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Alcohol Removal From Beer by Reverse Osmosis

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Abstract: In this work reverse osmosis technology was used for removing alcohol from beer. The process was carried out in a diafiltration mode and it was possible to obtain a final beer with low ethanol content (less than 0.5% v/v). Several cellulose acetate and polyamide membranes were tested with transmembranar pressures ranging from 20 to 40 bar. Temperature and feed flowrate varied from 5 to 20°C and from 2 to $7\,\mathrm{l \cdot min^{-1}}$, respectively. It was observed that permeate flux and alcohols rejection increase with the feed pressure, whereas esters rejection decreases with pressure. Permeate flux increases with temperature, while rejections decrease with it. Concentration polarization occurs at low feed flowrates.

Keywords: Reverse osmosis, beer dealcoholization, membrane selection, cellulose acetate, polyamide

INTRODUCTION

Nowadays a significant increase is observed in the consumption of non-alcoholic beverages, which is mainly due to medical or health reasons. In addition, people are becoming aware of problems that alcohol can bring regarding civic responsibilities.

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There is a suitable range of processes for producing non-alcoholic (ethanol content less than 0.5% by volume) or low alcohol beer (ethanol content less than 1.0% by volume). These can be divided in processes of restricted alcohol formation and in alcohol removal processes. The last ones include heat- and membrane-based processes. In heat treatment processes alcohol can be removed from beer by vacuum distillation or water vapor stripping under vacuum. In vacuum distillation beer is heated under vacuum and ethanol is removed by fractional evaporation in a distillation column, while in stripping the alcohol is removed from beer by a stripping medium (e.g. water vapor), which contacts with beer in a counter-current flow. In membrane separation processes alcohol can be removed by dialysis or reverse osmosis (1).

In the reverse osmosis (RO) process, the product to be treated flows tangentially to the membrane surface and a portion of the feed flowrate (permeate) crosses the membrane selectively, while the other fraction (retentate) remains in the feed side. This kind of process is called cross-flow filtration or tangential filtration (1). The RO occurs when the transmembranar pressure exceeds the osmotic pressure (2). This principle can be applied to remove alcohol from beer if a membrane semi-permeable to the ethanol is used. Ethanol (and water) permeates the membrane against the osmotic pressure and is recovered in the permeate side. On the other hand, larger molecules, such as beer aroma and flavor compounds, mostly remain at the retentate side (concentrated beer).

Beer aroma profile consists of a large group of volatile organic compounds (VOCs) at low concentration (ppm level), that are responsible for the odor and taste of beer (3–6). These beer aroma compounds can belong to several functional group categories such as alcohols, esters, aldehydes, lactones, carboxyl acids, phenols, and ethers (4, 5). Each aroma compounds group is responsible for a typical flavor. High alcohols, for example, which are the major group of aroma compounds in the beer (ethanol is the compound in highest quantity), provide an alcoholic, fruity, and immature flavor. Esters confer a sweet and fruity flavor to the beer, while aldehydes are associated to the freshness (immaturity) of the beer (7).

The RO process has some advantages compared to other dealcoholization processes. RO requires low energy consumption compared to distillation processes and the feed beer can be processed at low temperatures (ranging from 1 to 5°C). The low alcohol beer quality is similar to the standard beer because RO semi-permeable membranes are specific to retain the larger beer flavor and aroma compounds. These characteristics contrast with the ones assigned to the heat processes, where temperature sensitive compounds can suffer some damages (chemical alterations and physical losses), and with restricted alcohol processes, where the fermentation is stopped and the beer aroma does not develops such as in a regular alcoholic beer (1). Besides these advantages, RO is a very versatile process since various beer types can be dealcoholized in a given unit and various alcohol contents can be obtained. In addition, it is a modular technology, with ease scaling-up.

The RO process has been reported by several authors for removing ethanol from fermented beverages such as cider, wine, and beer (8, 9). López et al. studied the use of RO for producing low alcohol content cider in both diafiltration and batch modes (8). Several authors describe the economic feasibility of RO for ethanol removal processes. According to their results, RO is not viable for reducing the ethanol content from alcoholic beverages under 0.45% (9). On the other hand, RO is a profitable process for the recovery and purification of ethanol from fermentation beer, compared with typical processes such as distillation (10, 11). RO has also been used in large scale to concentrate fruit juices and wine must (12, 13).

The aim of this work is the evaluation of RO effectiveness for removing alcohol from a fermented beer with about 5.5% v/v ethanol content, in order to produce non-alcoholic beer with less than 0.5% v/v of ethanol content. After selecting the most promising membrane, some tests were carried out in order to study the effect of the most critical operation conditions in the process performance.

THEORETICAL BACKGROUND

The RO separation process can be described by the solution-diffusion theory (2). According to it the water flux J_w can be represented by the following equation:

$$J_w = A(\Delta P - \Delta\pi) \tag{1}$$

where A is the solvent permeance factor, ΔP is the transmembranar pressure difference, and $\Delta\pi$ is the osmotic pressure between both sides of the membrane.

When highly selective membranes are used the water flux is approximately equal to the permeate flux, J_p, which can be determined experimentally from the following equation:

$$J_w \approx J_p = \frac{m_p}{at} \tag{2}$$

where m_p is the permeate mass, a is the effective membrane area, and t is the permeation time. Although ethanol also permeates the membrane, its flux is relatively small compared to the overall one, which is mostly water.

The flux of the solute, J_s, is smaller than the solvent flux when membranes with high selectivity are used and can be written as:

$$J_s = B\Delta c_s \tag{3}$$

where B is the solute permeance factor and Δc_s is the solute concentration difference between feed and permeate sides.

The selectivity of a membrane for a given solute is evaluated by the rejection coefficient R:

$$R = \frac{c_b - c_p}{c_b} = 1 - \frac{c_p}{c_b} \tag{4}$$

where c is the solute concentration, in the feed bulk (b) and permeate (p) sides, respectively.

Once the solute and solvent fluxes can be related by $J_s = c_p J_w$ and combining Eqs. (1) and (3), the rejection coefficient R can be expressed as:

$$R = \frac{A(\Delta P - \Delta\pi)}{A(\Delta P - \Delta\pi) + B} \tag{5}$$

MATERIALS AND METHODS

Experimental Procedure

A lab reverse osmosis unit, which is sketched in Fig. 1, was used for conducting the dealcoholization experiments. The beer stored in the feed tank (1 – Fig. 1) is pumped batch-wise by means of a centrifuge pump (2) to the membrane module (3) with 155 cm^2 effective membrane area. A fraction of the feed stream is recycled to the feed tank through a plate heat exchanger (5). The retentate is also recycled to the feed reservoir through the same heat exchanger and its flowrate measured by a rotameter (6). Water and ethanol permeate through the membrane against the osmotic pressure and

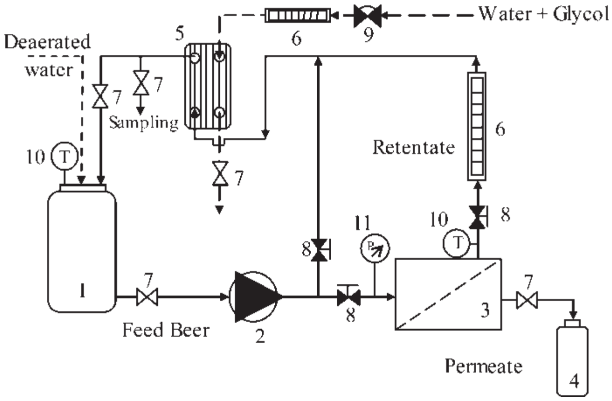


Figure 1. Sketch of the reverse osmosis unit used for removing alcohol from beer (1 – feed tank, 2 – centrifuge pump, 3 – membrane module, 4 – permeate reservoir, 5 – plate heat exchanger, 6 - rotameters, 7 – on/off valves, 8 – needle valves, 9 – diaphragm valve, 10 – temperature sensors, 11 – manometer).

are collected at the permeate side (4), which flowrate is measured using a graduated cylinder and a chronometer. On the other hand, the bulky molecules (such as beer aroma and flavor compounds) remain at the retentate side. The feed pressure, which is measured by a manometer (11), and the retentate flowrate are adjusted by regulating needle valves (8). Two temperature sensors (10) measure the feed and membrane module temperature, which is controlled by a diaphragm valve (9) that regulates the cooling water flowrate. Since water is also removed with ethanol the RO process was carried out in diafiltration mode: the volume of feed beer in the tank (1) was maintained approximately constant by adding deaerated deionized water every hour. By this way the concentrations of non-permeable compounds, such as proteins, polyphenols, non-fermentable sugars, bitter and color compounds are maintained approximately constant along with the osmotic pressure, whereas the ethanol content is continuously reduced. This is the principle of alcohol removal by means of RO.

Membranes

The most used membrane in alcohol removal is made of cellulose acetate (CA), which has a high water and alcohol permeability and a high rejection to the compounds with high molecular weight such as proteins, polyphenols, sugars and bitter and colour compounds.

In this work several membranes made of cellulose acetate and polyamide were used, provided by Alfa Laval (Sweden) and Centec (Germany), respectively. The membranes characteristics are given in Table 1.

Feed Solution and Aroma Compounds

The beer used in the present study was a regular alcoholic beer, whose ethanol content was about 5.5% by volume. Nine aroma compounds, four alcohols (ethanol, propanol, isobutanol, and isoamyl alcohol), two esters (ethyl acetate and isoamyl acetate), one aldehyde (acetaldehyde), and a sulphur compound (dimethyl sulphide) were followed using a GC. In this study only the permeation of alcohols and esters, the most important beer aroma compounds, are tracked. Their properties are given in Table 2.

Analytical Methods

A density meter (DMA 4500, Anton Paar) coupled with an Alcolyzer Plus (Anton Paar) was used to determine the density and the ethanol content of the solutions. For determining the aroma content on both feed and permeate streams a GC (Varian Star 3400) was used. These analytical methods correspond to the standard methods by EBC – the European Brewing Convention (15).

Table 1. Characteristics of the RO membranes used

Membrane reference	Supplier	Type	MMCO[a] $(g \cdot mol^{-1})$	P^{b}_{max} (bar)	T^{b}_{max} (°C)
DSS-CA995P	Alfa Laval	Cellulose triacetate/diacetate blend on polyester	200	50	30
BW RLC	Centec	Polyamide	Not available	41	45
BW 30 LE	Centec	Polyamide	Not available	41	45
SW 30 HR	Centec	Polyamide	Not available	41	45
ACM 4	Centec	Polyamide + composite fiberglass	Not available	41	45
ACM 2	Centec	Polyamide + composite fiberglass	Not available	41	45

[a] Molecular mass cut-off.
[b] Maximum operating conditions.

RESULTS AND DISCUSSION

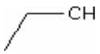
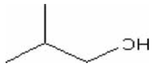
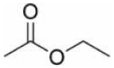
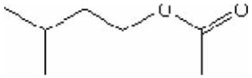
Ethanol Removal from Beer

Experiments with fresh and clarified alcoholic beer were carried out in order to produce non-alcoholic beer (less than 0.5% v/v of ethanol) by means of reverse osmosis. A restricted taste panel recognized a promising taste in the produced beer. Figure 2 shows the ethanol content during the dealcoholization process, from 5.4% v/v of the initial feed beer to 0.49% v/v of the final one. This figure shows that the ethanol content decreases following a negative exponential, characteristic of the diafiltration operating mode (2). It was observed that the permeate flux was maintained approximately constant (5.06×10^{-4} $g \cdot s^{-1} \cdot cm^{-2}$) during the RO process because it was operated in a diafiltration mode. The addition of deaerated deionized water to the feed tank is done in order to keep the beer osmotic pressure approximately constant.

Membrane Selection

The choice of the most promising membrane was made based on Fig. 3. This figure shows, for each membrane, the normalized permeate flux as a function of the ethanol rejection. The best membrane should have the highest permeate flux and the lowest ethanol rejection (it is aimed to permeate the ethanol). The best performing membrane is the DSS-CA995P, a cellulose acetate membrane

Table 2. Beer aroma compounds properties

Compound	Structure formula	Molecular weight (g/mol)	Boiling point (°C)	Beer threshold[a] (ppm)	Range of concentration[a] in beer (ppm)	Typical aroma
Ethanol		46	78	14000	—	Alcoholic
Propanol		60	98	800	7.5 – 13.8	Alcoholic
Isobutanol		74	108	200	8.6 – 56.6	Alcoholic
Isoamyl alcohol		88	132	68	27 – 122	Alcoholic, banana
Ethyl acetate		88	77	30	8.2 – 47.6	Fruity, solvent
Isoamyl acetate		130	149	1.2	0.8 – 6.6	Banana

[a] Source: Meilgaard (14).

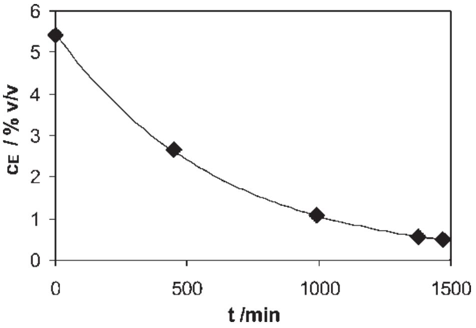


Figure 2. Ethanol content history at the retentate side for 5°C, 40 bar and 7 l · min^{-1} feed flowrate (dot – experimental data, line – exponential fitting).

by Alfa Laval – Table 1. The other membranes show very low permeate fluxes and also higher ethanol rejections. Similar results with cellulose acetate and polyamide membranes were observed by other authors (8).

Influence of the Operation Conditions

After selecting the membrane (DSS-CA995P) several laboratory experiments were performed in order to study the performance of such membrane under a range of operation conditions. In order to guarantee the uniformity of the beer, beer from the same batch was stored at 5°C in glass bottles and used for all the experiments. Table 3 summarizes the operation conditions employed as well as the membrane performance in terms of ethanol rejection, total permeate flux, and permeate flux for each aroma compound. Experiments were performed at three pressure differences, five temperatures, and three feed

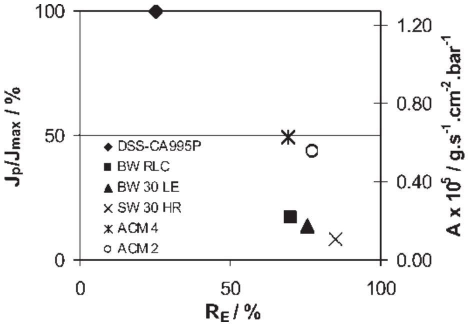


Figure 3. Normalized permeate flux and permeance as a function of the ethanol rejection for all tested membranes. Operating conditions: T = 5°C, $\Delta P = 40$ bar and $Q_f = 7$ l · min^{-1}.

Table 3. Rejection and ethanol and aromas permeate fluxes for membrane DSS-CA995P

Run	P_f	T	Q_f	$c_{0,E}$	$c_{p,E}$	R_E	$J_p \times 10^4$	$J_E \times 10^6$	$J_{Pr} \times 10^9$	$J_{iB} \times 10^9$	$J_{AA} \times 10^9$	$J_{EA} \times 10^9$	$J_{iAA} \times 10^9$
#	barg	°C	$l \cdot min^{-1}$	% v/v	% v/v	%	$g \cdot s^{-1} \cdot cm^{-2}$	$g \cdot s^{-1} \cdot cm^{-2}$	$g \cdot s^{-1} \cdot cm^{-2}$	$g \cdot s^{-1} \cdot cm^{-2}$	$g \cdot s^{-1} \cdot cm^{-2}$	$g \cdot s^{-1} \cdot cm^{-2}$	$g \cdot ^{-1} \cdot cm^{-2}$
7	**20**	5	7.0	5.28	5.09	3.60	1.26	5.11	1.87	0.98	6.76	1.87	0.10
8	**30**	5	7.0	5.27	4.87	7.59	2.11	8.17	2.88	1.41	9.88	3.25	0.19
9.1	**40**	**5**	**7.0**	5.28	4.72	10.61	2.99	11.23	4.00	1.96	13.79	4.51	0.26
9.2	**40**	**5**	**7.0**	5.27	4.75	9.87	3.10	11.70	4.15	2.05	14.45	4.89	0.30
9.3	**40**	**5**	**7.0**	5.26	4.74	9.89	2.95	11.12	3.87	1.87	13.21	4.64	0.28
10	40	**10**	7.0	5.26	4.81	8.56	3.38	12.93	4.79	2.38	16.82	5.39	0.33
11	40	**15**	7.0	5.28	4.88	7.58	3.77	14.66	5.50	2.86	20.18	6.14	0.40
12	40	**18**	7.0	5.26	4.89	7.03	4.30	16.77	6.36	3.43	24.03	6.92	0.45
13	40	**20**	7.0	5.25	4.92	6.29	4.85	19.02	7.41	4.07	28.45	7.84	0.48
14	40	5	**4.5**	5.26	4.74	9.89	2.88	10.86	3.94	1.89	13.31	4.55	0.28
15	40	5	**2.0**	5.27	4.79	9.11	2.81	10.70	4.04	1.92	13.57	4.55	0.28

P_f – feed pressure, T – temperature, Q_f – feed flowrate, $c_{0,E}$ – initial feed concentration of ethanol, $c_{p,E}$ – 120 min permeate concentration of alcohol, R_E – ethanol rejection, J – flux, p – permeate, E – ethanol, Pr – propanol, iB – isobutanol, AA – amyl alcohols, EA – ethyl acetate, iAA – isoamyl acetate.

flowrates. It is worth noting that, in these experiments, a more concentrated beer in non-permeable compounds was used compared to that described in the section on Ethanol Removal from Beer, consequently the osmotic pressure is higher, which results in a decrease of the permeate flux (cf. Eq. (1).

The membrane permeability towards water was measured before and after this set of experiments, using Milli-Q ultra pure water (0.054 $\mu S \cdot cm^{-1}$). The water permeability observed before beer experiments was 1.25×10^{-5} $g \cdot s^{-1} \cdot cm^{-2} \cdot bar^{-1}$, while the permeability after was 1.30×10^{-5} $g \cdot s^{-1} \cdot cm^{-2} \cdot bar^{-1}$ (relative difference 4.0%). From these results, it can be assumed that the membrane keeps its performance during the whole set of experiments with beer (Table 3).

Run 9 was performed in triplicate in order to assess the experimental errors. The permeate mass flux and ethanol rejection relative standard deviations were 2.5% and 4.2%, respectively – Table 3. The relative standard deviations of the fluxes were 2.7%, 3.4%, 4.6%, 4.5%, 4.1%, and 6.0% for ethanol, propanol, isobutanol, amyl alcohols, ethyl acetate, and isoamyl acetate, respectively.

Influence of the Feed Pressure

Table 3 and Fig. 4 show that the permeate flux increases linearly with the pressure difference. These results are in agreement with the solution-diffusion transport theory – Eq. 1. According to this equation, it is possible to determine the solvent permeance factor A and the osmotic pressure difference $\Delta\pi$ across the membrane. Permeate flux should be zero when the osmotic pressure is equal to the pressure difference through the membrane, so, from the previous linear regression the osmotic pressure was obtained: 5.70 bar at 5°C. From the plot slope it was obtained the solvent permeance factor, $A = 8.75 \times 10^{-6}$ $g \cdot s^{-1} \cdot cm^{-2} \cdot bar^{-1}$, at 5°C.

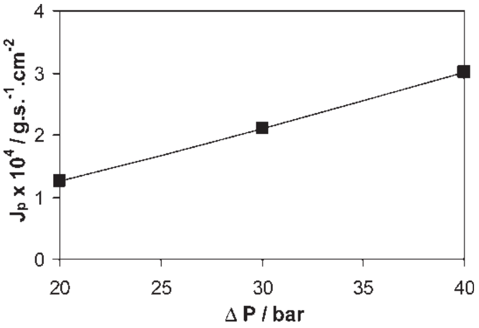


Figure 4. Permeate flux as a function of the pressure difference at 5°C and $7\,l \cdot min^{-1}$ feed flowrate (line – linear fitting).

Table 3 shows that ethanol exhibits the highest flux through the membrane, followed by amyl alcohols, ethyl acetate, propanol, isobutanol, and isoamyl acetate. The order of these fluxes is in agreement with the order of the aroma compounds' concentration in the feed beer. Regarding the dependence of the beer aroma compounds fluxes with pressure difference, it is possible to observe a linear increase of all fluxes with the pressure difference, although this increase is more noticeable for esters than for alcohols. For isoamyl acetate and ethyl acetate a flux increase of 185% and 150% was observed, respectively, from 20 bar to 40 bar (runs 7 and 9), while for alcohols the increments were 122%, 115%, 104%, and 99% for ethanol, propanol, amyl alcohols, and isobutanol, respectively (runs 7 and 9).

Figure 5 shows the influence of the pressure difference on the rejection of ethanol and other aroma compounds. For ethanol and high alcohols, as the pressure difference increases the aroma rejection also increases, as well as their permeation fluxes (Table 3). However, the solvent (water) permeation increase (139% from 20 to 40 bar – Fig. 4) is higher than the alcohols one (with the exception of propanol), which causes a decrease in the permeate aroma concentration. As a result of the reduction of concentration, the c_p/c_b ratio decreases and the aroma rejection increases, according with Eq. (4). For esters the opposite behavior was verified. Similar results concerning the influence of the feed pressure on the permeate flux and rejection coefficients were observed by other authors (8, 12).

Since pressure affects the aroma compounds' rejection in different ways, the optimal value should be determined in order to minimize the beer aroma losses and in order to improve the aroma profile of the dealcoholized beer. From Fig. 5, the increase of alcohols rejection, which is reached by increasing the pressure difference from 20 to 40 bar, is much higher than the esters rejection decrease. Therefore, in the subsequent runs we will operate at 40 bar, the maximum pressure that the used lab setup allows to reach, once increasing the feed

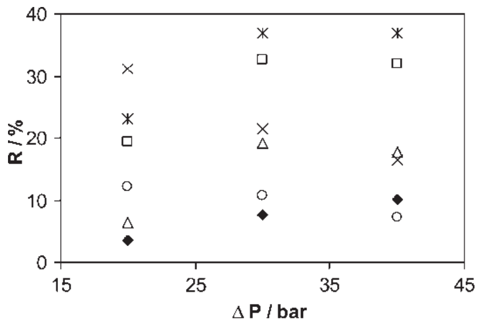


Figure 5. Ethanol and other aromas rejection as a function of the pressure difference at 5°C and 7 l · min^{-1} feed flowrate (◆ ethanol, △ propanol, ∗ isobutanol, □ amyl alcohols, ○ ethyl acetate, × isoamyl acetate).

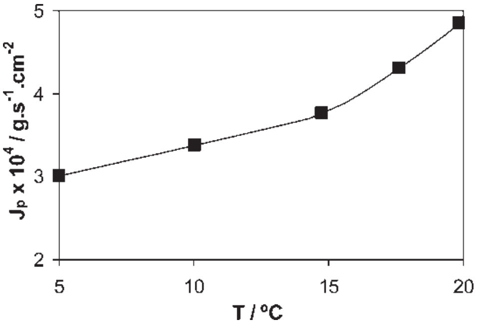


Figure 6. Permeate flux as a function of the temperature, at 40 bar and 7 l · min^{-1} feed flowrate (lines are only for readability).

pressure results in higher aroma rejection, higher permeate, and ethanol fluxes and besides that ethanol removal is high enough.

Influence of the Temperature

Table 3 and Fig. 6 show that the permeate flux increases with the temperature following an almost exponential behavior – Arrhenius dependence. Table 3 shows that the fluxes of ethanol and of the aroma compounds also increase with the temperature. Again, the increase of the aroma fluxes depends on the compound's nature, with isobutanol and amyl alcohols being more affected by the temperature. For these compounds a flux increase of 108% and 106% was observed, respectively, when changing the temperature from 5°C to 20°C (runs 9 and 13). For the other compounds the increments were 68%, 85%, 68%, and 72%, for ethanol, propanol, ethyl acetate, and isoamyl acetate, respectively. Figure 7 shows the effect of temperature on the rejection of the aroma compounds. For all compounds the rejection decreases with the temperature. As the temperature increases, the aroma permeation through the membrane increases. The solvent flux also increases with the temperature, but in a smaller extent (61% from 5°C to 20°C – Fig. 6). Consequently the ratio between the aroma flux and the permeate flux increases with the temperature as well as the c_p/c_b ratio, which causes a decrease in the rejection. Therefore, the lowest operating temperatures give the highest rejections (especially for esters), and despite the permeate flux decrease, in the subsequent runs we will operate at 5°C.

Influence of the Feed Flowrate

Some experiments were carried out at different feed flowrates in order to evaluate the concentration polarization effect. The feed flowrate was

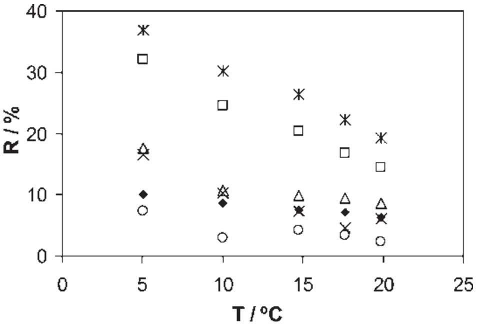


Figure 7. Ethanol and other aromas rejection as a function of the temperature, at 40 bar and 7 l · min^{-1} feed flowrate (◆ ethanol, △ propanol, ∗ isobutanol, □ amyl alcohols, ○ ethyl acetate, × isoamyl acetate).

varied from 2 to 7 l · min^{-1}, the maximum flowrate allowed by the lab set-up used. From Table 3 and Fig. 8 it is possible to conclude that the permeate flux increases with the feed flowrate. Table 3 shows that ethanol flux is the most affected by the concentration polarization. The increase observed in permeate and ethanol fluxes, by increasing the feed flowrate from 2 to 7 l · min^{-1}, were 7.2% and 6.1%, respectively, while for the other aroma compounds the increase was less than 3% (runs 15 and 9). Figure 9 shows the effect of the feed flowrate on the permeate concentration of ethanol and other aromas (a) and on their rejection (b). From Fig. 9a one can see that the concentrations of the beer aroma compounds are approximately constant within the range of feed flowrates used. On the other hand the rejection of the aroma compounds increases, although only very slightly, with the feed flowrate (Fig. 9b). The increment of the rejection for all the aroma compounds was in the range of 1–5% (percentage points). This is

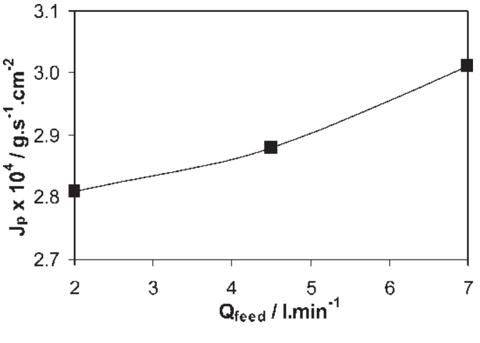


Figure 8. Permeate flux as a function of the feed flowrate, at 5°C and 40 bar (lines are only for readability).

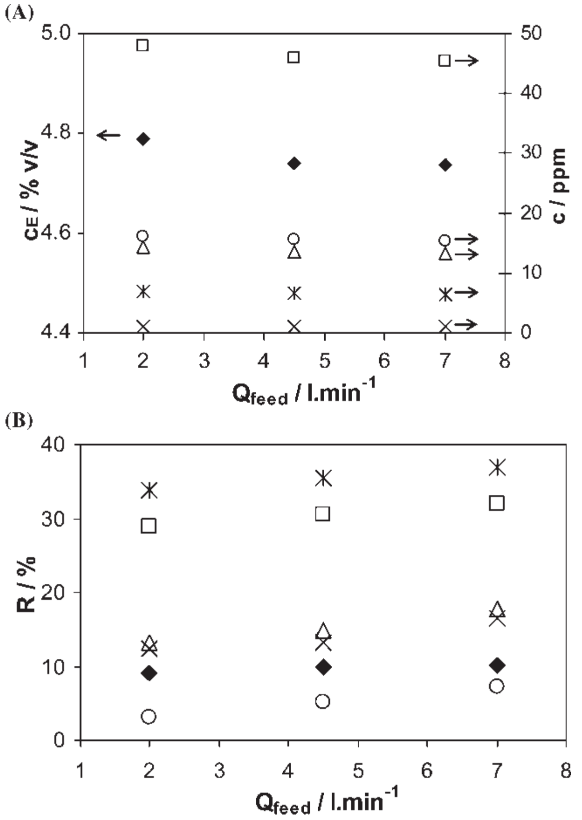


Figure 9. (A) Ethanol and other aromas permeate concentration and (B) Ethanol and other aromas rejection as a function of the feed flowrate, at 5°C and 40 bar (◆ ethanol, △ propanol, ∗ isobutanol, □ amyl alcohols, ○ ethyl acetate, × isoamyl acetate).

mainly due to the permeate flux increase with the feed flowrate (Fig. 8). As the feed flowrate increases, the concentration polarization decreases by increasing the turbulence in the feed side. Other authors reported similar results for the influence of the feed flowrate on the permeate flux and rejection coefficients (12). Consequently, high feed flowrates should be used in order to avoid the concentration polarization which causes a decrease of the permeate flux and a decrease of the rejection of ethanol and of the other aroma compounds.

CONCLUSIONS

In this work reverse osmosis was used in a diafiltration mode for removing ethanol from an alcoholic beer. When operated at low temperatures, this process proved to be effective for producing non-alcoholic beer (ethanol content less than 0.5% by volume) with high aroma content.

Six RO membranes made of cellulose acetate and polyamide were tested. The acetate cellulose membrane, DSS-CA995P, was the one providing simultaneously a higher permeate flux and a lower ethanol rejection.

The most critical operation conditions were analyzed, in order to evaluate their influence on the permeate flux and aroma compounds rejections. Higher pressures results in higher aroma rejection (although esters rejection slightly decrease with feed pressure) and in a higher permeate flux, despite ethanol rejection also increases. Low temperatures results in higher rejection to the aroma compounds; however, ethanol rejection increases as well. High feed flowrates reduce the concentration polarization effect.

LIST OF SYMBOLS

A	solvent permeance ($g \cdot s^{-1} \cdot cm^{-2} \cdot bar^{-1}$)
a	effective membrane area (cm^2)
B	solute permeance ($cm \cdot s^{-1}$)
c	concentration ($g \cdot cm^{-3}$)
Δc	concentration difference between both sides of the membrane ($g \cdot cm^{-3}$)
J	flux ($g \cdot s^{-1} \cdot cm^{-2}$)
m	mass (g)
P	pressure (bar)
ΔP	transmembranar pressure difference (bar)
Q	flowrate ($cm^3 \cdot s^{-1}$)
R	rejection (-)
T	temperature (°C)
t	time (s)

Greek Letters

$\Delta \pi$	osmotic pressure difference between both sides of the membrane (bar)

Subscripts

AA	amyl alcohols
b	feed bulk
E	ethanol
EA	ethyl acetate
f	feed

iAA	isoamyl acetate
iB	isobutanol
Pr	propanol
p	permeate
s	solute
w	water
0	initial conditions

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