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Studies on treatment of a thermo-mechanical process effluent from paper industry using ultrafiltration for water reuse

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ABSTRACT

The effluent generated at the thermo-mechanical process end of paper industry is a complex wastewater with high concentration of dissolved and colloidal substances and polyphenolic extractives. Based on the decrease of the turbidity and the removal of polyphenolic extractives during the chemical pretreatment, sodium hydroxide (NaOH) and sodium dodecyl sulfate (SDS) are found to be better for cleaning the effluent and making suitable for ultrafiltration (UF) experiments. During UF experiments, the flux evolution is found to be "classical" and clearly indicates that the increase of the cross-flow velocity produces a flux increase in the case of a molecular weight cut-offs 10 kDa polyethersufone membrane. As the "irreversible fouling" is more important with NaOH pretreatment effluent than with the SDS pretreatment effluent, it can be assumed that the SDS can increase solubility of low molecular weight lipophilic extractives in water phase. It is because of the fact that the hydrophobic core of surfactant micelles can accommodate a certain amount of lipophilic organic compound and consequently decrease the fouling potential of thermo-mechanical process effluent in UF process. With the combination of chemical pretreatment with UF process, a stable permeate flux was observed for a volume reduction factor equal to 5. This result showed that using NaOH or SDS as pretreatment for UF process improved the efficiency of thermo-mechanical process effluent treatment by increasing the membrane run time. The chemical oxygen demand value of permeate was below 250 mg/L which is suitable for reuse of water in the as process streams.

Keywords: Thermo-mechanical pulping; Ultrafiltration; Wood extractible; Colloidal effluent

1. Introduction

The pulp and paper industry is a very water intensive industry and ranks third in the world, after the metals and the chemical industries in terms of freshwater consumption. It is estimated that 273–450 m^3 of water is required to produce one ton of paper and for the same purpose about 60–300 m^3 of wastewater is discharged [1,2]. This huge volume of wastewater is mainly submitted to physicochemical (equalization, primary settling, and flocculation) and biological (activated sludge process) treatments [3]. However, the shortage of available water sources (due to the water scarcity and the limitations of groundwater use) and the competitive markets impose on many paper mills to make great effort to be more environmentally friendly, increasing the recycling of the treated wastewater in order to reduce the freshwater consumption

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and to lower the wastewater treatment plant capacity [4]. Advanced treatments, such as flotation [5], evaporation [6], and membrane filtration [7–9], are necessary to improve wastewater discharge quality and to reuse treated wastewater in process stream. The implementation of membrane technologies in the paper industry has a long history. In the early days, the membranes were used in the paper industry for concentration of dilute pulping wastes [10]. Nuortila–Jokinen et al. have valuable contribution in the implementation of membrane processes in the paper industry focusing on the problem of recirculation of water, e.g. the application of ultrafiltration (UF) and nanofiltration for paper machine circulation of water [11] make up water [12–14] and comparison of membrane processes for internal purification [15]. Membrane technologies have proved to be an attractive and effective method to purify discharged water for reuse in the paper manufacturing process. UF attracted the attention as a suitable method for the treatment of pulp and paper industry effluent, where most of the polluting substances consist of high molecular mass compounds. Furthermore, the UF has been widely described as a promising process for purification, concentration, and recovery of bioactive compounds.

During thermo-mechanical process for the paper manufacturing unit, wood and water stream have their first contact in order to produce the paper pulp. During this process, the water is recirculated to a high extent in a modern paper mills to minimize the consumption of water. Dissolved and colloidal substances (DCS) are released from the pulp and recirculated in these internal water loops. The water loops contain fine fibrous material which is due to the small size of these particles [16]. Other substances such as hemicelluloses, lignans, low molecular weight lignin, pectin's, wood resin, and phenolic extractives are also released to the process water [17–19], these substances, such as phenol extractives, are valuable compounds which could be utilized in food, pharmaceutical, and chemical industry. So, there is an interest to separate bioactive compounds from the process waters. One feasible alternative for separation of these compounds is UF [20–22]. However, fouling still limits the adoption of UF in pulp and paper mill waste water purifications. Different procedures have been developed for reducing the fouling effects, such as pre-treatment of the feed solution and improvement by operating conditions. The main objective of this study is to optimize a UF process with pretreatment of wastewater for reuse. The effect of various physical and chemical pretreatments, such as sodium dodecyl sulfate (SDS) and sodium hydroxide (NaOH), was investigated to make the wastewater suitable for UF application. The SDS surfactant has mainly been used as membrane cleaning product [23,24] and more recently used in the micellar enhanced ultrafiltration (MEUF) treatment for the removal and concentration of polyphenols and phenols [25,26]. The effect of operating conditions, such as transmembrane pressure (TMP), feed flow rate and volume reduction factor (VRF), on the membrane fouling was investigated. On the other hand, the recovery of polyphenols is also considered for its end use in various applied industries. Fig. 1 presents the schematic objective of this study.

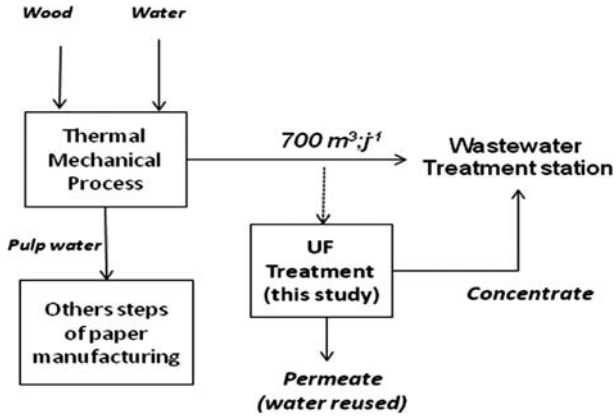

Fig. 1. Schematic representation of the objective of this study.

2. Experimental part

2.1. The thermo-mechanical process effluent

The actual industrial effluent which has been taken up for the study is generated from thermo-mechanical process of a paper industry. Fifty liters of the industrial effluent were taken and stored at initial consistency in a freezer at −24°C [27].

2.2. UF membrane and equipments

The used experimental set-up (Tangential Flow Filtration system, TFF) which was supplied by Pall cooperation France is shown in Fig. 2. Two Centramate™ Cassettes with Omega polyethersulfone (PES) membranes were used for this work. Polyethersulfone is widely used due to hydrophilic character, thermal stability, mechanical strength, and chemical inertness. According to the manufacturer, the effective membrane area is of 0.018 m^2 and the molecular weight cut-offs (MWCO) are 1 and 10 kDa for respective membrane. The temperature was maintained at 25°C for each experiment. During optimization of the operating

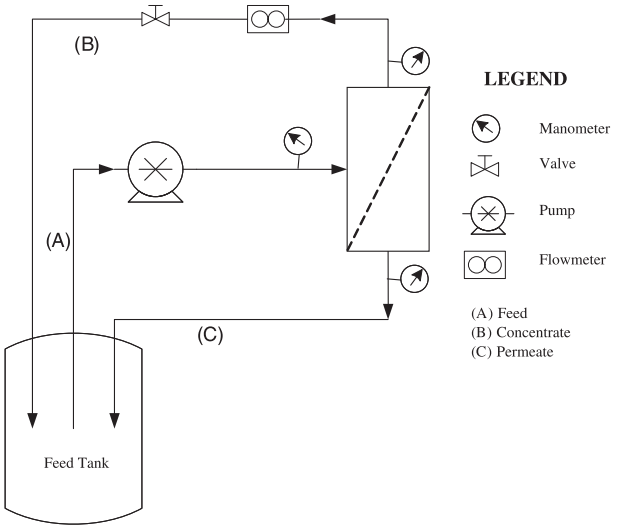

Fig. 2. Schematic representation of the UF experimental units.

conditions, the experiments were carried out at constant concentration (concentrate and permeate were circulated back to the storage tank). Then, the permeate was not recirculated for the concentration mode. The feed flow rate (Q_{Feed}) ranged from 100 to 800 mL min^{-1} and the limit pressure of the set-up is 6 bar.

2.3. Water flux and cleaning

Membrane permeability was determined using pure distilled water. Flux values of distilled water at different operating pressures were measured and were plotted against pressure difference. The average value of membrane permeability (J_0) as measured was 1,500 L m^{-2}h^{-1}bar^{-1} for the 10 kDa membranes and 90 L m^{-2} h^{-1} bar^{-1} for the 1 kDa membrane. After testing, the set-up was washed with pure distilled water and the water fluxes (J_i) were measured in the same conditions as for the permeability. The values reported in this work for these different fluxes are average values which result from the three experiments (the precision is about 5%). The membranes are cleaned after each run with the procedure described by the manufacturer, using NaOH (0.5 M) with NaOCl (400 ppm) that is circulated in close system at 35°C.

2.4. Analytical techniques

The chemical oxygen demand (COD), pH, total suspended solids (TSS), and the turbidity were measured based on the standard methods for the examination of water and wastewater [28]. The TSS concentration was determined by filtering a well-mixed sample through a glass fiber filter (Whatman Grade 934AH filters) and then the residue retained on the filter was weighed after being dried in the oven at 105°C for 12 h. The calibration of the turbidity apparatus (Turbidirect and Lovibond) was carried with the following standards solutions: 0.1, 20, 200, and 800 NTU. Total polyphenols in the actual paper industry effluent were estimated spectrophotometrically by the Folin–Ciocalteu method (Boizot and Charpentier, 2006) and using Gallic acid as reference standard [29]. The particle size was measured by using Malvern Zetasizer Nano series supplied by Malvern instruments. The technique of dynamic light scattering (DLS) is used for the determination of the size of particles in the nanometer range. The Malvern Zetasizer Nano series uses patented optics that provides exceptional levels of sensitivity and enable the determination of particle size in samples. The instrument offers size measurement in a single system allowing the generation of information important in determining dispersion stability and understanding and controlling the behavior of nanoparticles in dispersion. The rejection ($R\%$) and the VRF were calculated by the following equations:

$$R\% = 100 \times \left(\frac{1 - C_p}{C_f}\right) \quad (1)$$

$$\mathrm{VRF} = \frac{V_f}{V_c} \quad (2)$$

where C_p and C_f are the permeate and the feed concentrations, respectively, and V_f and V_c are the initial volume of the feed and the final volume of the concentrate, respectively.

2.5. Pretreatments

The centrifugation was carried out at 4,000 rpm for 20 min with [Allegra X15R] supplied by Beckmann Coulter, USA. Filtration was made using 0.2 μm rated AERVENT^{TM} 50 cartridge filter supplied by Millipore, France. Adsorption of colloidal particles was carried out using macroporous resin AMBERLITE XAD-7 and polyvinylpolypyrrolidone, PVPP (Sigma Aldrich) in adding an amount of adsorbent (50 mg) with 100 mL of effluent. The pH of the tested solutions ranged from 3 to 8. The pH adjustment was made by the addition of 0.1 M NaOH or 0.1 M HNO_3. The effluent was also subjected to pretreatment with SDS that is the well-known anionic surfactant in chemical world and it is produced from Sigma Aldrich. A fixed amount of SDS was mixed with 100 mL of effluent using magnetic stirrer for 30 min and then allowed to settle the particles.

3. Results and discussion

3.1. Characteristics of the effluent of the thermo-mechanical process

Average values of effluent characteristics are presented in Table 1. The discharged effluent is diluted to measure the turbidity. The colloidal nature of effluent is very high. The colloidal particles are stable with poor aggregation sensitivity that is due to a steric stabilization [30] by wood polymer, e.g. polysaccharides (mainly galactomananes from hemicelluloses fraction) and electrostatic stabilization [31] by carboxyl and hydroxyl groups present on the surface. According to Puro et al. [22], such colloidal particles are for instance lipophilic extractives, generally called as wood resin. Particle size measurements showed a modal distribution with an average particle diameter equal to 283 nm. It is interesting to compare this result with the discharge effluent from thermo-mechanical process loops and the results of Nylund et al. [32]. They investigated the character and the stability of dispersed colloidal substances present in aqueous suspensions of unbleached thermo-mechanical pulp. Particle size measurements showed a bimodal size distribution and the electron micrographs revealed that the particles were spherical in shape with a diameter less than approximately 300 nm. Other authors also confirmed this result [33–35]. As the effluent is frozen, the effluent characteristics are constant at each occasion of the UF experiments. The total polyphenols concentration is about 430 mg L^{-1}.

Table 1
Characteristic of the actual thermal mechanical process effluent

Turbidity	1,050 NTU
Color	Dark Brown
pH	6.1
COD	4,230 ± 30 mg O_2 L^{-1}
Suspended solid	450 mg L^{-1}
Total polyphenols	430 mg L^{-1}
Average particle size	283 nm

3.2. Pretreatment studies

The effluent obtained from paper plant was colloidal in nature with a high fouling character and was not suitable for direct UF experiments. The effect of different physical–chemical pretreatments was investigated in order to reduce its fouling character to make it suitable for UF experiments. The effect of centrifugation, filtration, and adsorption on the particles size and turbidity was first investigated and the results are presented in Fig. 3. The centrifugation at 4,000 rpm for 20 min does not have much visible effect on the nature of effluent which is justified by observed insignificant change in colloidal nature of effluent. The filtration using 0.2 μm filter was found to be effective for the turbidity (~280 NTU) but it was very slow. Adsorption of colloidal particles using AMBERLITE XAD-7 and PVPP (0.5 g L^{-1}) was also studied. Though XAD-7 was better in reducing the colloidal particle size and the turbidity, 205 nm and 510 NTU, respectively, but

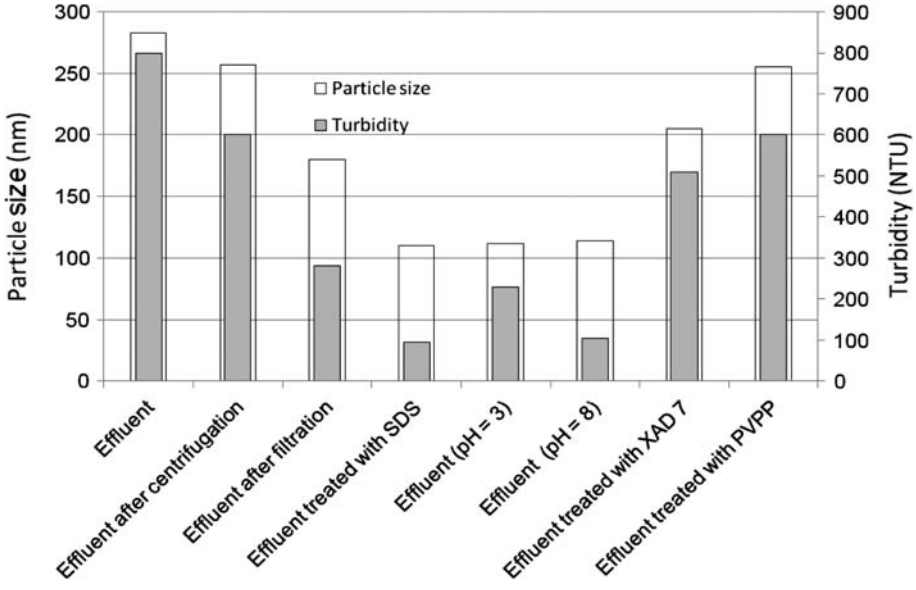

Fig. 3. Effect of physical and chemical pretreatments on particle size and turbidity.

the effect was not enough to remove the colloidal particles and to clear the effluent for UF experiments. The variation of the adsorbent amount does not change significantly the results. Indeed, the turbidity of the effluent after adsorption is always higher than 500 NTU, whatever the amount of adsorbent is.

The effluent was subjected to chemical pretreatments to remove foulants including stable thermo-mechanical process colloids. Their effect on colloidal particle size and turbidity was investigated and results are also presented in Fig. 3. The results about the effect of pH by addition of HNO_3 and NaOH show that the effluent contains less colloidal particles and becomes significantly clear, the turbidity is 105 and 230 NTU for pH = 8 and pH = 3, respectively. As a well-know surfactant in Chemistry, the effect of SDS (CH_3 $(CH_2)_{11}O$-SO_3Na) on chemical treatment of thermo-mechanical process effluent was investigated. For the pretreatment of effluent, the concentration of SDS ranges from 4×10^{-2} M to 4×10^{-1} M. This concentration range is higher than the critical micellar concentration (CMC) of the used surfactant SDS in distilled water which is 9.7×10^{-3} M [36]. It was observed that the turbidity decreases at 95 NTU for a SDS concentration of 4×10^{-1} M. Either the addition of HNO_3 or NaOH or SDS was equally good in reducing the colloidal particle size to almost same extent to around 110–115 nm.

The effect of the pH and surfactant (SDS) on the concentration of polyphenolic compounds was investigated and results are presented in Fig. 4. Results indicate that the loss of polyphenolic compounds is much higher with the SDS than with the variation of pH (acid or alkali media). The concentration of phenolic compounds in effluent decreases with the increase of SDS concentration. The loss of phenolic compounds is about 63% for a concentration of 4×10^{-2} M. It can be suggested that beyond the CMC, the surfactant molecules aggregate into structures known as micelles and then these latter can facilitate the solubilization of organic matters and integrates them into its hydrophobic core to form large organic compounds–surfactant structures [25]. On the other hand, the pH is a key factor influencing the physical–chemical behavior of phenolic compounds, for instance their adsorption with the colloidal extractives particles contained in thermo-mechanical process effluent [37]. Consequently, the variation of pH leads to changes in the attraction and repulsion forces inter and intramolecular and can also affect the solubility and the molecular conformation of polyphenols and the interactions with the carboxyl and hydroxyl groups on the surface of colloidal extractives particles. At acidic pH, the uptake of phenolics by different colloidal extractives particles is enhanced, because the phenolic compounds are undissociated and the dispersion interactions predominate. At alkaline pH, the phenomena of adsorption may decrease since the dissociation of hydroxyl groups and carboxyl groups occur.

Out of all these chemical tested for pretreatment, NaOH and SDS were selected for chemical pretreatment of larger volume of actual effluent collected from the site of paper industry. Though SDS leads to significant loss of polyphenols, its behavior was investigated in order to decrease fouling potential of effluent in UF. In tanks containing 10 liters of effluent, pH was adjusted at 8 in the first tank and SDS was added with a concentration of 4×10^{-2} M. The mixture was mixed thoroughly using magnetic stirrer for 30 min and then allowed to settle the suspended colloidal particles. The solution was centrifuged and the clear solution was stored before UF experiments.

3.3. Optimization of UF operation

The most important parameter in the membrane filtration processes is the permeate flux which is influ-

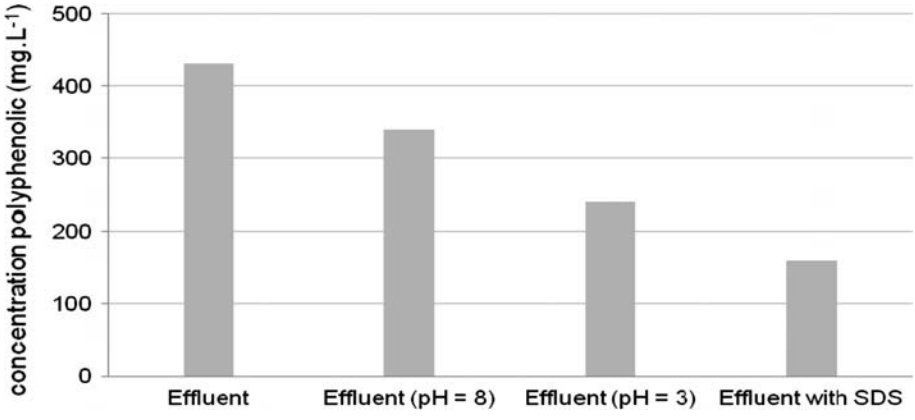

Fig. 4. Effect of pretreatments on the concentration of polyphenolic compounds, (SDS) = 4×10^{-2} M.

enced by the TMP and the cross-flow velocity or its equivalent feed flow rate. In order to establish their influence, total recycling mode is performed for each experiment which lasted around 120 min, times enough for reaching stationary state conditions, and then state steady permeation flux is measured. The variation of permeate flux with the increase in the TMP at three feed flow rates is shown in Figs. 5–8 for both the membranes (10 and 1 kDa). The effluents used in the case of both the membranes are pretreated by NaOH and SDS, respectively. The trend of variation in case of 10 kDa was found to be similar for effluents treated by both NaOH and SDS. As it is seen, the permeate flux increases when the TMP increases and at higher pressures, almost a constant value of permeation flux is reached. This effect is caused by the formation of a cake layer on the membrane surface, which accelerates the membrane fouling as observed by other authors also [38,39]. The TMP at which a constant value of permeation flux is reached can be considered as the optimum, because in that range of TMP the tendency to cake layer formation and the subsequent fouling effect is low. Once the permeate flux constant value is reached for this limiting TMP value, the membrane fouling by cake formation layer formation is enhanced and it is not interesting to work with a higher TMP [40–41].

Figs. 5 and 6 reveal that cake formation and limiting fluxes occurred to different feed flow rates at different TMP values. As it is seen, permeate fluxes increase when the feed flow rate is increased, probably due to an increase of the turbulence at the membrane interface, which removes some of the accumulated components in the cake layer by hydrodynamic forces, and thus reducing the cake and

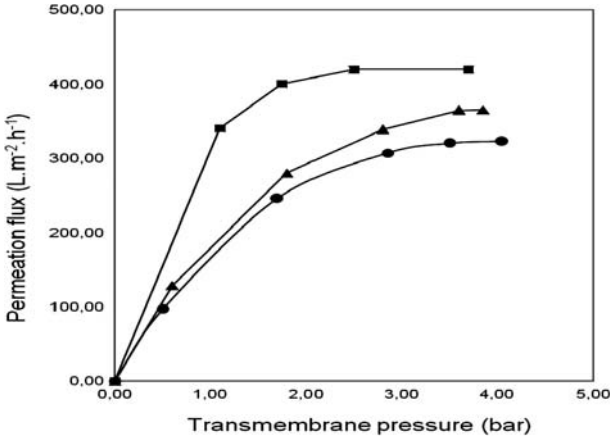

Fig. 5. Effect of TMP on the permeate flux at 20°C with 10 kDa membrane–SDS pretreatment (Q_{Feed}: ■ 0.6 L h^{-1}; ▲ 0.4 L h^{-1}; and ● 0.3 L h^{-1}).

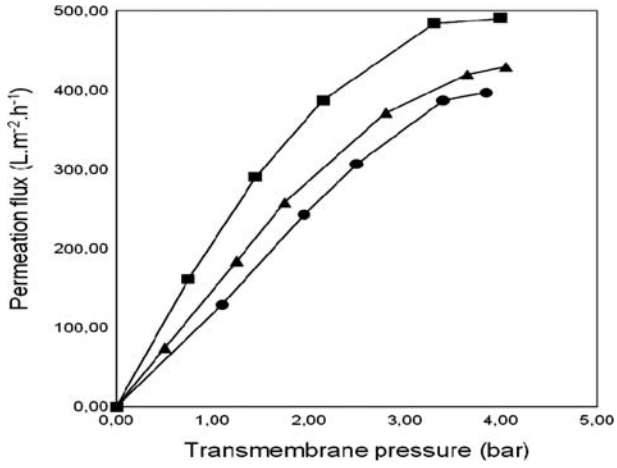

Fig. 6. Effect of TMP on the permeate flux at 20°C with 10 kDa membrane—NaOH pretreatment, pH = 8 (Q_{Feed}: ■ 0.6 L h^{-1}; ▲ 0.4 L h^{-1}; and ● 0.3 L h^{-1}).

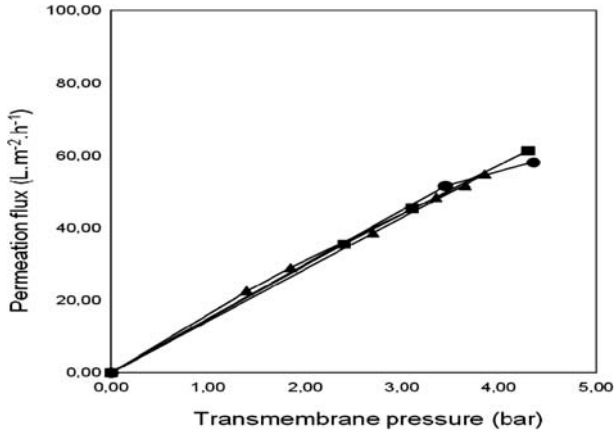

Fig. 7. Effect of TMP on the permeate flux at 20°C with 1 kDa membrane—SDS pretreatment (Q_{Feed}: ◆ 0.8 L h^{-1}; ■ 0.6 L h^{-1}; ▲; 0.4 L h^{-1}; and ● 0.3 L h^{-1}).

polarization layer. The permeate flux obtained is also higher with NaOH pretreated effluent than those with the SDS pretreated. For example, when the effluent obtained with the NaOH pretreatment is ultrafiltrated through the MWCO 10 kDa membrane under TMP of 4 bar and feed flow rate of 0.6 L h^{-1}, a steady-state flux of 490 L m^{-2} h^{-1} is reached whereas the membrane produced a 15% lower flux with the SDS pretreated effluent, with a steady-state flux of about 420 L m^{-2} h^{-1}. When a TMP higher than 2.5 bar was applied for the SDS pretreatment effluent, an increase in the feed flow rate above 0.6 Lh^{-1} did not improve

membrane fluxes, probably because under these conditions, the permeate flux was limited by the dense structure of the deposited fouling layer which is formed by the SDS micelles. A TMP higher than 3 bar can be applied for the NaOH pretreatment effluent.

In order to understand the flux decline mechanism, the permeability, J_0, and the flux of water after experiments, J_i, were compared. According to the literature [42,43], the flux decline can be decomposed into a reversible and an irreversible component. The fraction of the initial water flux which cannot be recovered by a water washing is called irreversible fouling and is related to adsorption or precipitation and/or membrane pore clogging by organic and inorganic compounds. It is observed that the "irreversible fouling" is more important with NaOH pretreatment effluent than with the SDS pretreatment effluent. Indeed, the flux of water after experiments in the first case is very lower ($J_i = 220\,\mathrm{L\ m^{-2}\ h^{-1}}$) than the one measured in the second case ($J_i = 872\,\mathrm{L\ m^{-2}\ h^{-1}}$). According to Puro et al. [22], the lipophilic extractives, such as fatty and resin acids in pulp and paper mill process water, fouled the membranes and their adsorption on the membrane is at least one of the fouling mechanisms. It can be assumed that the SDS can increase solubility of low molecular weight lipophilic extractives in water phase because the hydrophobic core of surfactant micelles can accommodate a certain amount of lipophilic organic compound as explained by several authors [44,45]. Consequently, the adsorptive fouling may be lower with the SDS pretreatment effluent.

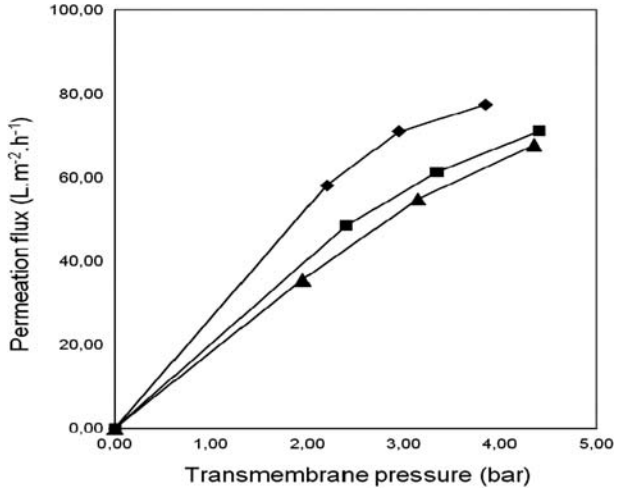

Fig. 8. Effect of TMP on the permeate flux at 20°C with 1 kDa membrane—NaOH pretreatment, pH = 8 (Q_{Feed}: ◆ 0.8 L h^{-1}; ■ 0.6 L h^{-1}; ▲ 0.4 L h^{-1}).

As it is shown in Figs. 7 and 8 for the 1 kDa membrane with both pretreated effluents, the permeate flux increases when the TMP increases and no constant value of permeation flux is reached. Furthermore, it is interesting to observe that the variation of permeation flux with TMP is linear in the case of the MWCO 1 kDa membrane with the SDS pretreatment effluent. The feed flow rate, from 0.2 to 0.8 L min^{-1}, does not affect the permeate flux. This result indicates less severe fouling phenomena. However, the permeate fluxes with the MWCO 1 kDa membrane are much lower than the flux obtained with the MWCO 10 kDa membrane. For example, the MWCO 1 kDa membrane with the NaOH pretreatment effluent produced about 80% lower flux with the MWCO 10 kDa membrane.

The polyphenols concentration in permeate is described in Table 2 for both membranes and both types of pretreatments. The permeate solution is clear and slightly yellow. The MWCO 10 kDa membrane retains a higher part of polyphenolic compounds with NaOH pretreated effluent than with SDS pretreated one, i.e. 94.1 and 62.5%, respectively. The polyphenolic compounds after SDS pretreatment are better retained in the concentrate with the MWCO 1 kDa membrane than with the MWCO 10 kDa membrane. This result shows that the MWCO 10 kDa membrane does not remove the lower molecular weight polyphenolic compounds.

3.4. Influence of concentration on UF performance

The treatment of actual effluent of paper industry requires a maximal recovery rate in order to obtain a permeate which can be reused. For this investigation, the UF set-up was run in the concentration mode and the 10 kDa membrane was used. Effects of the VRF on flux are shown in Fig. 9 for

Table 2
Polyphenols concentration of thermo-mechanical process wastewater and of permeate (TMP = 3 bar and Q_{Feed} = 0.6 L h^{-1})

	10 kDa membrane		1 kDa membrane	
	pH = 8 (NaOH)	SDS	pH = 8 (NaOH)	SDS
Pretreated effluent	340	160	340	160
Permeate	20	60	5	15
% Rejection	94.1	62.5	98.5	90.6

both pretreated effluents (NaOH and SDS). The pH was adjusted at 8 with NaOH and SDS was added with a concentration of 4×10^{-2} M. Present study conducted on paper industry effluent indicates that hydrodynamic parameters can significantly affect performances of UF process. The applied pressure and feed flow rate were fixed at 3 bar and 0.6 $L h^{-1}$ for the 10 kDa membrane. A clear decline of permeate flux occurs with the increase in VRF due to increasing fouling effect on the membrane. Moreover, this curve could be divided into two segments, an initial stage with a rapid decrease of the permeate flux and a second stage with a very slight decrease in J to reach a steady-state. The permeation flux for the NaOH pretreated effluent was 165 $L m^{-2} h^{-1}$, whereas it was 186 $L m^{-2} h^{-1}$ for the SDS pretreated effluent which gets quickly stabilized.

On the basis of results presented above, this behavior of effluents may be attributed to the concentration polarization, namely the extractive lipophilic compounds for the NaOH pretreatment effluent and in the case of the SDS pretreated effluents, micelles deposited quickly on the membrane surface and blocked in the membrane pores in a short time. While the concentration of colloids and particles increases in the concentrate, the thickness of the layer is controlled by hydrodynamic parameter. From a certain thickness, the feed flow rate favors the back migration of potential foulants from the membrane surface to the bulk liquid phase. Coupling chemical pretreatment with UF process, a stable permeate flux was observed for a VRF equal to 5. This result showed that using NaOH or SDS as pretreatment for UF process improved the efficiency of thermo-mechanical process effluent treatment by increasing the membrane run time. The characteristic of permeate and concentrate at the end of the concentration are given in Table 3. The permeate quality obtained at 3 bar satisfied the actual process water quality for COD parameter. The COD value of permeate was below 250 mg/L which is suitable for reuse as process water. As a conclusion, it was observed that the resulting permeate was colorless and free from suspended solids.

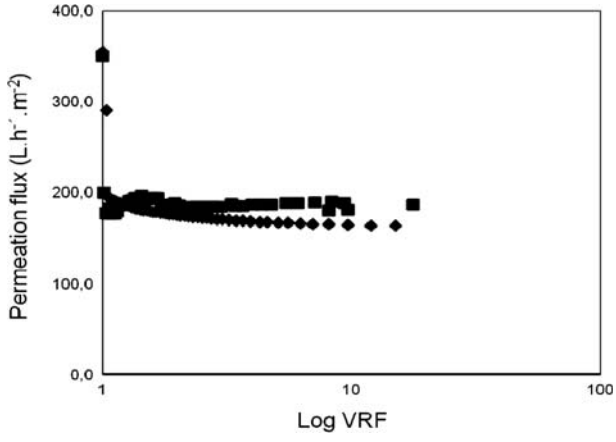

Fig. 9. Evolution of the permeation flux with the volume retention factor with the following conditions: 10 kDa Membrane, TMP = 3 bar, and Q_{Feed} = 0.6 L h^{-1} (◆ NaOH pretreatment and ■ SDS pretreatment).

Table 3
Characteristics of permeate and concentrate at the end of the concentration (PTM = 3 bar and Q_{Feed} = 0.6 L h^{-1})

	10 kDa membrane	
	NaOH pretreatment	SDS pretreatment
Initial polyphenols concentration (mg L^{-1})	340	160
Polyphenols concentration in permeate (mg L^{-1})	50	71
Polyphenols concentration in concentrate (mg L^{-1})	1,490	495
VRF	5	6.7
$COD_{permeate}$ (mg L^{-1})	180	230

4. Conclusion

The actual effluent obtained from paper plant was colloidal with a high fouling character and was not suitable for direct UF experiments. Amongst different physical–chemical pretreatments tested, NaOH and SDS were selected for chemical pretreatment of larger volume of actual effluent because they reduce the colloidal character of the effluent without a high loss of polyphenolic compounds. It is interesting to observe that the "irreversible fouling" is stronger with NaOH pretreatment effluent than with the SDS pretreatment effluent. It can be assumed that the SDS can increase solubility of low molecular weight lipophilic extractives in water phase because the hydrophobic core of surfactant micelles can accommodate a certain amount of lipophilic organic compound. In concentration mode, the permeate quality obtained at 3 bar and with VRF higher than 5 satisfied the actual process water quality for COD parameter. The COD value of permeate was below 250 mg/L which is suitable for reuse as process water.

Abbreviations

DCS	—	dissolved and colloidal substances
SDS	—	sodium dodecyl sulfate
MEUF	—	micellar enhanced ultrafiltration
TMP	—	transmembrane pressure, bar
Q_{Feed}	—	feed flowrate, mL min^{-1}
VRF	—	volume reduction factor
PES	—	polyethersulfone
MWCO	—	molecular weight cut-off, g mol^{-1}
J_0	—	membrane permeability, L m^{-2} h^{-1}
J_i	—	water flux after experiment, L m^{-2} h^{-1}
COD	—	chemical oxygen demand, mg O_2 L^{-1}
TSS	—	total suspended solids, mg O_2 L^{-1}
$R\%$	—	rejection, %
C_p	—	permeate concentrations, mol L^{-1}
C_f	—	feed concentration, mol L^{-1}
V_f	—	initial volume of the feed, L
V_c	—	final volume of the concentrate, L
CMC	—	critical micellar concentration, mol L^{-1}

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