} - \frac{1}{T_r + 273} \right) + \ln\mu_r \\ Ea = -1.80 \times 10^4 C - 1.90 \times 10^4 (R^2 = 0.964) \\ \ln(\mu_{20}) = -7.88C^2 + 19.7C - 6.78 (R^2 = 0.999) \end{cases} \quad (3)$$

166 where coefficients a, b, c, d are as the functions of  $C$  in Eq. (1) and (2); Temperature  
167 dependence of  $\mu$  is fitted with the Arrhenius-type equation, with  $E_a$  is the activation energy in  
168 kJ/mol,  $R$  is the universal gas constant,  $\mu_r$  is the viscosity in Pa·s at reference temperature,  
169  $T_r = 20^\circ C$ . Then, properties of BREOX solutions are estimated by Eq. (1, 2 and 3).  
170 Consequently, a 35% (mass concentration) diluted BREOX solution was chosen as a test fluid

171 (with  $\mu = 0.35 \text{ Pa}\cdot\text{s}$ ,  $C_p = 3650 \text{ J}/(\text{kg}\cdot^\circ\text{C})$  and  $\rho = 1040 \text{ kg}/\text{m}^3$  at  $T = 20^\circ\text{C}$ ). Temperature of the  
172 feeding tank was controlled at about  $20^\circ\text{C}$  by adjusting the thermostat (room temperature was  
173 controlled at  $20^\circ\text{C}$ ).

174 Water was used in RTD to achieve turbulent regime. Its thermal – physical properties and  
175 their thermal dependency were taken from literature [21]. At  $20^\circ\text{C}$ , the values are: density  
176  $\rho = 998.2 \text{ kg}/\text{m}^3$ , specific heat capacity  $C_p = 4181.8 \text{ J}/(\text{kg}\cdot^\circ\text{C})$  at constant pressure, viscosity  
177  $\mu=1.0 \text{ mPa}\cdot\text{s}$ . (under 100 kPa).

## 178 2.4 Methodology

179

### 180 2.4.1 Theory of Residence Time Distribution (RTD)

181 The residence time of an element in a fluid is defined as the time elapsed from its entry into  
182 the system until it reaches the exit. The distribution of these times is called the RTD function of  
183 the fluid  $E(t)$ , or  $E$ -curve, and represents the fraction of fluid leaving the system at each time  
184 [22]. Practically, experimental injection cannot be a perfect and direct signal. In the experiment  
185 point of view, normalized signals  $x(t)$  and  $y(t)$  were defined for inlet and outlet, presents as  
186 Eq.(4). The product of the convolution can be replaced in the Laplace domain by a simple  
187 product, where  $X(s)$ ,  $Y(s)$  and  $G(s)$  are the Laplace transform of  $x(t)$ ,  $y(t)$  and  $E(t)$ , as Eq.(5)  
188 presents:

$$y(t) = \int_0^t E(u)x(t - u)du \quad (4)$$

189 and

$$Y(s) = G(s) \cdot X(s) \quad (5)$$

190 Practically,  $x(t)$  and  $y(t)$  are calculated from experimental signal  $C_{in}(t)$  and  $C_{out}(t)$   
 191 respectively, expressed as Eq. 5, and its cumulative function can be obtained as Eq. 6.

$$E(t) = \frac{C_{out}(t)}{\int_0^{\infty} C_{out}(t)dt} \text{ and } F(t) = \int_0^{\infty} E(t)dt \quad (6) \text{ and } (7)$$

192 RTD function can be expressed by moments and centred moments of orders  $\Gamma$  [23]. The  
 193 mean residence time,  $t_s$ , is characterized by a moment of first order,  $\Gamma^1$ . The holding time, a  
 194 theoretical value  $\tau$ , is calculated by the volume of the tested system and the feeding flowrate, as  
 195 Eq.(9) shows. For most of the simple system,  $t_s$  and  $\tau$  are equal indicating a perfect  
 196 macromixing. However, in some complex system, it is not the case. Knowing  $k$  defined by  
 197 Eq.(10), flow behaviour can be diagnosed if the system has a shortcut or a dead zone (volume  
 198  $V_2$ ), effective volume  $V_1$  is defined by  $t_s$ .

$$\Gamma^1 = t_s = \int_0^{\infty} tE(t)dt \text{ and } \tau = \frac{V}{Q_f} \quad (8) \text{ and } (9)$$

199 and

$$k = \frac{t_s}{\tau} = \frac{V_1}{V_{RVF}} \quad (V_1 = t_s \times Q_f, V_{RVF} = V_1 + V_2) \quad (10)$$

200 The centred moments of second order,  $\Gamma^{2'}$ , presents the variance  $\sigma^2$ , as Eq. (11) shows, and  
 201 its corresponding dimensionless term  $\beta^2$ , as Eq. (12) shows. The second centred moment is a  
 202 very important parameter to describe the width of a distribution, ideal plug flow reactor has  
 203  $\beta^2 = 0$ ,  $\beta^2 > 0$  indicates an axial dispersion, the smaller the value the narrow the distribution  
 204 curve and the lower the axial dispersion as well [24].

$$\Gamma^{2'} = \sigma^2 = \int_0^{\infty} (t - t_s)^2 E(t)dt = \int_0^{\infty} t^2 E(t)dt - t_s^2 \text{ and } \beta^2 = \frac{\sigma^2}{t_s^2} \quad (11) \text{ and } (12=$$

205        *2.4.2 Experimental strategy and operating procedures*

206        Thermal balance and the hydrodynamic study of Residence Time Distribution were  
207 conducted according to a defined conditions and procedures. Each experiment was studied in  
208 function of the various operating conditions concerning different test fluids, feeding flowrates,  
209 and mixing rate of RVF module in both laminar and turbulent regimes.

210        RTD experiments were conducted according to defined conditions and procedures. Each  
211 experiment were conducted in triplicate (or more) in function of the various operating conditions  
212 concerning different test fluids (water and Breox 35%), feeding flowrate,  $Q_f$ , (25 to 300 L/h) and  
213 mixing rate  $N$  (0 to 50Hz) in laminar and turbulent regimes. During tracing experiments, fluid  
214 properties and operating parameters were stable, inlet fluid temperature was between 17 and-  
215 22°C ( $\pm 0.14^\circ\text{C}$ ) under laminar regime and between 13 and 15°C ( $\pm 0.1^\circ\text{C}$ ) under turbulent  
216 regime.

217        *2.4.3 RTD: data treatment and analysis*

218        Tracing experiments were carried out and analysed according to the methodology described  
219 by Thereska et al [25]. The experimental distribution functions enable to diagnose the  
220 functioning of pilot and industrial processes.

221        In the first step, a set-up with fluid circulation connected with RVF module and related  
222 sensors were conducted (to optimize experiments and quality of the measurements).

223        In the second step, experiments were conducted with designed experiment protocol and raw  
224 data was acquired.

225        In the third step, the processing of experimental raw data was performed by smoothing,  
226 convolution, background noise reduction, data selection, normalization and standardization. Raw

227 data (electrical conductivity) was acquired by data logger, expressed as  $\sigma_{in}$  and  $\sigma_{out}$  at  
 228 temperature  $T_{in}$  and  $T_{out}$ , were recalculated at  $T_{ref}$  (25°C), based on equation  $\sigma = \sigma_{25^\circ C} + a \cdot$   
 229  $T_{25^\circ C}^n \cdot (T - 25)$ , with  $a=0.022$  and  $n=0.93$  [26]. Base line was then subtracted and conductivity  
 230 signal  $\sigma - \sigma_0(t)$  was converted into salt concentration,  $C$ . Mass balance was established by  
 231 comparing inlet and outlet signals,  $q_{in} = \int_0^\infty C_{in}(t) \cdot Q(t) \cdot dt$  and  $q_{out} = \int_0^\infty C_{out}(t) \cdot Q(t) \cdot dt$ .  
 232 Concentration signals were normalized by total amount of tracer as follows:  $x(t) = \frac{C_{in}(t)}{\int_0^\infty C_{in}(t)dt}$  and  
 233  $y(t) = \frac{C_{out}(t)}{\int_0^\infty C_{out}(t)dt}$ , by taking the contribution of injection effect into account; Thereafter,  
 234 cumulative function can be calculated by  $X(t) = \int_0^\infty x(t)dt$  and  $Y(t) = \int_0^\infty y(t)dt$ . In the case of a  
 235 perfect inlet impulsion,  $x(t)$  is a Dirac distribution and distribution function  $E(t)$  will be equal to  
 236  $y(t)$ . In the fourth step, moment and centred moments were discussed concerning mean residence  
 237 time, and RTD curve including dispersion, asymmetry, and spreading. These moments enable to  
 238 diagnose the behaviour of the reactor as a function of flow and mixing regimes.

239 In the fourth step, a systemic approach is then conducted by software (DTS Progepi, RTD  
 240 Software Analysis). This software was used to correctly modelling the experimental response to  
 241 an input of any complex set-up consisted of connected elementary reactors [27]. This step is  
 242 based on the identification of parameters (hypothesis of a model based on the interconnection of  
 243 elementary reactors more or less complex) by adjusting the simulated response according to the  
 244 experimental data. The software realizes optimization by Rosenbrock's method, allowing  
 245 simultaneously optimize up to 6 parameters in a reduced way, which corresponds to the  
 246 difference,  $\sum_0^{NP} [y(t)_{cal} - y(t)]^2$ , between the distribution function  $y(t)_{cal}$  calculated by the  
 247 model and the experimental curve  $y(t)$ .

248

249 **3 Results and discussions**

250 An analytical study concerning experimental observations is firstly reported for thermal  
 251 balance and tracing experiments. Then moments are calculated and discussed as a function of  
 252 mixing regime. Finitely reactor modelling through systemic approach is proposed.

253 *3.1 Thermal balance*

254 In order to realize thermal balance, power consumption of RVF module was estimated from  
 255 power consumption curve. The flow is supposed to be incompressible and stationary, and we  
 256 neglect the gravity neglected. A non-slip condition is imposed on the walls and the inlet speed  
 257 profile is the same as the outlet profile, then it gives:

$$\Delta P \cdot Q + \iint_A \sum_{j=1}^3 \sum_{i=1}^3 \tau_{if} n_i U_j ds + \iint_A \sum_{i=1}^3 (-P) n_i U_i ds = \iiint_D \rho \varepsilon_V dv \quad (13)$$

258 With 1<sup>st</sup> term, necessary pump power to drive the fluid in the circulation loop; 2<sup>nd</sup> term,  
 259 external viscous forces of by the impeller; 3<sup>rd</sup> term, external forces of the pressure by the  
 260 impeller and 4<sup>th</sup> term, total power dissipation in the field.

261 Moreover, we assume the uniform temperature at the input and output sections and the heat  
 262 capacity independent of T, heat dissipation can be simplified by effective power:

$$P_{\text{eff}} = \iiint_D \rho \varepsilon_V dv = \rho C_p (T_{\text{inlet}} - T_{\text{outlet}}) Q_f \quad (14)$$

263 Thermal balance (viscous dissipation) is highly correlated to mixing power. As a result,  
 264 temperature increases significantly with the increase of mixing rate and the reduction of flow-  
 265 rate. For example, as Fig. 3-A shows, in laminar flow (BREOX solution) with  $Q_f = 25$  L/h and  
 266  $N = 25$  Hz, temperature increased 11°C; in turbulent flow (water), with  $Q_f = 50$  L/h and  $N = 50$  Hz,  
 267 temperature increased 9°C.

268 In agreement with theory (Eq.13 and 14), Fig. 3-B shows the variation of heat dissipation  
 269 and efficient power consumption [W] under different mixing rate in both laminar and turbulent  
 270 regimes. Due to its higher viscous force (2<sup>nd</sup> term of Eq. 13) in laminar regime, temperature (as  
 271 well as heat dissipated) increases faster than in turbulent regime (for example  $Q_f = 50$  and 100  
 272 L/h). The effective power consumption is estimated from power consumption curve which was

273 established in a previous research [10],  $N_p = \left( B \frac{1}{n} + \left( \frac{K_p}{Re_{mixing}} \right)^{\frac{1}{n}} \right)^n \cong \frac{K_p}{Re_{mixing}}$ , (equation (14)) where  
274  $n=2$ ,  $B=0.10$ ,  $K_p = 520$ , by knowing mixing Reynolds.

275 In a bioprocess context, maintaining ideal culture temperatures is vital for optimal cell  
276 growth. Which temperature is selected will depend on the nature of the cells to be cultured. In  
277 addition to culturing, there are temperature considerations when it comes to storing cells. The  
278 maximum temperature for growth depends on the thermal sensitivity of secondary and tertiary  
279 structures of proteins and nucleic acids. The minimum temperature depends mainly on the  
280 freezing temperature. Different physiological groups of microorganisms adapt to different  
281 temperature. Psychrophiles have optimal temperatures for growth below 15°C. Mesophilic have  
282 optimal growth temperatures in the range between 20 and 40°C. Thermophiles grow best  
283 between 50 and 70°C. There are known thermos-extremophiles growing at temperature higher  
284 than 70°C [XX-1]. For example, prokaryote cells *E. coli*'s optimal temperature to live in is  
285 around 37°C and *Streptomyces griseus* is at 25 to 35°C; for eukaryote cell *Saccharomyces*  
286 *cerevisiae* is 31 to 35°C and *Saccharomyces uvarum* around 30 to 36°C [XX-2]. Considering a  
287 temperature increase limited to 4°C (compatible with cell culture), restricted operating conditions  
288 (minimum flowrate and maximum mixing rate) can be estimated from Eq. (13 and 14) including  
289 thermal balance and power consumption.

290 **(figure 3a and b)**

### 291 3.2 Analytical studies

292 Analytical results will be discussed concerning distribution and cumulative distribution  
293 functions, and moments. Two flow regimes (laminar regime  $Re_{mixing} < 1 \times 10^3$ , turbulent  
294  $Re_{mixing} > 3 \times 10^4$ ), different  $Q_f$  and  $N$  (laminar regime:  $Q_f = 25, 50, 100$  L/h,  $N = 0, 2, 10, 25$  Hz;  
295 turbulent regime:  $Q_f = 50, 100, 150, 300$  L/h,  $N = 0, 2, 10, 25, 50$  Hz) were scrutinized in  
296 agreement with established friction and power consumption curves, and corresponding to  
297 industrial practice.

298 *3.2.1 Distribution and cumulative distribution functions*

299 Following Thereska et al. [25], experimental inlet and outlet RTD signals,  $x(t)$  and  $y(t)$  are  
300 formulated. The measured conductivity values were converted into concentration values at a  
301 reference temperature (25°C). The concentration profiles were obtained as a function of time and  
302 figure 4 illustrates typical inlet and outlet RTD normalized signals, in laminar and turbulent  
303 regimes respectively.

304 **(figure 4a and b)**

305 *Qualitative comparison on inlet and outlet RTD signals and mass balance*

306 Inlet signal,  $x(t)$  is only affected by nominal  $Q_f$  (from 25 up to 300L/h in laminar and  
307 turbulent regimes). Inlet curve,  $x(t)$  at given operating conditions indicates a good repeatability.  
308 Considering normalized inlet signal,  $\tau \cdot x(t) = f(t/\tau)$  almost identical functions were observed  
309 in laminar and turbulent regimes which indicate an accurate reproducibility (control of injected  
310 volume and tracer amount, injection time and repetition). However,  $x(t)$  peak values in laminar  
311 regime are significantly inferior to turbulent regime whereas spreading is larger. Differences can  
312 be attributed to injection device (efficiency of static mixer), injection time and flow regime. In  
313 turbulent regime, tracer solution was well-mixed and homogenized in bulk before passing  
314 through the measurement cell, then detection was accurate. In laminar regime, tracer solutions  
315 were poorly mixed in laminar regime, with inhomogeneous concentration along a cross-section,  
316 then detection might present slight deviation between experiments.

317 Outlet signals,  $y(t)$  are affected by  $N$  and  $Q_f$  and express the RVF behaviour. Figures 3a and  
318 3b illustrate the impact of  $N$  on outlet functions. In laminar regime,  $y(t)$  at 0 Hz appears as a  
319 sharp and unsmoothed signal. Under these conditions, RVF module exhibits none mixing  
320 efficiency and our remarks are similar to inlet signal. For  $N>0$ Hz,  $y(t)$  present a stable outlet

321 signal with a lower peak and consequently a larger spreading. In turbulent regime, smooth  
322 signals were obtained due to turbulence, internal geometrical complexity and mixing rate. The  
323 increase in mixing rate generates a larger asymmetric Gaussian curve.

324 *Impact of mixing rate  $N$  and feeding flowrate  $Q_f$  in turbulent and laminar regimes*

325 Figures 5a and 5b compare the outlet RTD signals,  $y(t)$  as a function of  $N$  and regime for a  
326 given  $Q_f$  (100 L/h).

327 **(figure 5a and b)**

328 In turbulent regime, it shows the sliding of peak value from 0.037 to 0.021 1/s, with the  $N$   
329 increase from 0 to 25 Hz. In laminar regime, peak value slides from 0.021 to 0.014 1/s with the  $N$   
330 increase from 0 to 50 Hz.

331 Cumulative distribution functions,  $Y(t)$  were plotted in figures 6a and 6b as a function of  $N$   
332 and  $Q_f$ . With various  $Q_f$ , it can be clearly seen in both flow regimes,  $Y(t)$  of higher  $Q_f$  has steeper  
333 acceleration than the lower  $Q_f$  as expect, consider that the molecule flow out from the RVF  
334 module faster when it was driven by a higher  $Q_f$ . On the other hand, with various  $N$ ,  $Y(t)$  of  
335 turbulent regime(see figure 5b) has a noticeable growth: in each cluster of colored curves, with  
336 the increase of  $N$ , the  $Y(t)$  turn to be flatter, and slowly reach the plateau of the curve. Yet there is  
337 also a large difference of  $N$  in laminar regime (see figure 5a), but it has no such significant  
338 impact.

339 **(figure 6a and b)**

340 *3.2.2 Discussion of moments*

341 The average operating conditions and calculated RTD parameters under laminar and  
342 turbulent regimes are reported in table 1 and table 2. In some extreme operating conditions,

343 significant temperature increase (difference between inlet and outlet) was observed both in  
344 laminar and turbulent flow. For example, temperature increased by 10.8 °C and 8.8 °C  
345 respectively in laminar ( $Q_f= 25$  L/h,  $N=25$  Hz) and turbulent regimes ( $Q_f= 50$  L/h,  $N=50$  Hz).

346 **(table 1)**

347 **(table 2)**

348 *Moment of 1<sup>st</sup> order (mean residence time)*

349 Moment of first order  $\Gamma^1$  represents the mean residence time  $t_s$  in the system, as expressed  
350 by Eq. (5). The product  $t_s \cdot Q_f$  represents the effective volume  $V_I$ , indicates the used volume in  
351 the system.

352 Figures 7a and 7b report the evolution of mean residence time,  $t_s$  as a function of mixing  
353 rate,  $N$  in laminar and turbulent regimes.

354 **(figure 7a and b)**

355 In laminar regime,  $t_s$  remain constant at a given  $Q_f$ , with a mean value  $t_s=50\pm5$ ,  $95\pm3$  and  
356  $152\pm2$  s for 25, 50 and 100 L/h respectively, whatever the  $N$  is. In turbulent regime,  $t_s$  increases  
357 linearly as a function of  $N$  at a given  $Q_f$ ,  $t_s$  can be generally described by  $Q_f$  and  $N$ :

$$t_s = \alpha N + \tau_0 \quad (15)$$

358  $V_I$  can be expressed by:

$$V_I = t_s \cdot Q_f = \alpha N + V_0 = 0.0106 \cdot N + 1.15 \quad (16)$$

359 Where  $\alpha$  and  $\tau_0$  is as function of  $1/Q_f$  ( $R^2 \geq 99\%$ ), and  $t_s = \frac{V_I}{Q_f}$  and  $\tau_0 = \frac{V_0}{Q_f}$ .

360 Figure 8 plots  $V_I$  as a function of mixing Reynolds number. In laminar flow which in the  
361 range of  $Re_{mixing} < \times 10^3$ ,  $V_I$  is constant at the given  $Q_f$ , it shows  $V_I = 1.12 \text{ L} \pm 0.06$  at  $Q_f = 25 \text{ L/h}$ ,  
362  $V_I = 1.27 \text{ L} \pm 0.07$  at  $Q_f = 50 \text{ L/h}$ , and  $V_I = 1.34 \text{ L} \pm 0.02$  at  $Q_f = 100 \text{ L/h}$ .  $V_I$  is dependent from  $Q_f$ ,  
363 and  $N$  does not seem to have significant impact on  $V_I$ . In turbulent regime, initial used volume  
364 ( $N=0 \text{ Hz}$ ) is at about  $1.15 \text{ L}$  and it extends with the increase of RVF mixing rate. In this case, the  
365 effective volume is only mixing rate dependent whereas flowrate does not have any effect. It is  
366 noticeable that  $V_I$  and  $t_s$  depend on mixing rate in turbulent regime.

367 **(figure 8)**

368  $V_I$  and  $t_s$  reflect the real movement of the tracers in RVF module (including shortcut, bypass  
369 or dead-zone that may exist). While  $\tau$  represents the holding time based on the assumption that  
370 tracer molecules ideally move all over RVF module ( $V_{RVF}$ ). Therefore, effective ratio defined by  
371  $t_s/\tau$  or  $V_I/V_{RVF}$  becomes one of the important parameters to diagnose the flow system. The closer  
372 is the ratio to 100%, the closer the system to the perfect mixer. In laminar regime, the effective  
373 ratio was equal to 70%, 79%, and 84% at 25, 50, 100 L/h respectively. The main factor that  
374 improves this ratio is the increase of the  $Q_f$ , and it seems mixing rate doesn't drive the fluid to  
375 reach all over the system. To explain, at first,  $N$  was limited to 25 Hz which might be not high  
376 enough to drive the fluid. Besides, it probably due to that laminar regime is very stable as widely  
377 known, the mixing effect in this kind of flow regime is poor. However, under turbulent regime,  
378 initial effective volume equal to  $1.15 \text{ L}$  ( $N=0 \text{ Hz}$ ) is almost the same value as under laminar  
379 regime at 25 L/h, and it has a rapid growth as the increase of mixing rate. One can note that  $V_I$  is  
380 tending towards  $V_{RVF}$  which is corresponding to an optimal use of the available volume. Overall,  
381 these observations lead to the fact that, under laminar regime, mixing is mainly governed by the  
382 flowrate  $Q_f$ ; while under turbulent regime, mixing is largely governed by the stirring speed  $N$ .

383 *Centred moment of 2nd order, (reduced variances,  $\beta^2$ )*

384 Figure 9 plots the evolution of the experimental reduced variance  $\beta^2$  against mixing  
385 Reynolds. There is a significant decrease in reduced variance under both laminar and turbulent  
386 regimes. It is noticeable that the higher  $Q_f$  was, the closer to a perfect mixer, the system seems,  
387 whereas with higher  $Re_{mixing}$  it tends to a plug flow reactor. Considering  $Q_f = 50$  and  $100$  L/h in  
388 both flow regime, two logarithmic regressions are plotted, which denotes that  $\beta^2$  and mixing  
389 effect ( $Re_{mixing}$ ) are somehow related.

390 **(figure 9)**

391 *3.23 Reduced signal of outlet distribution function  $y(t)$*

392 In laminar regime, effective volume was highly correlated to  $Q_f$  whereas in turbulent  
393 regime,  $N$  played a role as the dominant parameters. In order to confirm or to refute the  
394 uniqueness of hydrodynamics behaviour of RVF module, distribution functions  $y(t)$  were  
395 reduced by experimental mean residence time  $t_s$  and expressed as  $y(t/t_s) \cdot t_s$ .

396 Figure 10 plots these reduced distributions as a function of  $t/t_s$  at the given operating  
397 condition. Then overlapping coefficient,  $OVL = \int_0^t \min [f_1(x), f_2(x)] dx$  ) is calculated to  
398 compared experimental data.

399 In laminar regime at given feeding flowrate  $Q_f = 100$  L/h, (see figure 9a1) reduced  
400 distribution functions are separated and the peak values slide from 1.83 to 1.07 with the increase  
401 of  $N$ . Furthermore, for three feed flowrates,  $Q_f$  at given  $N$  (see figure 9a2), reduced distribution  
402 functions are perfectly overlapped ( $OVL = 0.86$ ).

403 Figure 10a1 and a2 indicate that RVF behaviour is the same at a given  $N$  whatever  $Q_f$   
404 values.

405 In turbulent regime, reduced distribution functions,  $y(t/t_s) \cdot t_s$  are perfectly overlapped  
406 (Figure 10a, with OVL=0.85) in all conditions indicating the uniqueness of hydrodynamics  
407 behaviours. It can be reasonably assumed that flow behaviour in turbulent regime is somehow  
408 the same, whatever flowrate,  $Q_f$  and mixing rates,  $N$  are. Since the reduced distribution functions  
409 showed its uniqueness in whole or in part in different flow regime, flow behaviours in the RVF  
410 module probably can be explained by a unique model with an equivalent known system.

411 **(figure 10a and b)**

### 412 *3.3 Systemic analysis and modelling of RTD*

413 After the analytical studies of RTD, the hydrodynamic behaviours were described by a  
414 systemic analysis by modelling RTD outlet signals using DTS Progepi v4.2. Our objective is to  
415 model and to establish an analytical solution of RTD functions considering the complexity of  
416 RVF module.

#### 417 *3.31 Proposal of reactor models*

418 Three models were proposed to fit the outlet function  $y(t)$  of RVF module in order to  
419 obtain a better agreement. Inlet function  $x(t)$  was taken into account by considering the  
420 convolution with outlet function  $y(t)$ . For each tested configuration, a Plug Flow reactor was used  
421 to describe the tubes upstream and downstream of the RVF module. The RVF module was  
422 described by three different associations of ideal reactors (figure 11).

423 **(figure 11)**

424 Model 1: A plug flow reactor in serie with a plug flow reactor with axial diffusion. The  
425 value of the volume was fixed equal to  $V_{RVF}$  and adjusting Peclet number  $Pe_L$ . Consequently, this

426 model exhibit only 1 degree of freedom ( $Pe_L$ ). RTD function is described by an analytical  
 427 solution (Eq.17).

$$E(t) = \frac{1}{2} \left( \frac{Pe_L}{\pi \tau t} \right)^{1/2} \exp \left( -\frac{Pe_L(\tau - t)^2}{4\tau t} \right), \text{ where } \tau = \frac{V_{RVF}}{Q_f} \quad (17)$$

$$\text{with } \frac{t_s}{\tau} = 1 + \frac{2}{Pe_L}, \quad \beta^2 = \frac{\sigma^2}{t_s^2} = \frac{2}{Pe_L} + \frac{8}{Pe_L^2} \quad (18)$$

428 Model 2: A plug flow reactor in serie with J continuous stirred tank reactors. The value of  
 429 the volume was fixed equal to  $V_{RVF}$ . This second model is defined by the value of J, the  
 430 residence time of the plug reactor ( $\tau_p$ ) and the residence time of the J CSTR ( $\tau_{cs}$ ). This model  
 431 has been tested in previous studies [17, 26-28]. The corresponding expressions for the transfer  
 432 function,  $G(s)$  and  $E(t)$  are formulated by Eq. (19) and Eq.(20):

$$G(s) = \frac{\exp(-s\tau_p)}{\left( 1 + \left( \frac{s\tau_{cs}}{J} \right) \right)^J}, \text{ where } \tau = \frac{V_{RVF}}{Q_f} \quad (19)$$

$$E(t) = H(t - \tau_p) \left( \frac{J}{\tau_{cs}} \right)^J (t - \tau_p) \exp \left( -\frac{J(t - \tau_p)}{\tau_{cs}} \right) \quad (20)$$

433 Model 3: A plug flow reactor in serie with J continuous stirred tank reactors. This model is  
 434 a modified version of model 2. Indeed, the value of the volume was taken equal to  $V_I$   
 435 (experimental values from Tables 1 and 2) instead of the total volume of RVF module.

436 3.3.2 Model adjustment and comparison

437 Even if inlet signals can be neglected, we observed that the injection were slightly different  
438 from ideal Dirac functions, especially in laminar regime. In order to better fit the experimental  
439 functions,  $y(t)$ , the inlet functions  $x(t)$  were considered with all models to simulate  $E(t)$ .

440 Figure 12 plots the modelling curve  $y(t)$  of models 1, 2 and 3 fitting with the experimental data  
441  $y(t)$  (one operating condition).

442 **(figure 12)**

443 Table 3 sums up overlapping coefficient values for models 1, 2 and 3.

444 **(table 3)**

445 Significantly, model 3 can be preferred in both laminar and turbulent regimes. Table 4 shows the  
446 values of  $J$  for this model.

447 **(table 4)**

448 To conclude this systemic approach, the model 3 defined by the effective volume  $V_I$  and  
449  $J=2.5\pm 0.6$  can be chosen to describe flow behaviour in RVF module.

450

#### 451 **4 Conclusions**

452 For MBR using dynamic filtration module, RTD is an efficient way to diagnose bioprocess  
453 efficiency. In present work, tracer experiments were applied to investigate RTD in an impeller-  
454 rotating filter (RVF module) in laminar and turbulent regimes.

455 Firstly, experimental observation and analysis of RTD in this complex module are  
456 discussed. It has allowed the characterization of the flow behaviour and the determination of  
457 defined parameters.

458 Results mainly demonstrate that:

459 • Thermal effect was introduced in order to have the knowledge of temperature change and  
460 heat dissipation in a bioprocess context (cell culture). Thermal balance (heat dissipation) is  
461 correlated to mixing power (power consumption curve). The temperature increased dramatically  
462 at high rotation speed, especially in laminar flow (ex. +11°C under operating conditions  $Q_f=25$   
463 L/h and  $N=25$  Hz). In turbulent flow, with  $Q_f=50$  L/h and  $N=50$  Hz, temperature increased up to  
464 9°C. Considering a temperature increase limited to 4°C (compatible with cell culture), restricted  
465 operating conditions (minimum flowrate and maximum mixing rate) can be estimated from  
466 thermal balance and power consumption curve.

467 • Under laminar regime, mean residence time,  $t_s$  and effective volume,  $V_I$  remained  
468 constant for all imposed flowrates  $Q_f$ , whatever mixing rate,  $N$ . Under turbulent regime,  $t_s$   
469 increased linearly as a function of  $N$  at a given  $Q_f$ . The effective volume  $V_I$  was only  $N$   
470 dependent, whereas  $Q_f$  had no effect.  $V_I$  ranged from 1.15 up to 1.6 L corresponding to effective  
471 ratio from 72% up to 100%. In brief, the governing parameter of the mixing in laminar regime  
472 was mainly the feeding flowrate  $Q_f$ , while in turbulent regime it was the mixing rate,  $N$ .

473 • Centred moments of 2<sup>nd</sup> order, reduced variances  $\beta^2$ , are as a linear function of mixing  
474 Reynolds number for the given flowrate,  $\beta^2$  slightly increased with  $Q_f$ .

475 Secondly, a systemic analysis lead to model of RTD. Three conventional reactor models  
476 (exhibiting analytical solutions) were evaluated to predict the distribution function,  $E(t)$   
477 considering convolution of inlet,  $x(t)$  and outlet,  $y(t)$  functions. Modelling of RTD by PFR+(J)  
478 CSTR model (effective volume,  $V_I$  and  $J = 2.5 \pm 0.6$ ) accurately estimate the mean residence time  
479 and its associated distribution.

480 Interactions between biological matrices and hydrodynamics in Dynamic Filtration must be  
481 deeply studied to intensify bioprocesses. Even if RTD lead to identify critical operating  
482 conditions, global bioprocess performances arise from a local interactions including velocity  
483 distribution, shear stress, turbulence, local temperature, etc. [17]. Future studies might include:

484 • The investigation of local hydrodynamic (velocity fields, local velocity profiles, wall  
485 shear stress etc.) through PIV (Particle Image velocimetry) measurement [19, 28, 29] and CFD  
486 approach (fluid streamlines) in order to quantify local shear stress and its time-evolution as well  
487 as the flow pattern and coherent flow structures;

488 • The investigation of RTD with Non-Newtonian fluids to understand and simulate the  
489 rheological behaviour of biological suspensions;

490

491

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499

500

501 **Reference**

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612 **Figures caption**

613 Fig. 1 Scheme, top view of one filtration cell and global view of Rotating and Vibrating  
614 Filtration module.

615 Fig. 2 Experimental setup and injection device (a) schematic of experimental setup, C1, C2:  
616 Electrical conductivity sensors; (b) Injection device; (c) Photo of experimental setup.

617 Fig. 3 Temperature variation of the test fluid with different mixing rate (A) and and Heat  
618 dissipation [W] as a function of calculated mixing power consumption [W].\*\*\*\*\*  
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620 Fig. 4 Inlet and outlet distribution functions,  $x(t)$  and  $y(t)$  in (a) laminar regime, operating  
621 conditions: BREOX 35% solution,  $\mu=0.35$  Pa·s,  $Q_f=100$  L/h,  $N=0$  ( $T_{in}=22.7 \pm 0.01^\circ\text{C}$ ,  
622  $T_{out}=23.0 \pm 0.02^\circ\text{C}$ ) and 25 Hz ( $T_{in}=22.2 \pm 0.14^\circ\text{C}$ ,  $T_{out}=26.3 \pm 0.13^\circ\text{C}$ ); and in (b) turbulent  
623 regime, operating conditions: water,  $\mu=1$  mPa·s,  $Q_f=100$  L/h,  $N=0$  ( $T_{in}=13.0 \pm 0.12^\circ\text{C}$ ,  
624  $T_{out}=13.1 \pm 0.11^\circ\text{C}$ ) and 50 Hz ( $T_{in}=14.8 \pm 0.02^\circ\text{C}$ ,  $T_{out}=19.3 \pm 0.02^\circ\text{C}$ ).

625 Fig. 5 Outlet distribution functions,  $y(t)$  in (a) laminar regime, operating conditions:  $\mu=0.35$  Pa·s,  
626  $Q_f=100$  L/h,  $N=0, 2, 10, 25$  Hz; and in (b) turbulent regime, operating conditions: water,  
627  $\mu=1$  mPa·s,  $Q_f=100$  L/h,  $N=0, 2, 10, 25, 50$  Hz.

628 Fig. 6 Cumulative functions,  $Y(t)$  in (a) laminar regime, operating condition: 35% BREOX  
629 solution  $\mu=0.35$  Pa·s,  $Q_f=25, 100$  L/h,  $N= 2, 10, 25$  Hz; and for (b) turbulent regime,  
630 operating conditions: water,  $\mu=1$  mPa·s,  $Q_f=50, 150, 300$  L/h,  $N=2, 10, 25, 50$  Hz.

631 Fig. 7 Mean residence time,  $t_s$  as a function of mixing rate,  $N$  in (a) laminar regime, operating  
632 conditions: BREOX 35% solution  $\mu=0.35$  Pa·s,  $Q_f=25, 50, 100$  L/h,  $N=0, 2, 10, 25$  Hz; and

633 for (b) turbulent regime, operating conditions: water,  $\mu=1$  mPa·s,  $Q=50, 100, 150, 300$  L/h,  
634  $N=0, 2, 10, 25, 50$  Hz.

635 Fig. 8 Efficient volume,  $V_1$  as a function of mixing Reynolds number,  $Re_{Mixing}$ . In laminar  
636 regime, operating conditions: BREOX 35% solution  $\mu=0.35$  Pa·s,  $Q_f=25, 50, 100$  L/h,  $N=2,$   
637  $10, 25$  Hz; in turbulent regime, operating conditions: water,  $\mu=1$  mPa·s,  $Q_f=50, 100, 150,$   
638  $300$  L/h,  $N= 2, 10, 25, 50$  Hz.

639 Fig. 9 Reduced variance,  $\beta^2$  as a function of mixing Reynolds number  $Re_{Mixing}$ . In laminar  
640 regime, operating conditions: BREOX 35% solution  $\mu=0.35$  Pa·s,  $Q=25, 50, 100$  L/h,  $N=0,$   
641  $2, 10, 25$  Hz; un turbulent regime, operating conditions: water,  $Q=50, 100, 150, 300$  L/h,  $N=$   
642  $2, 10, 25, 50$  Hz.

643 Fig. 10 Reduced distributiion function,  $t_s \cdot y(t)$  as a function of reduced time,  $t/t_s$ , in (a) laminar  
644 regime (operating conditions in a1: BREOX 35% solution,  $\mu=0.35$  Pa·s,  $Q=100$  L/h,  $N=0, 2,$   
645  $10, 25$  Hz, in a2: BREOX 35% solution,  $\mu=0.35$  Pa·s,  $Q=25, 50, 100$  L/h,  $N=25$  Hz) and in  
646 (b) turbulent regime (operating conditions: water,  $\mu=1$  mPa·s,  $Q=50, 300$  L/h,  $N=0, 50$  Hz).

647 Fig. 11 Proposed structure to describe RTD within RVF module; Model 1: Plug flow reactor  
648 open to diffusion by imposing  $V_{RVF}$ ; Model 2: perfect mixing cell in series by imposing  
649  $V_{RVF}$  and model 3: perfect mixing cell in series by imposing the efficient volume,  $V_1$ .

650 Fig. 12 Comparison of the fitting curves with model 1, 2 and 3. (a): laminar regime with BREOX  
651 35% solution,  $Q_f=100$  L/h,  $N=25$  Hz; (b) turbulent regime with water,  $Q_f=100$  L/h,  $N=10$   
652 Hz.

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655 **List of tables:**

656 Table 1: Operating conditions and calculated RTD parameters in laminar regime (SD: standard  
657 deviation).

658 Table 2: Operating conditions and calculated RTD parameters in turbulent regime (SD: standard  
659 deviation).

660 Table 3: Overlapping coefficient values for models 1, 2 and 3.

661 Table 4 : J value in Model 3

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