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Effects of temperature on the permeability and critical flux of the membrane in a moving bed membrane bioreactor

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ABSTRACT

Effects of temperature on the permeate flux and the permeability of the membrane have been studied in a membrane bioreactor system with a moving bed pilot plant to treat real urban wastewater. In the present study, the permeability of the membrane has been determined under four different suspended solids concentrations and three different degrees of fouling in order to compare the effects of the temperature in different operational conditions. The permeate flux, critical flux and permeability of the membrane at seven different temperatures between 10 and 35˚C have been checked. The study showed that the permeate flux increased to 19.2 and 21.2% between 10 and 15˚C and between 15 and 20˚C respectively, which was higher than the 8.70% obtained between 20 and 25˚C, and similarly it increased to 15.6 and 15.6% obtained between 25 and 30˚C and between 30 and 35˚C, respectively. This trend has been also observed in critical flux values, under the different conditions of suspended solids and fouling degree tested. The data obtained on the permeability of the membrane was fitted to a multiple linear regression using dynamic viscosity and temperature as independent variables.

Keywords: Temperature; Permeate flux; Critical flux; Permeability; Membrane bioreactor

1. Introduction

Membrane separation processes are widely used in water desalination, biochemical processing, industrial wastewater treatment, food and beverage production and pharmaceutical applications [1]. Membrane bioreactors (MBR) represent an attractive treatment technology in wastewater management since they produce a high quality effluent at a very low surface demand [2].

In practical application processes, the efficiency of membrane filtration and separation is limited by concentration polarization and membrane fouling problems [3]. Membrane fouling results from the interaction between the membrane material and the components in the activated sludge, so it is attributed to the physicochemical interactions between the biofluid and membrane [4] and it has been the main obstacle in the wide application of MBR, as it causes decreasing permeate flux or increasing

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transmembrane pressure (TMP) [5]. Fouling can take place through a number of physicochemical and biological mechanisms which all relate to increased deposition of solid material onto the membrane surface and within the membrane structure [6]. Membrane fouling is usually divided in two categories: (i) physically reversible fouling, which can be removed by physical cleaning because it develops from the accumulation of sludge particles whose particle sizes are larger than the membrane pore size, and (ii) physically irreversible fouling, which requires chemical cleaning [7] because it results from the attachment of colloids and solute inside the membrane pores [4]. The major factors affecting fouling described by Gao et al. [8] are biochemical kinetics parameters, temperature, membrane characteristics, characteristics of mixed liquor, operational style and reactor hydraulic conditions.

Many techniques have been implemented to reduce membrane fouling such as hydrodynamic factors considering feed pretreatment, working at sub-critical flux, backwashing, increase in shear stresses at the membrane surface and use of effective chemical cleaning agents [9]; however, the critical flux approach has opened up interesting perspectives, particularly sub-critical flux operations or close to them [10,11]. Judd & Judd explained the two distinct forms of the sub-critical concept which defined as [6]: (i) the flux obtained during sub-critical flux is equated to the clean water (CW) flux measured under the same conditions; (ii) the sub-critical flux is the flux rapidly established and maintained during start-up of filtration, but does not necessarily equate to the CW flux.

Temperature is an environmental variable that is difficult to control in a full wastewater plant but it must be considered in both biological and physical processes such as the membrane. The temperature in a wastewater treatment plant (WWTP) experiences daily and seasonal fluctuations [2]. Temperature influences on the microbial community, biological activity rate and sludge morphology [2]. The effects of the temperature on the biological process have been widely studied, including, for example, on the growth rate of wastewater bacteria [12], on the treatment efficiency, solids discharges, sludge physicochemical properties and microbiology [13] or under aerobic and anoxic conditions [14]. However, the temperature of the mixed liquor has also an important effect on the permeate flux and fouling of a membrane [4,15]. Fluctuation patterns of the filterability are coherent with seasonal temperature fluctuations [2], and deterioration of the activated sludge filterability in winter is a common observation in MBR installations treating domestic sewage [16–19]. Goosen et al. [1] showed that the flux can be improved with the change in the feeding temperature due primarily, though not completely, to viscosity effects on the water. The effect of temperature on membrane permeability due to the changes of viscosity can be described by Darcy's law. In the Darcy's equation, the permeation velocity is directly proportional to the TMP and inversely proportional to the total hydraulic resistance [20]. However, the observed seasonal changes in MBR cannot be explained only by changes in the viscosity [21].

The aim of the present study was to analyse and model the influence of the sludge temperature on the ultrafiltration membrane flux of a submerged membrane bioreactor with a moving bed, modifying the temperature of the sludge between 10 and 35°C. This study was done under three different membrane conditions (fouled membrane after operation, after chemical cleaning with hypochlorite and after chemical cleaning with hypochlorite and citric acid) and four different suspended solid concentrations in the membrane tank taking into account the rheological characteristics of the sludge to analyse the behaviour of the permeate flux.

2. Materials and methods

2.1. Experimental procedure

2.1.1. Description of the pilot-scale experimental plant

In this research, a pilot-scale experimental plant was used. A schematic of the process configuration and pilot plant used is shown in Fig. 1(a). The pilot plant was situated in the WWTP Puente de Los Vados, Granada, Spain. The urban wastewater used was taken from the outlet of the primary settler, so this wastewater had been mechanically pretreated before being fed to the pilot plant. The plant used had two bioreactors: a cylindrical bioreactor with operating working volume of 358 L, where carriers were contained and a rectangular tank with 87 L of operating volume in which three Zenon hollow fibre ultrafiltration membrane units were submerged. The biodegradation takes place in the first bioreactor (MB), followed by a membrane reactor with submerged modules where solid separation takes place. The modules used were ZW-10, whose configuration is outside/in hollow fibre with a nominal membrane surface area of 0.93 m^2, a nominal pore size of 0.04 and 0.1 μm of absolute pore size. The typical operating TMP of this module is 0.10–0.50 bar with a maximum TMP of 0.62 bar.

The carrier used was K1, which has been developed by AnoxKaldness. This carrier has been used in moving bed research [22–25] and is also used in several full-scale WWTPs [26–28]. It is a cylindrical high

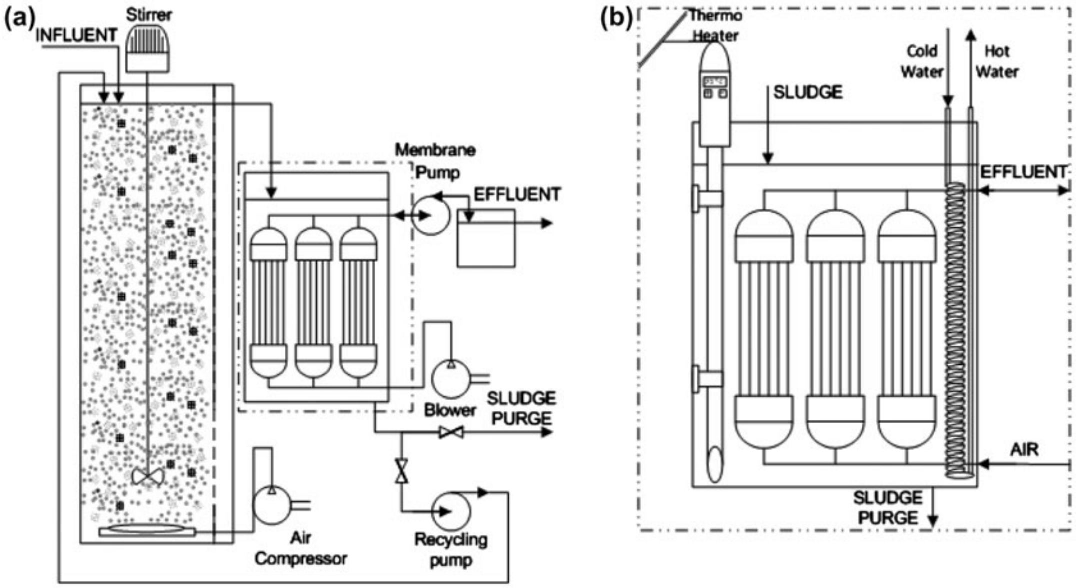

Fig. 1. (a) Schematic diagram of moving bed-membrane bioreactor pilot plant with three modules of ultrafiltration submerged membrane ZW-10 used in this research and (b) diagram of the membrane tank with the serpentine and thermoheater installed to modify the temperature.

density polyethylene ring with a cross-shaped cut-out of 11 mm in length, 10 mm in diameter and 7 mm in height. Its density is 0.92–0.96 g/cm^3 and its specific surface 800 m^2/m^3 with 500 m^2/m^3 of specific surface area protected. The carriers were contained in the cylindrical reactor with a 35% filling ratio (ratio between apparent volume of carrier and operative volume of bioreactor).

A serpentine and a thermo heater were installed in the membrane tank in order to modify the temperature of the feeding sludge of the membrane, (Fig. 1(b)). The serpentine was connected to a peristaltic pump to recycle cold water cooling the sludge from environmental temperature to 10°C. The thermoheater installed in the membrane tank serves to modify the temperature from 10°C to 40°C. The control of the temperature was carried out in the same tank to analyse the effect of the temperature in the filtrated sludge.

2.1.2. Operating conditions

The experiments done in the pilot plant consisted of measuring the permeate flow of the membrane, changing the TMP from 0.10 to 0.85 bars to analyse the behaviour of the membrane at critical situation of working. This allows us to obtain the relation between the permeate flow during a cycle of permeate (three replicates) and the TMP under the different conditions tested with the values of permeate flows in relation to the TMP needed to obtain it. Once the permeate flow (Q) was known in each TMP, the flux (J) was calculated as shown in Eq. (1), considering the membrane surface area (A):

$$J = Q/A \tag{1}$$

Permeability (K) was obtained from the flux and TMP, as shown in Eq. (2), taking the average value of the sub-critical interval.

$$K = J/\mathrm{TMP} \tag{2}$$

Field et al. defined critical flux as the flux which causes a very fast increase in TMP [29], so below critical flux conditions, an increase in the flux is correlated with a proportional increase in the TMP. The critical flux of the membrane under the different conditions studied was determined with the procedure described by Espinasse et al. [30] according to the definition of Field et al. [29].

The operative variables, which were checked included concentration of suspended solids, temperature and membrane condition. The first operative variable was the membrane condition and three different fouling degrees were tested. Firstly, the tests were done with the fouled membrane after the pilot plant had been working with a permeated flux of 6.82 $L/m^2\,h$ in phases of 9.75 min of permeating and 0.25 min of backwashing under a flux of 10.22 $L/m^2 h$. Table 1 shows the operation condition and duration for each concentration of MLSS tested. The duration and sludge retention time (SRT) in each condition was different as a consequence of the concentration of MLSS. The three different MLSS of the sludge were obtained by operating with the condition indicated in the Table 1. The duration of the cycle decreased when the concentration of MLSS increased from 27 to 11 d. SRT increased with MLSS due to the fact that the HRT was constant through the tests. These durations were defined according to a previous research [31], securing that the membrane had been fouled in a similar form.

Once the above conditions were tested, organic cleaning with hypochlorite (200 mg/L) was done for 4 h, and then same conditions were checked. When these tests were finished, organic and inorganic cleaning with hypochlorite (200 mg/L) for 4 h and then with citric acid (2 g/L) for 4 h at pH = 6 was carried out and then the same experiments were done.

The second operative variable was the concentration of suspended solids inside the membrane tank. The influence of the suspended solid concentration on the permeate flux was checked to study the direct effect of the viscosity on the permeability. Both CW and three different concentrations of suspended solids with different rheological characteristics were tested as shown in Table 1.

The third condition tested was the temperature. From the environmental temperature, the sludge was cooled down to 10°C using the serpentine. After tests were done at this temperature, the sludge was then heated to 15, 20, 25, 30 and 35°C. The temperature range in this research was chosen the same as that of the temperature of the bioreactor of the pilot plant in Granada (Spain) during the months between February and September 2011.

2.2. Physical and chemical determination

The solids in suspension were determined by gravimetric methods [32]. The viscosity of the activated sludge was measured at different temperatures with a viscosimeter (Brookfield, Model LVDVE) using a spindle number 18 and a small sample adapter at 60 rpm. The relationship between temperature (T) and dynamic viscosity (μ) was determined using Andrade's equation (Eq. (3)), fitting Andrade equation coefficients (A and B):

$$\mu = A \exp\left(-T/B\right) \qquad (3)$$

The viscosity obtained is related at 20°C in order to be compared. Since mixed liquor has non-Newtonian rheology, the viscosity obtained is the apparent viscosity.

Table 1
Operating conditions of the pilot plant (Hydraulic retention time, solids retention time and MLSS) and duration of the experiment according to each MLSS concentration studied

Sludge condition	Duration (d)	HRT (h)	SRT (d)	MLSS (mg/L)
I	27	24	7.06	933± 88
II	16	24	14.34	1,822 ± 19
III	11	24	20.04	2,800 ± 33

2.3. Scanning electron microscopy

After the different types of cleaning,membrane fibres were analysed by scanning electron microscopy (SEM). Individual pieces of the membranes were fixed with glutaraldehyde (5% v/v) in 0.2 M sodium cacodylate buffer (pH 7.1), washed, and post-fixed in OsO_4, before being dehydrated with graded ethanol solutions (10, 30, 50, 70, 90 and 100% ethanol). All chemicals were purchased from Sigma-Aldrich (St. Louis, MO, USA). The samples were transferred to fresh 100% ethanol, and critical point-dried with liquid carbon dioxide at 36.1°C and 7.37×10^{-5} bar, using a Samdri 780B apparatus (Tousimis, Rockville, USA). Samples were coated with gold before being examined by electron microscopy. Micrographs were taken with a JEOL JSM 5310LV microscope (JEOL Ltd., Tokyo, Japan) and analysed by the software provided with the equipment.

3. Results and discussion

Different fluxes were obtained in relation to the conditions tested. However, the same pattern of flux made it possible to define independently the temperature, concentration of suspended solids and membrane condition. The membrane flux increased when TMP increased, showing a linear correlation from 0.05 bar until critical flux. The slope decreased from critical flux. Therefore, the increase in the TMP did not show significant differences on the permeate flux. Table 2 shows the effect of the variables (temperature and concentration of suspended solids in the feeding sludge) in the permeate flux in relation to three of the TMP tested in the present research (0.1, 0.5 and 0.85 bar) under each membrane condition (fouled membrane after operation, membrane after chemical cleaning with hypochlorite and membrane after chemical cleaning with hypochlorite and citric acid). Each

Table 2
Flux of the membrane (L/m^2 h) under the minimum TMP checked (0.1 bar), maximum TMP typical operating (0.5 bar) and maximum TMP tested (0.85) with fouling at the three membrane conditions (fouled membrane after operation, membrane after organic cleaning and membrane after organic and inorganic cleaning) and the seven temperatures tested (10, 15, 20, 25, 30, 35℃). The values of suspended solids checked are 2,800 ± 33 (S1), 1,822 ± 19 (S2) and 933 ± 88 (S3) mg/L

			S1			S2			S3			CW		
	Temperature (℃)	TMP (bar)	0.10	0.5	0.85	0.10	0.5	0.85	0.10	0.5	0.85	0.10	0.5	0.85
Fouled membrane	10		1.61	7.53	9.89	1.72	7.96	10.22	1.83	6.67	10.65	2.37	8.39	13.87
	15		2.04	8.60	11.61	2.15	8.82	12.15	2.37	8.92	12.47	2.90	9.68	15.81
	20		2.58	9.78	13.66	2.90	9.89	14.41	3.33	11.51	15.16	3.44	11.72	17.74
	25		2.80	10.22	15.05	3.23	10.54	15.91	4.09	12.90	16.77	4.09	13.23	20.97
	30		3.12	10.97	16.13	3.55	11.29	17.31	5.05	14.19	18.71	5.05	15.38	23.44
	35		3.66	11.61	17.20	3.98	12.04	19.03	5.70	15.48	20.65	6.02	18.06	27.20
After organic cleaning	10		2.26	7.96	11.18	2.37	9.14	12.69	2.69	9.25	13.76	2.80	9.46	14.62
	15		2.47	9.89	14.84	2.58	10.75	15.27	3.01	10.86	16.77	3.12	13.01	22.04
	20		2.80	11.94	17.85	2.90	12.58	18.28	4.09	13.23	19.14	3.98	16.77	27.53
	25		3.23	12.80	19.57	3.33	13.76	20.00	4.19	14.41	21.72	4.41	18.06	28.82
	30		3.55	14.84	21.29	3.76	15.05	22.26	5.27	15.70	24.73	5.38	21.51	35.70
	35		3.76	15.91	22.47	4.73	18.17	25.70	5.38	18.49	29.25	6.13	23.66	42.69
After organic & inorganic cleaning	10		2.37	8.28	12.04	2.47	9.68	13.98	2.80	9.78	14.19	3.01	12.15	20.11
	15		2.80	9.89	15.05	2.80	10.86	16.13	3.12	10.97	17.20	3.66	13.98	23.23
	20		3.01	12.47	18.92	3.23	12.58	19.57	4.19	13.33	20.65	4.30	17.63	29.46
	25		3.33	13.55	20.43	3.87	14.19	22.15	4.30	14.52	22.80	4.62	18.49	30.54
	30		4.41	15.38	24.95	4.52	18.49	27.96	5.38	18.71	28.17	5.59	22.15	36.67
	35		3.87	18.39	28.60	5.59	21.94	31.61	5.38	23.66	35.05	7.31	28.39	45.81

column shows the average value of the flux of every temperature tested under the four situations of the concentration of suspended solids checked in the present study (2,800 ± 33, 1,822 ± 19 and 933 ± 88 mg/L and CW).

3.1. Effect of the temperature in the permeate flux

The operation of the membrane can be sensitive to changes in feed temperature [33–35]. This fact was checked in this study, with an average increase of 45.7% between 20 and 35℃ and 76.7% between 15 and 35℃. The permeate flux of the membrane increases with the temperature. With fouled membrane after operation with 2,800 ± 33 mg/L of MLSS, the permeability rises from 15.06 to 23.22 L/m^2 h bar. However, this difference increases with the concentration of suspended solids, when under the same membrane condition, CW and the same range of temperatures, the permeability increases from 16.78 to 36.12 L/m^2 h bar.

The flux increases when the temperature of the feeding sludge increases, but these increases are not proportional to the temperature. The average increase with the temperature depends on the temperature increase, the highest being between 10 and 35℃ with a value of 110.5%, while the lowest is between 20 and 25℃ with an average increase of 8.7%. Within a range of 5℃, it has been shown that the effect of the temperature is greater at lower temperatures than higher. Within the range between 10 and 15℃ and between 15 and 20℃, the average increase is around 20% (19.2 and 21.2% respectively), while at the highest ranges it is around 15% (15.6% between 25 and 30℃ and 15.6% between 30 and 35℃). The values of flux obtained in the present research are similar to the values obtained by Wang et al. [36] and higher than those of Lan et al. [37].

According to the definition of Field et al. [29], the critical flux of the membrane was determined in each condition tested. The value of critical flux also changed with the temperature, and the TMP of critical flux increases with the temperature, independently of the other variables. Table 3 shows the critical flux obtained under the different conditions of membrane and feeding sludge tested in relation to the temperature.

The effects of the temperature on the critical flux are clear. As the temperature increases the critical flux also increases by values around 100% between 10 and 35℃. Again the smallest difference is observed within the temperature range of 20–25℃. Poyatos et al. [31], with similar modules of the membrane, obtained a value of critical flux of 29.90 L/m^2 h, and the values obtained in the present research are similar, although the effect of the temperature is important as this research shows. After organic and inorganic cleaning, with the most concentrated sludge, the critical flux raised from 10.13 L/m^2 h to more than 28.61 L/m^2 h, the maximum value of flux obtained in the sub-critical range. The data on the critical flux are similar to the values reported by Jiang et al. [38] of around 30 L/m^2 h.

3.2. Effect of the membrane condition in the permeate flux

The fouling degree of the membrane is one of the most important aspects in the permeate flux of the membrane [37]. The same tests with changing temperatures and concentrations of suspended solid were conducted before, after organic cleaning and after organic and inorganic cleaning. The fouled and cleaned membrane surfaces were also examined using SEM, using the images to determine the efficiencies of the cleaning procedures such as Veerasamy and Ismail described [39]. One fiber of the membrane was collected in each condition for SEM analysis to determine the real effect of the cleaning on the membrane. Fig. 2 shows, with the same focus distance, the membrane under fouled membrane after operation (Fig. 2(a)), after organic cleaning (Fig. 2(b)) and after organic and inorganic cleaning (Fig. 2(c)). Before the organic cleaning, it was possible to see biomass attached to the fiber, including cells and bacterial and extracellular polymeric substances. Before and after the organic and inorganic cleaning, no differences were detected, and no organic corps matter was observed in any case. These data are according to the recovery values obtained.

The recovery of the membrane flux, measured at 20℃, was 43.9% with organic cleaning and 3.8% with organic and inorganic cleaning. The recovery of the membrane flux with the organic cleaning was similar to the value obtained by He et al. with the same reactive in a full-scale MBR [40]. The recovery after the inorganic cleaning was so low because the membrane had been working only during the tests after organic cleaning and the fouling was low. Indeed the inorganic fouling was generally lower because the feed of the pilot plant is pretreated urban effluent coming from a primary settler. The membrane condition affects the critical flux. As the fouling degree of the membrane decreases, the TMP value of the critical flux increases. With a temperature of 20℃ and an MLSS of 2,800 ± 33 mg/L, the TMP of the critical flux was 0.73, 0.76 and 0.78 bar before, after organic cleaning and after organic and inorganic cleaning, respectively. With a typical concentration of suspended solids in a MB-MBR process (2,800 ± 33 mg/L) and a medium temperature of 20℃, the permeability was 19.56, 23.88 and 24.94 L/m^2 h bar in the 3° of fouling tested, being higher when the level of cleaning is higher. However, the effect of the membrane condition on the permeate flux was greater with CW, as shown in Table 2, the temperature of the feeding sludge being at a maximum, and in these conditions the permeability rose from 36.12 to 56.78 L/m^2 h bar.

3.3. Effect of MLSS in the permeate flux

Another important aspect to consider in the permeate flux of a membrane is the concentration of suspended solids of the feeding sludge, the influence of which was evident across all the different conditions tested, as it is shown in Table 2. There are differences between the four concentrations of suspended solids, but the greatest increase obtained was with CW at a temperature of 35℃ after organic and inorganic cleaning of the membrane. The permeability was 36.78,

Table 3
Critical flux of the membrane (L/m^2 h) under different conditions tested. The values of suspended solids checked are 2,800 ± 33 (S1), 1,822 ± 19 (S2) and 933 ± 88 (S3) mg/L. The values not obtained are indicated by

	Fouled membrane			After organic cleaning			After organic & inorganic cleaning		
Temperature (℃)	S1	S2	S3	S1	S2	S3	S1	S2	S3
10	9.57	9.65	9.71	10.12	12.12	12.48	10.13	12.24	12.81
15	11.00	11.35	11.85	12.93	14.37	15.40	13.10	14.70	15.76
20	13.54	14.01	14.61	16.56	16.65	17.25	16.71	–	–
25	13.75	15.60	16.14	17.34	17.89	18.95	17.83	–	–
30	15.00	16.76	18.02	19.17	20.36	22.39	–	–	–
35	16.61	18.67	20.65	19.83	21.82	–	–	–	–

43.88, 47.32 and 56.76 L/m^2.h.bar with 2,833, 1,833 and 933 mg/L of suspended solids and CW, respectively. The concentration of suspended solids also affects the critical flux. The same trend was identified with the different degrees of fouling checked. However, the influence of the sludge is not only produced by dynamic viscosity [21]. Although dynamic viscosity increases with the concentration of suspended solids, the temperature is influential too [1]. In this research, similar values of dynamic viscosity were found with two different concentrations of sludge and two different temperatures, but the permeate flux was not the same. For example, before cleaning the membrane with 2,800 ± 33 mg/L of MLSS at 35°C, the dynamic viscosity was 3.54 cP, similar to the dynamic viscosity with 1,822 ± 19 mg/L of MLSS and 20°C (3.55 cP). However, the permeability was higher in the most concentrated sludge (23.22 L/m^2 h bar) than in the lowest concentrated (19.78 L/m^2 h bar) because the temperature was higher in the first one.

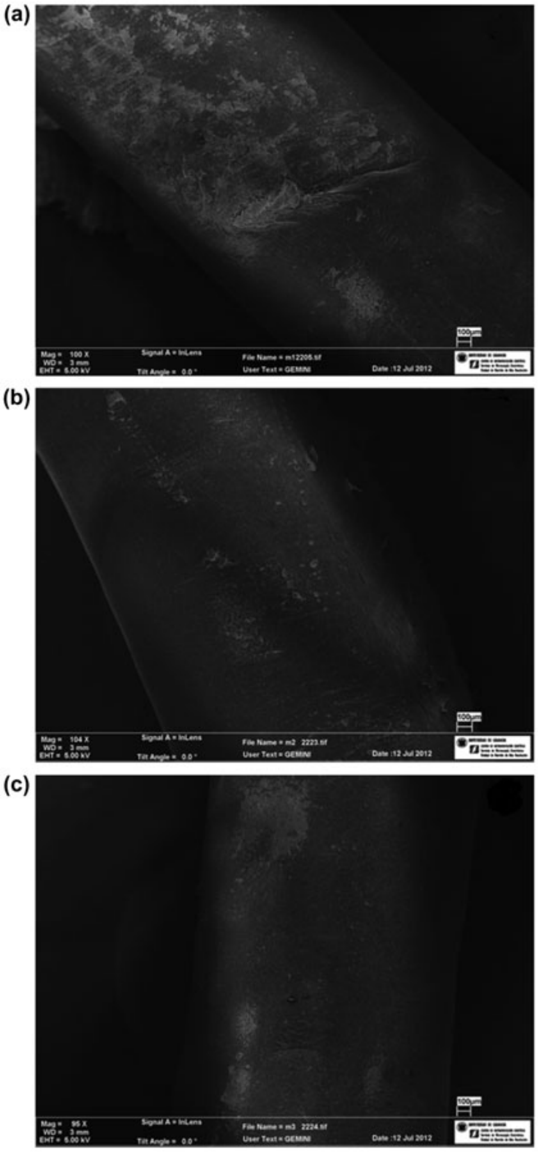

Fig. 2. Photograph of SEM analysis of the fibre of the membrane: (a) before, (b) after organic cleaning and (c) after organic and inorganic cleaning.

3.4. Permeability as a function of temperature and viscosity

The temperature has a double effect on the permeability of the membrane, on the one hand in the rheological properties of the permeate and on the other hand through the physical behaviour of the membrane. In order to model the permeability of the membrane under different membrane conditions tested in the present research, because the mixed liquor and temperature are related throughout viscosity, the dynamic viscosity was considered as the representative variable of the feeding sludge in the modelling of the permeability. So, in the model, permeability was defined in relation to the viscosity and temperature, where the temperature include the effects of physical behaviour in the membrane, under the different membrane conditions studied to carry out a multivariable analysis with a multiple linear regression.

The value of permeability used was defined as the average of the values of permeability in the sub-critical range (Table 4). Obviously, the variables studied (temperature, membrane condition and concentration of suspended solids) have the same effects in the permeability as in the permeate flux. Permeability increases with temperature and decreases when the degree of fouling and MLSS increase. Knowing the relation between the variable and the permeability, permeability values lower than the critical flux obtained in the research were fitted to a multiple linear regression. The fit obtained is shown in Eq. (4) (fouled membrane after operation), Eq. (5) (membrane after organic cleaning) and Eq. (6) (membrane after organic and inorganic cleaning), with correlation rates (R^2) of 0.893, 0.874 and 0.904, respectively.

$$K = 18.6459 + 0.5303 \times T - 2.5474 \times \mu \quad (4)$$

$$K = 22.1223 + 0.6893 \times T - 3.3136 \times \mu \quad (5)$$

$$K = 27.1302 + 0.7398 \times T - 4.5988 \times \mu \quad (6)$$

The sign of each proportional constant shows whether the relation is positive (permeability increases with

Table 4
Permeability of the membrane (L/m^2 h bar) under different conditions tested. The values of suspended solids checked are 2,800 ± 33 (S1), 1,822 ± 19 (S2) and 933 ± 88 (S3) mg/L and CW

	Temperature (℃)	S1	S2	S3	CW
Fouled membrane	10	14.49 ± 1.01	15.11 ± 1.18	14.58 ± 1.23	17.11 ± 1.37
	15	16.77 ± 1.09	17.35 ± 1.07	17.97 ± 1.54	19.57 ± 1.69
	20	19.24 ± 1.52	20.07 ± 1.93	22.94 ± 3.01	23.67 ± 2.85
	25	20.27 ± 1.59	21.57 ± 2.16	26.14 ± 4.18	27.26 ± 3.70
	30	22.30 ± 2.12	23.10 ± 2.44	28.94 ± 5.02	31.06 ± 4.06
	35	23.84 ± 2.73	24.91 ± 0.85	32.23 ± 6.08	36.64 ± 3.90
After organic cleaning	10	15.91 ± 1.62	17.82 ± 1.23	18.39 ± 1.38	18.96 ± 1.37
	15	19.53 ± 1.21	21.27 ± 0.97	22.29 ± 1.86	26.36 ± 0.80
	20	24.09 ± 1.41	24.97 ± 1.21	27.19 ± 1.86	34.07 ± 1.52
	25	25.84 ± 1.85	27.63 ± 1.52	30.33 ± 4.37	37.23 ± 2.37
	30	29.64 ± 1.49	30.87 ± 2.39	33.28 ± 4.69	43.89 ± 1.85
	35	31.89 ± 1.64	36.95 ± 4.92	39.72 ± 4.70	48.89 ± 1.77
After organic & inorganic cleaning	10	16.51 ± 1.95	18.60 ± 1.51	19.27 ± 1.45	24.63 ± 1.19
	15	20.77 ± 2.85	22.74 ± 2.07	23.39 ± 1.99	28.77 ± 2.11
	20	24.86 ± 1.12	24.93 ± 1.66	27.52 ± 3.83	35.37 ± 1.39
	25	27.40 ± 1.63	28.95 ± 2.63	30.74 ± 4.52	37.97 ± 2.43
	30	31.85 ± 3.66	36.50 ± 3.11	37.23 ± 3.34	45.24 ± 2.59
	35	37.22 ± 2.36	42.80 ± 3.65	44.84 ± 2.14	5.47 ± 2.45

temperature) or negative (permeability decreases when dynamic viscosity increases). The values of the constants depend on the membrane condition: when the fouling of the membrane decreased, the constants of the model presented a higher value, so the effect of the variable was greater too. Variables that were not controlled in the present study but that could affect the permeability of the membrane, such as pH or membrane characteristics, are included in the constant of the linear regression. This constant is higher when the cleaning degree is higher, so the permeability is higher too. The model shows the behaviour of the permeability observed in the research and that the two variables used in the model present a similar quantitative influence in the range of temperature (from 10 to 35℃) and dynamic viscosity (from 1 to 5 cP) tested. Independently of the membrane condition, the permeability estimated by the model showed an increase greater than 60% between 10 and 35℃ with a dynamic viscosity of 1 cP (increase of 62.0, 68.0 and 61.8% under fouled membrane after operation, membrane after organic cleaning and membrane after organic and inorganic cleaning, respectively). The variations due to the dynamic viscosity are of the same order of magnitude between 1 and 5 cP (typical values of the dynamic viscosity obtained during the research) and at a temperature of 20℃ the increase is higher than 60% too (61.7, 68.5 and 97.2% under fouled membrane after operation after organic cleaning and after organic and inorganic cleaning, respectively). In relation to the influence of the membrane condition at medium temperatures (20℃) and dynamic viscosity values (2.5 cP), the model represented an increase of 33.0% between the greatest and least degree of cleaning.

The data obtained in the present research show the importance of the temperature in the filtration of the membrane. The way in which the permeate flux changes can be predicted by a simple model.

4. Conclusions

Results were obtained under different temperatures conditions between 10 and 35℃, 3° of fouling (fouling membrane after operation, after chemical cleaning with hypochlorite and after chemical cleaning with hypochlorite and citric acid) and four concentrations of suspended solids in the feeding sludge studied. The conclusions were as follows:

- An average increase of the membrane flux around 20% (19.2 and 21.2%) within 5° is observed at lower temperatures (between 10 and 15℃ and between 15 and 20℃), while at higher temperatures this increase is reduced to about 15% (15.6 and 15.6% between 25 and 30℃ and between 30 and 35℃, respectively), but both are higher than 8.7% obtained between 20 and 25℃.

- The critical flux and permeability of the membrane increase with temperature (with the most concentrated sludge and fouled membrane after operation the critical flux rises from 9.57 to 16.61 L/m^2 h between 10 and 35°C) and the degree of cleaning (at 20°C with the most concentrated sludge the critical flux rises from 13.54 to 16.71 L/m^2 h) and decrease with dynamic viscosity (at 10°C and under fouled membrane after operation the critical flux falls from 13.87 to 9.57 L/m^2 h from the lowest concentration to the most concentrated sludge).
- The permeability of the membrane can be modelled linearly, with temperature and dynamic viscosity as independent variables, presenting a positive and a negative value, respectively, in the linear model, allowing us to predict the influence of the temperature on the operation of a membrane bioreactor plant. The model showed that the variation of the temperature and dynamic viscosity in the range studied is of the same order of magnitude (higher than 60% in both), that is also similar to the value of constant in the model, indicating that the influence of the temperature is as important as that of the dynamic viscosity.

In view of these results, the effect of the temperature that has been observed is greater at low and high than at medium temperature range. This effect is important in the performance of the WWTP with membrane, as temperature is an environmental parameter that is not possible to control.

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