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Investigation of hydrodynamic behavior of the moving bed biofilm reactor packed with Kaldnes K1

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ABSTRACT/RESUME

Abstract: *The research study below aims to characterize the hydrodynamics of a Moving Bed Biofilm Reactor filled with Kaldnes K1. Firstly, find the type of reactor (stirrer or piston) and finally set the operating conditions for carrying out the biological denitrification in an MBBR reactor.*
The hydrodynamics were determined by means of pulse tracer tests and by calculating distribution curves of the residence time at different stirring speeds (100 - 300 rpm), for different support infill (0 - 165.2 g) and at different influent feed rates (0.1 - 2 L.h^{-1}).
The moving bed biofilm reactor (MBBR) showed rector behavior, it is a perfectly stirred reactor, and the optimaloperating conditions are for stirring speeds of 100 rpm, quantities of support of 165.2 gand afeed rate 0.816 L h^{-1}.

I. Introduction

In recent years special attention has been paid to biofilm systems **[**1**]**used in the biological treatment of different effluents and under different conditions. Biofilms attached to carrier materials were applied in moving bed biofilm reactors (MBBR) [2], the great advantage of this technology is the high biomass content leading to more cost-effective treatment [3]**.**The MBBR process requires an accentuated mechanical or hydrodynamic mixture, where the supports are circulated continuously to facilitate sufficient mass transport to the biofilm developing on the supports[4].
Resistance Time Distribution(RTD) techniques have long been recognized in the chemical industry as powerful tools for characterizing flow patterns and diagnosing malfunctions in complex flow equipment such as packed bed catalytic reactors [5]. The basic principle of the technique is to inject an inert tracer, such as a dye, a conductive solution or a radioactive compound, in the form of an "impulse" or a "step change" and determine the output concentration of the tracer material. The form of the “response signal” can be used to determine certain parameters such as the average residence time of the fluid in the equipment, the presence of dead volumes and / or bypass flows, as well as the intensity of the effects of mixing along the radial and axial directions [5].
The hydraulic characteristics of mobile attached growth systems have a significant impact on system performance, supports of different sizes and shapes can influence flow paths and hydraulic speeds with an impact on mass transfer of oxygen and substrate [6]and the dynamics of biofilm, including growth, thickness and detachment, [7].[8]reported some uncertainties in hydrodynamics at the reactor level regarding the interaction between the biofilm and the bulk phase and reactor design. Thus, the effect of the structure and morphology of the biofilm on the mass transport processes in the MBBR must be well deciphered because the presence and structure of the biofilms influence the local flow regime and the transport of substrates in the biofilm. [9]
Few studies have examined the impact of supports on hydraulic flow models and mixing conditions, the majority of these studies have helped to identify hydraulic limitations, such as inactive volume (stagnant flow), short- hydraulic circuits and preferred flow paths [10]. Thedead volume or

stagnant areas reduce the actual volume available for chemical and biochemical reactions, reducing processing capacity [11].
The objectives of this study set the reactor behavior and the operating conditions, the effect of the variation of three main operating parameters to quote the speed of agitation, the flow rate of the influent and the fraction of filling by the support used, on the hydrodynamic behavior of the MBBR reactor

II. Materials and methods

II.1. Experimental setup

The hydrodynamic study was carried out in an MBBR reactor, designed for the biological denitrification of water, it is mainly composed of a reactor with a capacity of 2.25 liters, filled with quantities of the carrier medium (Kaldnes 1) varying between 0 and 165.2g and having a percentage from 0 to 52.5% of the total effective volume of the reactor. The supports used (Kaldnes 1) are made of polyethylene with a density of 0.95 and an effective specific surface of 800 m^2 / m^3. The support has a cylindrical shape, having a height of 8 mm and a diameter of 9 mm[12,13].
The influent is supplied by a peristaltic pump (brand), varying the flow rate between 0.1 and 2 $L.h^{-1}$, magnetic stirring varying between 100 and 300 rpm allowing contact between the tracer and the water, hydrodynamic studies were performed in the absence and presence of a variant amount of support **(Figure .01).**
01).

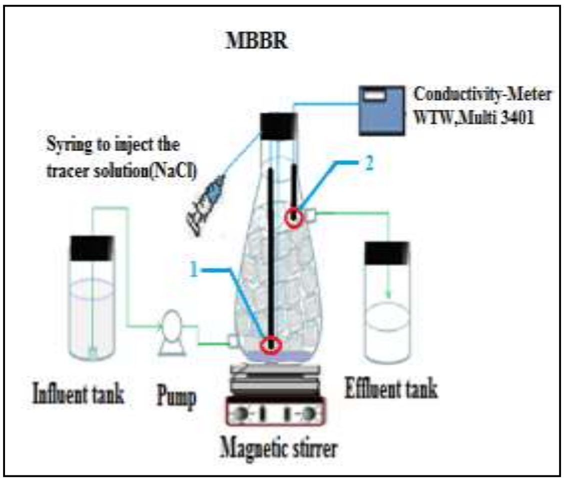

Figure 1.*Schematic diagram of the MBBR reactor considered in the RTD measurements.*

II.2. Analytical methods

The experiments carried out for the characterization of the hydraulic behavior of the MBBR used in the next studies of the biological denitrification of waters were established on the basis of the RTD curves. The hydrodynamic characteristics of the reactor have been verified using sodium chloride (NaCl) as a tracer, on the one hand since it is an economical tracer and its implementation is simple and on the other hand the possibility of using current measuring equipment, a conductivity meter with continuous recording by injecting salt allows to disturb the conductivity of the water.
The hydrodynamic studies carried out in the present study were carried out in clean environments (without biofilm) with clear water, but it should be noted that in some studies, the hydraulic behavior of the reactors was carried out in a clean environment (without biofilm) use distilled water, low conductivity and use a clean tracer like Nacl [14]. also hydrodynamic studies carried out in the presence of purifying biomass (with biofilm), considering that the tracers used were not absorbed by the sludge particles, had no inhibitory effect on bacteria and would not be used as a nutrient by micro-organisms [10].
To obtain the RTD curves, a sodium chloride solution (3 M) about 5 ml was injected instantaneously in the form of a **Dirac** at the inlet of the reactor (point 01, Figure 1), The concentration and the volume injected were previously optimized, so that the injection is carried out without disturbing the flow within the reactor but the pulse must be detectable by the conductivity-meter.Signal detection at the reactor outlet (point 02, Figure 1) is carried out by measuring the conductivity and the values are expressed in NaCl concentration (c (t)) using a previously established curve linking the conductivity to the different salt concentrations (Conductivity: $1.836.10^3$ c(t) +64.714) *µs/cm*.
The experiments are carried out for approximately 3 times the hydraulic retention time of the reactors[15], The conductivity meter used is a conductivity meter (Multi-parameter WTW, Multi 340I). The measurement is associated with an integrated temperature measurement allowing automatic compensation of the conductivity value as a function of the temperature of the solution. (T = 22 ± 2 ° C).

II.3. Theoretical interpretations

The RTD is linked to the output concentration of the tracer (C (t)) by the distribution function of the residence time (E (t)), which describes quantitatively how much time a fraction of the fluid has passed in the reactor.[16]

$$E(t) = \frac{c(t)}{\int_0^\infty c(t)d(t)} \quad \textbf{(1)}$$

The normalization conditions imply that:

$$\int_0^\infty E(t)d(t) = 1 \quad \textbf{(2)}$$

$$\mu_n = \int_0^\infty t^n E(t)d(t) \quad \textbf{(3)}$$

The first pulse is the average time that the effluent molecules have stayed inside the reactor, and it is known as the average residence time ($\bar{\tau}_s$).

$$\bar{\tau}_s = \frac{\int_0^\infty tE(t)d(t)}{\int_0^\infty E(t)d(t)} = \frac{\mu_1}{\mu_0} = \frac{\int_0^\infty tE(t)d(t)}{1} = \int_0^\infty tE(t)d(t) \quad \textbf{(4)}$$

The second moment is taken from the mean and it is known as the distribution variance

$$\sigma_t^2 = \int_0^\infty (t - \bar{\tau}_s)^2 E(t)d(t) \quad \textbf{(5)}$$

Using the average residence time, E (t) can be expressed as a function of dimensionless time (θ).

$$E(\theta) = \bar{\tau}_s E(t) \quad \textbf{(6)}$$

Here $\theta = t/\bar{\tau}_s$, and $\bar{\tau}_s$ is average residence time.
The model correlates the average residence time and the variance of the RTD curve, obtained with tracing methods. In this model, the Peclet number is determined from σ_t^2 and the value of $\bar{\tau}_s$ obtained from RTD.

$$\sigma^2{}_\theta = 2\left(\frac{D}{\mu L}\right) - 2\left(\frac{D}{\mu L}\right)^2 * \left(1 - e^{-\mu L/D}\right) \quad \textbf{(7)}$$

Where D is the axial dispersion coefficient, μ is the average speed of the fluid and L is the axial distance from the reactor[16].

Among all the information contained in the RTD, the calculation of the moments of the distribution makes it possible to reach, to the exclusion of any modeling of the quantities such as the average value of the distribution, its dispersion, etc.
The order time (n) around the origin is defined by the following relation:

Pe represents the Peclet number, which is the inverse of the dispersion number (Pe = μL/D) can be calculated by the Equation (8) [16]:

$$\sigma^2{}_\theta = 2\left(\frac{1}{Pe}\right) - 2\left(\frac{1}{Pe}\right)^2 * \left(1 - e^{-\mu L/D}\right) \quad \textbf{(8)}$$

Pe can be used to characterize the axial back-mixing. The higher the value of Pe, the lower the back mixing[16]. σ^2 This is the dimensionless variance of the RTD expressed as follows:

$$\sigma^2{}_\theta = \sigma_t^2 / \bar{\tau}_s{}^2 \quad \textbf{(9)}$$

N is the number of theoretical agitated reservoirs and can be calculated by the Equation. (10).

$$\sigma^2{}_\theta = 1/N \quad \textbf{(10)}$$

$$\frac{D}{\mu L} = \frac{\sigma^2{}_\theta}{2} \quad \textbf{(11)}$$

Dead space (V_d,%) is calculated using the equation. (12) :

$$\frac{V_d}{V_R} = \left(1 - \frac{\bar{\tau}_s}{t}\right) * 100 \quad \textbf{(12)}$$

III. Results and discussion

An example of the time evolution of c (t) after injection of the tracer, as well as the evolution of E (t), moments of order 1 and 2 for a feed rate of **0.816 L. h^{-1}**, a quantity of support of165.2 **g**and a stirring speed of **100 rpm** are presented respectively in Figure 02. (a), (b), (c) and (d)
The mean residence time and the distribution variance are estimated by calculating the area under curve (c) and (d),

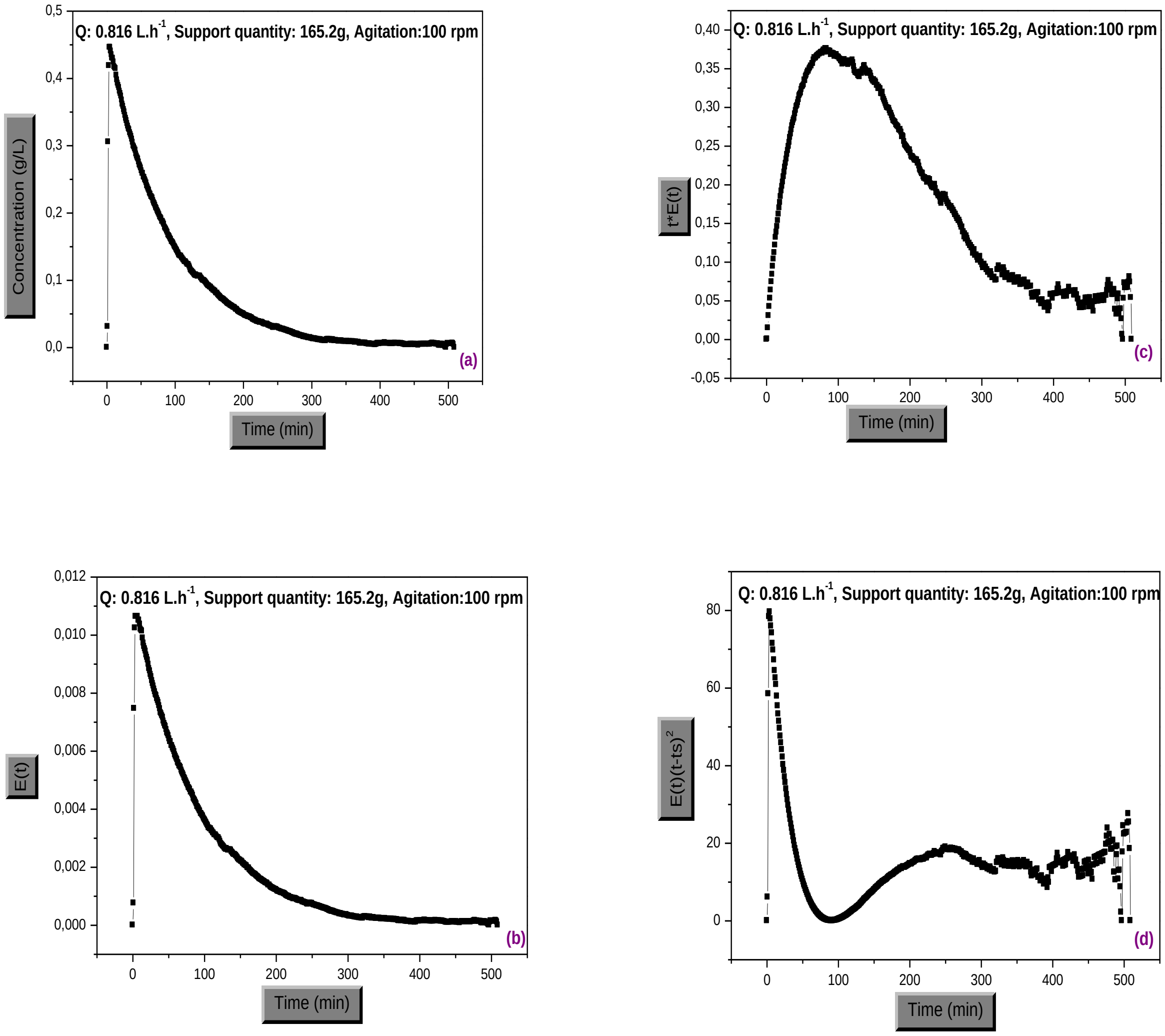

Figure 2. *Temporal evolution of c(t) , E(t) , tE(t) et*$(t-\bar{\tau}_s)^2$ *E(t) (feed rate: 0,816 L. h*$^{-1}$*, amount of support:165,2g , stirring speed: 100 rpm)*

RTD tests were carried out for different stirring speeds (Figure. 3 and 4), different quantities of supports (Figure .05 and 06) and different feed rates (Figure 7 and 8), The results of all the experiments carried out are summarized in Tables 1, 2 and 03.

III.1. Effect of stirring speed

The hydraulic efficiency ($\bar{\tau}_s/\tau$) was calculated for each condition studied, for a clear water supply flow rate of 0.816L.h^{-1} and by varying the stirring speed from 100 to 300 rpm (Table 1).
The distribution fraction of the residence time (E (t)) and the average residence time ($\bar{\tau}_s$) were determined using equations (1) and (6). Figure 3 shows the tracer distribution time during a pulse injection into the reactor as a function of the different agitation speeds tested.
Two key events must be carefully analyzed when reading the exit signal after injection of the tracer, the moment when the tracer appears for the first time in the effluent and the point where its maximum output concentration is recorded. [17]. All the curves recorded present a single concentration peak, followed by an exponential decay function, this is a characteristic behavior of a perfectly agitated reactor, but long streaks are recorded in the distributions of the curves, this could be linked to the presence of dead zones or stagnation, or the tracer will penetrate these zones by diffusion, then it will be eliminated very gradually [17], in the case of the presence of a short circuit, two peaks will be recorded, of which: the first corresponding to the

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short circuit and the second to the rest of the fluid (response of the reactor).
According to the results grouped in Table 1, The differences between the hydraulic residence time and the average residence time indicate that the reactor has deviated from the ideal flow behavior and that a malfunction is diagnosed [18].The average residence time was always shorter than the theoretical value, the hydraulic yields were always less than 100%, but while increasing the stirring speed, the average residence time is closer to the theoretical residence time which is 147.058 min, the average hydraulic efficiency improved from 61.52 to 68.56% when the stirring speed has been increased from 100 to 300 rpm, these results confirm the presence of dead zones which reduce the effective volume of the reactor [19].
In previous studies, the positive effect of aeration on hydraulic efficiency has also been observed. Indeed, the behavior of the reactor tended to be completely mixed due to the agitation favored by the injection of air [11,20],but since this reactor will be used in denitrification studies in an anoxic medium, the effect of air injection has not been studied.

The results indicated a reduction in dead zones from 38 to 31%, increasing the stirring speed from 100 to 300 rpm, a small impact in the clean case (without biomass), but in the case where the reactor works in the presence of biomass, agitation has a significant effect on the growth of biofilm .[21]indicates that a low stirring speed in an MBBR reactor promotes bacterial growth and the accumulation of biomass on the walls of the support,. on the other hand, a high stirring speed will influence the flow regime which becomes turbulent, will ingest by as a result, higher shear forces, under such conditions, the accumulation of biomass on the walls is reduced and the release of the biomass is favored. [22] Also reported that adequate turbulence is ideal for maintaining the necessary flow velocity to achieve efficient system performance. Extremely high turbulence detaches the biomass from the support and is therefore not recommended. In addition, the collision and the attrition of the media in the reactor cause the biofilm to detach from the external surface of the media. For this reason, the MBBR support is provided with fins on the outside to protect the loss of biofilm and promote the growth of biofilm.

Table 1. *Results of the RTDs obtained for the different agitation speeds*

Feed rate (L.h)	**Support quantity (g)**	**stirring speeds(tr.min^{-1})**	**τ (min)**	**$\bar{\tau}_s$ (min)**	**σ^2**	**$\bar{\tau}_s/\tau$ (HE) (%)**	**σ_θ^2**	**$D/\mu L$**	**Pe**	**V_d(%)**	**N**
					Test 01						
0.816	165.2	**100**	147.058	90.4815	7585.064	61.52	0.92	0.46	2,17	38	1,08
0.816	165.2	**200**	147.058	100.63	7597.254	68.42	0,75	0,37	2,66	31.55	1,33
0.816	165.2	**300**	147.058	100.83	7440.72	68.56	0,73	0,36	2,73	31.4	1,36

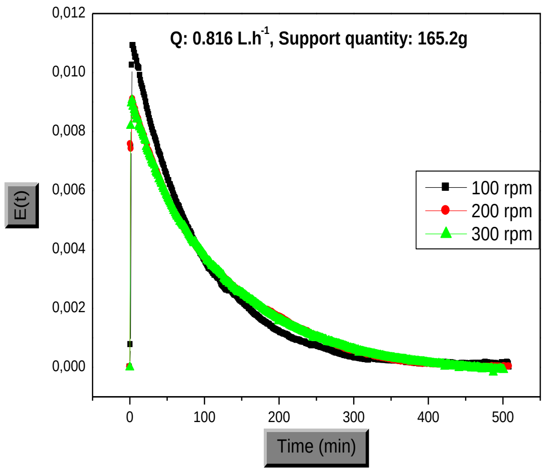

Figure 3. *The different distributions of the residence time for the different stirring speeds (Feed rate:* ***0.816 L. h^{-1}****, Quantity of support:* ***165.2 g****)*

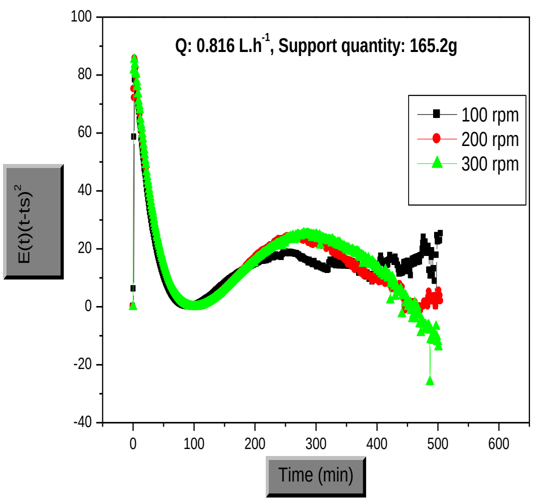

Figure 4. *Evolution of $(t - \overline{\tau_s})^2$ E(t) as a function of time for calculating the variance for the different stirring speeds (Feed rate:* ***0.816 L. h^{-1}****, Support quantity:* ***165.2g****)*

As the two preceding conditions have drawbacks and advantages, therefore, finding an adequate speed sufficiently large to reduce the percentage of dead zones in the MBBR, but sufficiently small, too, to avoid detachment of the biomass during the studies of denitrification would be ideal.

To analyze the number of dispersions (D / μL). [23]defined a low degree of mixing when D / μL ≤ 0.02 and a high degree of mixing when D / μL ≥ 0.2. For an ideal piston flow reactor, the dispersion coefficient D / μL = 0, while D / μL = ∞, is expected in a perfectly agitated reactor. The values of the dispersion coefficient (Table 01) varied from 0.3 to 0.4, suggesting a moderate to high degree of mixing. A mean Peclet number, the inverse of the dispersion number (μL / D), of 2.73 also confirmed the large degree of dispersion Pe<5, as indicated by Fogler[24]. The presence of media did not increase the values of the dispersion coefficients, but the same results were verified in the studies by Morgan-Sagastume and Noyola[20]. The backward mixing can also be characterized by the value of N-CSTR, an N ⩽ 3 indicating a higher backward mixing [24]. Values ranged from 1.08 and 1.36 in supports.

III.2. Effect of the amount of support

The filling fraction is the ratio between the volume of bio-carriers and the total volume of the reactor. The main advantage of MBBR technology is the ability to design the reactor size for a certain filling fraction and, therefore, more volume of bio-carriers could be added. This allows either better performance or an increase in the volumetric capacity of the reactor itself. However, the mixing and the hydrodynamics of the reactor can be compromised, for example, by the development of stagnant or dead zones.

In this part, the effect of the filling rate on the hydrodynamic behavior of the reactor has been studied always in its own condition, tracing studies have been carried out by injecting varying amounts of support 0, 41, 82 and 165.2g, times of average stays of 131,197 min, 112.25 min, 95.0368 min and 90.4815 min were obtained for a feed rate of 0.816L.h^{-1}, an agitation speed of 100rpm and the different quantities of supports, respectively. The results obtained and all corresponding calculations are grouped in Table 2 and the output signals are shown schematically in Figures 5 and 6.

The hydraulic efficiency decreases while increasing the amount of support injected into the MBBR, it reached 89.21%, 76.33%, 64.62% and 61.52% for amounts of supports of 0, 41, 82 and 165.2 g, respectively. The average residence time is always lower than the theoretical value which is 147.058min, presenting a percentage of dead volume varying between 10.5% and 38%. As mentioned above, the use of supports contributes to improving the performance of the reactors but contributes to the creation of dead zones.

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Table 2. Results of RTDs obtained for different quantities of support

Feed rate ($L.h^{-1}$)	Support quantity (g)	stirring speeds($tr.min^{-1}$)	τ (min)	$\bar{\tau}_s$ (min)	σ^2	$\bar{\tau}_s/\tau$ (HE) (%)	σ_θ^2	$D/\mu L$	Pe	V_d(%)	N
Test 0 2											
0.816	**0**	100	147.058	131.19	20674.20	89.21	1.20	0.60	1.66	10.5	0.83
0.816	**41**	100	147.058	112.25	11750.65	76.33	0.93	0.46	2.17	23.5	1.072
0.816	**82**	100	147.058	95.03	8593.28	64.62	0.95	0.47	2.12	35	1.05
0.816	**165.2**	100	147.058	90.48	7585.06	61.52	0.92	0.46	2.17	38	1.086

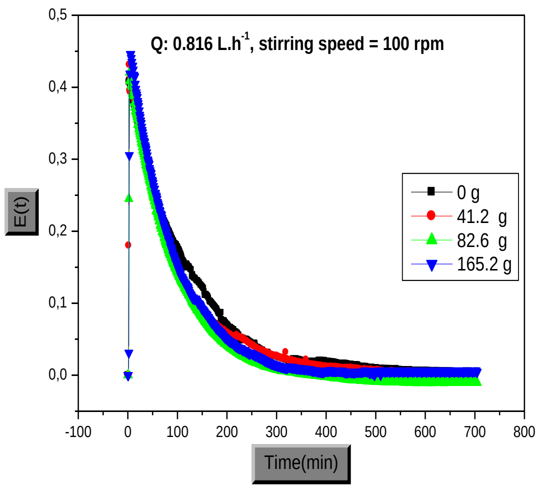

Figure 5. *The different distributions of the residence time for the different amounts of support (Feed rate:* ***0.816 L. h**^-1^*, Stirring speed:* ***100 rpm****)*

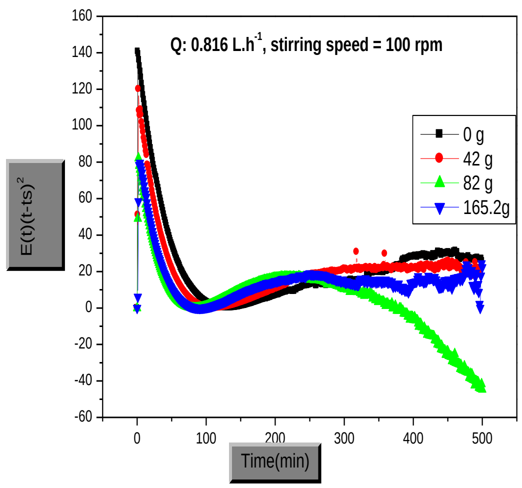

Figure 6. *Evolution of* $(t-\bar{\tau}_s)^2$ *E (t) as a function of time for calculating the variance for the different quantities of support (Feed rate:* ***0.816 L. h**^-1^*, Stirring speed:* ***100 rpm****))*

The number of dispersion varies between 0.4 and 0.6 in the reactor with and without support, the number of dispersion is always greater than 0.2, so we are in the case of high degree of mixing. It has been observed that the injection of the supports with different quantities into the MBBR has no effect on the dispersion coefficients (Table 02), and the number of dispersion without support is greater than those obtained with the different quantities of the support. N-CSTR number, varies between 0.83 and 1.

From these results, it is concluded that the amount of packing has greatly influenced the hydrodynamic behavior in the MBBR reactor. Some authors recommend that the filling fraction (percentage of the volume of the reactor occupied with supports in an empty tank) should vary between 60 and 70 % [25]and it must not exceed 70% to obtain adequate properties for mixing bio-carriers in aerobic systems [26]. In this study the maximum filling rate tested is 56% causing 38% of dead volume this is probably due to the geometric shape of the reactor used, exceeding this rate will certainly accentuate this percentage of stagnant areas and reduce the desired treatment performance.

III.3. Effect of feed rate

In this part, the effect of the flow rate on the hydrodynamic behavior of the MBBR was considered. The tracing studies were carried out by varying the flow rate of the clear water between 0.10 and 2 L.h^{-1}, a speed d agitation of 100 rpm and a quantity of support 165.2g. The results obtained and all the corresponding calculations are grouped in Table 3 and the output signals are shown diagrammatically in Figures 7 and 8.

n the various experiments carried out (Table 3), the average residence times obtained for the different flow rates tested are less than the estimated hydraulic residence times (Figure 9), this also reveals the same diagnosis of malfunction (the presence of dead zones). The effect is not regular this is due to the disturbance in the conductivity readings in certain situations caused by the high feed rate, but in general the increase in the feed rate has contributed to the reduction of dead zones, the percentage of Vd went from 38% for a supply flow of 0.10 L.h^{-1} to 5.47% for a supply flow of 2 L.h^{-1}, the increase in flow creates turbulence reducing stagnant areas caused mainly by the amount of support injected into the MBBR.

The number of disperses increases with the increase in the feed rate, so the behavior of the MBBR reactor, it is a perfectly stirred reactor, the same remark is observed for the Peclet number.

Table 3. *Results of RTDs obtained for different feed rates*

Feed rate (L.h^{-1})	**Support quantity (g)**	**stirring speeds(tr.min^{-1})**	**τ (min)**	**$\bar{\tau}_s$ (min)**	**σ^2**	***$\bar{\tau}_s/\tau$ (HE) (%)***	***σ_θ^2***	***D/µL***	**Pe**	**V$_d$(%)**	**N**
Test 03											
0.10	165.2	100	1200	743.683	309696.84	61.97	0.56	0.28	3.57	38	1.78
0.15	165.2	100	800	648.048	251826.80	81	0.60	0.30	3.57	19	1.78
0.25	165.2	100	480	370.703	95193.706	77.22	0.69	0.35	2.85	22.5	1.43
0.5	165.2	100	240	213.74	28502.91	89.05	0.62	0.31	3.22	10.95	1.61
0.816	165.2	100	147.058	90.4815	7585.064	61.52	0.92	0.46	2,17	38.48	1,08
2	165.2	100	60	56.72	2287.21	94.53	0.71	0.36	2.77	5.47	1.40

Algerian Journal of Environmental Science and Technology
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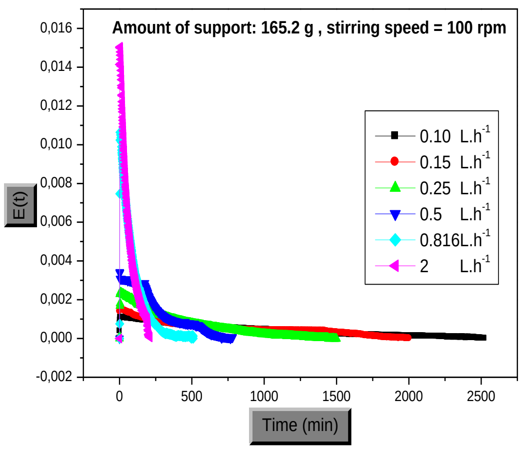

*Figure 7. The different distributions of the residence time for the different feed rates (Stirring speed: **100 rpm**, Amount of support of **165.2 g**.)*

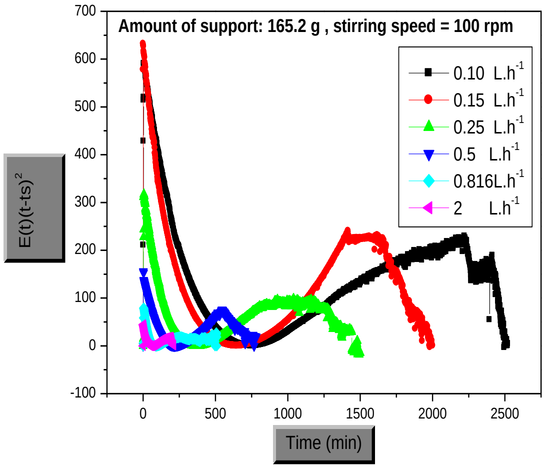

Figure 8. *Evolution of* $(t-\bar{\tau}_s)^2$ *E (t) as a function of time for calculating the variance for the different feed rates (Stirring speed: **100 rpm**, Quantity **165.2 g.**)*

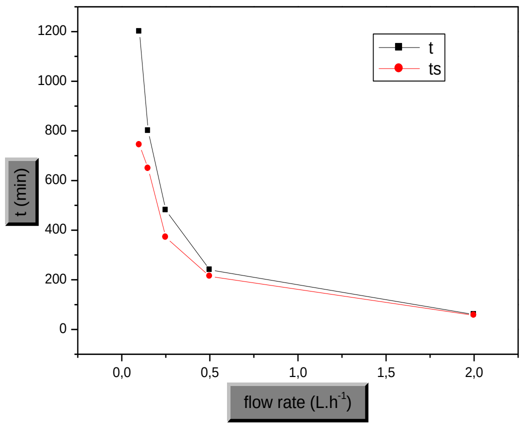

Figure 9. *Comparison between the residence time* τ *and* $\bar{\tau}_s$ *for the different feed rates (Stirring speed: **100 rpm**, Amount of support of **165.2 g**))*

IV. Conclusion

Before starting the biological denitrification studies in the biofilm and moving bed reactor packed with Kaldnes K1, an in-depth study was devoted to the hydrodynamic behavior of this reactor under different operating conditions and by varying the stirring speed, the quantity of packing injected and the feed rate of the influent.

The main purpose of this type of study is to collect enough data to be able to characterize the reactor, set the most appropriate operating conditions, propose a transport model and predict the performance of the biological reactor for a possibility of improvement or development in design.

First of all, it can be concluded that the behavior of the designed MBBR is a perfectly stirred reactor, the most significant effect on the hydrodynamic behavior and mainly on the detected malfunction (the presence of dead zones) is the fraction of filling by the padding used, the more this fraction is reduced the more the percentage of dead zones is minimized, this effect is reduced by increasing the feed rate which seems to be disgorged these zones, agitation does not have a significant effect especially for large fractions filling.

The stirring speed, the feed rate and the fraction of filling by the support used will be adjusted by taking into consideration the percentage of dead zones created by this choice, but also by taking into consideration the advantage of using this type of design. reactors in the biological denitrification of water, which is to achieve good degradation yields by ensuring that the conditions set do not alter and do not damage the development of biofilm on the walls of the lining.

V. Nomenclature

$\mathbf{E(t)}$ residence time distribution function (min^{-1})	$\boldsymbol{\mu}$ speed of the fluid(cm/s)
$\bar{\boldsymbol{\tau}}_s$ average residence time (min)	**L** axial distance (m)
$\boldsymbol{\mu}_n$ the moment	**D** axial dispersion coefficient (cm2/s)
$\boldsymbol{\mu}_1$ the moment of order (1)	$\boldsymbol{\sigma}^2{}_{\boldsymbol{\theta}}$dimensionless variance
$\boldsymbol{\mu}_0$ the moment of order (0)	**N** number of theoretical agitated reservoirs(dimensionless)
$\boldsymbol{\sigma}_t^2$ variance (min^2)	$\mathbf{V_d}$ Dead volume (L)
$\boldsymbol{\theta}$ dimensionless mean residence time	$\mathbf{V_R}$ reactor volume (L)
$\boldsymbol{\mu L/D}$ dispersion number (dimensionless)	**RTD** Resistance Time Distribution (min)

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