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Separation Science and Technology

Publication details, including instructions for authors and subscription information:

<http://www.informaworld.com/smpp/title~content=t713708471>

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Online publication date: 04 July 2003

To cite this Article Kim, Joo Heun , Kim, Chang Keun , Kim, Dong Won , Kim, Sung Soo , Park, Sang Kwon , Lee, Myung Cheon and Lim, Jong Choo(2003) 'Removal of Aromatic Organics in Aqueous Solution via Micellar-Enhanced Ultrafiltration', *Separation Science and Technology*, 38: 8, 1791 – 1811

To link to this Article: DOI: 10.1081/SS-120019409

URL: <http://dx.doi.org/10.1081/SS-120019409>

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SEPARATION SCIENCE AND TECHNOLOGY

Vol. 38, No. 8, pp. 1791–1811, 2003

Removal of Aromatic Organics in Aqueous Solution via Micellar-Enhanced Ultrafiltration

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ABSTRACT

The micellar-enhanced ultrafiltration (MEUF) process for obtaining pure water from aqueous solutions containing small amounts of toxic organics such as phenol and benzene has been studied. A homologous series of polyethyleneglycol alkylether having different numbers of methylene groups and oxyethylene groups was used for nonionic surfactants. Cellulose acetate and polysulfone membranes having different molecular weight cut-offs (MWCO) were used as hydrophilic and hydrophobic

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membranes, respectively. The performance of the MEUF process in removing organics was shown to depend on membrane characteristics, surfactant characteristics, organic characteristics, and operating conditions. The decline in the permeate flux with polysulfone membranes was serious, while that with cellulose acetate membranes was not remarkable. The rejection of organics increased with increasing hydrophobicity of surfactant when the feed solution contained the same amount of surfactant. The rejection of organics for the cellulose acetate membrane increased with decreasing membrane pore size and with increasing operating pressure. On the other hand, the rejection behavior of organics for polysulfone membranes was shown to depend on the characteristics of organics. The rejection behavior of phenol was also similar to that for cellulose acetate membrane, while that of benzene was totally different from that for the cellulose acetate membrane. Benzene rejection for polysulfone membranes decreased with increasing operating pressure and with decreasing pore size. Regardless of membrane characteristics, benzene was more effectively removed than phenol via the MEUF process. The performance of MEUF could be explained with the solubilization behavior of organics and hydrophobic interactions.

Key Words: Micellar-enhanced ultrafiltration; Phenol; Benzene; Non-ionic surfactant; Membrane characteristics; Hydrophobic interactions.

INTRODUCTION

The removal of toxic organic materials, present in small or trace quantities, from aqueous solutions is of great environmental concern. Conventional separation processes such as distillation or extraction are not desirable for this purpose, since these techniques require rather intense energy consumption and subsequent further purifications. Traditional ultrafiltration is also ineffective in removing the dissolved low molecular weight organics from water, since membranes capable of passing water but rejecting small organic molecules are simply not available.

Micellar-enhanced ultrafiltration (MEUF), whereby surfactant is added to the water stream containing organic solutes, has been shown to be effective in removing the dissolved organics.^[1-4] When surfactants are present in aqueous solutions above the critical micelle concentration (CMC), surfactant monomers begin to assemble in ordered, colloidal aggregates, i.e., micelles having aggregate diameters significantly larger than the largest pore diameter in the separation membrane. One of the most important consequences of



micellization is that micelles are capable of solubilizing a certain amount of organic compound as a solubilizate. The extent of solubilization depends on both the structure of the solubilizate and the surfactant. Organic compounds may be dissolved or solubilized within micelles at different locations such as hydrophobic core, palisade layer, and micelle surface. The site of incorporation of the solubilizate is closely related to its chemical structure. Organic solute species tend to locate preferentially in regions within the micelle that are similar chemically and in polarity to these molecules. For example, in an aqueous system it is generally accepted that nonpolar solubilizates, e.g., aliphatic hydrocarbons, are dissolved in the hydrocarbon core of the micelle, and semipolar and polar solubilizates, e.g., fatty acids and alkanols, may be oriented in the micelle with the polar group either buried or near the micelle surface.

Extensive studies have been performed to investigate the effect of operation variables such as pressure, flow rate, surfactant concentration, membrane pore size, amount of pollutants present, temperature, electrolyte, ionic strength, and pH on the performance of the MEUF process.^[5–12] The most serious limitation of the MEUF process is a continuous permeation flux decrease that is caused by several factors, such as concentration polarization, adsorption, gel layer formation, and plugging of membrane pores. Even in the absence of solute, a decrease in the membrane permeability has been found for low-rejecting membranes at a certain concentration of surfactant. The flux reduction has in these cases been attributed to adsorption of surfactant molecules in the membrane pores. The adsorption of surfactant onto membrane surface and pores can be due to various interactions between surfactant and membrane material.^[13–23]

In a previous work,^[24] we examined the effects of nonionic surfactants having different hydrophobicity and membranes having different hydrophilicity and molecular weight cut-off (MWCO) on the performance of the MEUF process in removing nonionic surfactants. The performance of the MEUF process in removing nonionic surfactants was shown to depend on the membrane characteristics, surfactant characteristics, and operating conditions. The flux through polysulfone membranes decreased remarkably due to adsorption mainly caused by hydrophobic interactions between surfactant and membrane material. The decline of solution flux for cellulose acetate membranes was not as serious as that for polysulfone membranes because of hydrophilic properties of cellulose acetate membranes. The surfactant rejections for the cellulose acetate membranes increased with decreasing membrane pore size and with increasing the hydrophobicity of surfactant. On the other hand, the surfactant rejections for polysulfone membranes showed totally different rejection trends than those for cellulose



acetate membranes. The surfactant rejections for the polysulfone membranes depend on the strength of hydrophobic interactions between surfactant and membrane material and molecular weight of surfactants. In this work, the MEUF process was applied to the removal of organics in aqueous solutions. Nonionic surfactants of polyoxyethyleneglycol alkylether, $H(CH_2)_nO(CH_2-CH_2O)_mH$, (C_nE_m) having different numbers of oxyethylene group (m) and alkyl group (n) were examined. The effects of the membrane properties such as MWCO and hydrophilicity, the characteristics of phenol and benzene, and operating pressure on the separation characteristics were investigated.

EXPERIMENTAL

The membranes used for MEUF were fabricated from two different types of polymers, as shown in Table 1. The hydrophilic membranes purchased from Millipore Co. (PLBC, PLCC, PLGC, and PLTK) were made from cellulose acetates. According to the information provided by the supplier, molecular weight cut-off (MWCO) for this set of cellulose acetate membrane is 3000, 5000, 10,000, and 30,000 respectively. The hydrophobic membranes were made in this laboratory from polysulfone (Udel, P-1700) that was supplied by Amoco Co. where polysulfone, Udel P-1700, is an amorphous polymer with a glass transition temperature of 185°C. Flat ultrafiltration membranes of polysulfone, supported by polyester fabrics, were prepared from polysulfone solution in n-methyl-2-pyrroridone (NMP) or dimethylformamide (DMF) by the wet phase inversion method. Polymer solution was cast onto the nonwoven polyester fabrics using a doctor blade with the thickness of 0.15 mm.

Table 1. Characteristics of the membranes used during this study.

Membrane	Polymer	Molecular weight cut-off	Sources
PLBC	Cellulose acetate	3000	Millipore Co.
PLCC	“	5000	“
PLGC	“	10,000	“
PLDK	“	30,000	“
D-21, 22, 23 ^a	Polysulfone in DMF	—	Fabricated in this lab.
N-21, 22, 23 ^a	Polysulfone in NMP	—	“

^aThe numerical value included as part of the code for the membranes indicates the nominal percent by weight of polysulfone in the casting solution.



The casting solution was immediately precipitated by immersion in a water bath. Details of polysulfone membrane fabrication are described elsewhere.^[25]

Nonionic surfactants of polyoxyethyleneglycol alkylether, $H(CH_2)_nO(CH_2CH_2O)_mH$, (thereafter referred to as C_nE_m) were provided by Nikko Chemicals Co. The numbers (n) of the hydrophobic alkyl group and those (m) of the hydrophilic oxyethylene group in a homogeneous series of polyoxyethyleneglycol alkylether, C_nE_m , were changed systematically for MEUF experiments. Surface tension using maximum bubble pressure tensiometer (Kruss Co., model: BP-2) was measured to determine the CMC of a nonionic surfactant, and dynamic light scattering method was used to measure the micelle size at room temperature. Some important characteristics of those surfactants are listed in Table 2. Two different organics such as benzene and phenol were used during this study where the concentration of each organic was fixed at 0.2 mM, unless otherwise stated.

Batch type Amicon 8050 cell was used for the ultrafiltration experiments. The feed volume of aqueous solution and the effective membrane area were 200 ml and 13.4 cm² respectively. The measurement of permeate flux was performed at room temperature and 3 bar, unless otherwise specified. Operating pressure in the batch cell was maintained by nitrogen gas. According to the measurement of permeate flux of pure water relative to that of surfactant solution as a function of stirring speed for each solution examined, the permeate flux of pure water relative to that of surfactant solution increased with stirring speed and then leveled off to an asymptotic limit at 600 rpm. Consequently every experiment described here was

Table 2. Characteristics of nonionic surfactants used during this study.

Surfactant	M.W. (g/mole)	CMC ^a (mole/L)	Micelle diameter ^b (nm)
$C_{10}E_8$	510	1.0×10^{-3}	5.0
$C_{12}E_8$	538	7.1×10^{-5}	7.0
$C_{12}E_7$	494	6.9×10^{-5}	—
$C_{12}E_6$	450	6.8×10^{-5}	—
$C_{12}E_5$	406	6.5×10^{-5}	6.0
$C_{14}E_8$	566	9.0×10^{-6}	—
$C_{16}E_8$	594	1.0×10^{-6}	12.0

^aCMC data were obtained by surface tension measurement at room temperature.

^bMicelle sizes were measured by dynamic light scattering method. Note that the solution concentrations were fixed at the value of 100 times of CMC.



performed at a magnetic stirrer speed of 700 rpm to minimize the concentration polarization. Note that permeate fluxes of pure water relative to that of surfactant solution at a plateau and stirring speed were varied with surfactant concentration.

Polyethyleneglycol (PEG) having various molecular weights was used to characterize the MWCO of the membranes. Concentrations of benzene and phenol in an aqueous solution were measured with an ultraviolet-visible spectrophotometer (Shimadzu Co., model: UV-240) at 256 nm and 270 nm respectively. The concentration of a nonionic surfactant in the aqueous solution was determined using a colorimetric method.^[26] Briefly, the blue complex of nonionic surfactant and ammonium cobalthiocyanate reagent formed in this method is extracted into benzene from a saturated salt solution and then measured with an ultraviolet-visible spectrophotometer at 320 nm. For the analysis of experimental results, the concentration of surfactant added to pure water was fixed at the value of 100 times of CMC, unless otherwise specified. The rejection parameter used to describe the separation efficiency of the membrane is defined as:

$$\text{Rejection} = 1 - (C_p/C_f) \quad (1)$$

where C_p and C_f are the concentrations in the permeate and the feed solution, respectively.

RESULTS AND DISCUSSION

Solubilization of Organics

In order to explore the solubilization behavior of organics in the micelle, solubilities of phenol and benzene in n-alkane and in oxyethylene regions were examined. Since a homologous series of the nonionic surfactants used in this work contains different number of oxyethylene group and length of alkyl chain, solubility of organics in n-alkane and oxyethylene regions might represent their solubilization behavior in the micelle. Benzene was completely dissolved in hexadecane, whereas phenol was little dissolved (less than 0.5 wt%). In PEG having molecular weight of 350, both organics were completely dissolved. The solubilities of benzene and phenol in 100 g of water at 10°C are known to be 0.07 g and 8.2 g, respectively.^[27] These results indicated that most of the benzene molecules stayed in the hydrophobic cores of the micelles, and some are in the palisades of the micelles. Note that benzene molecules do not stay in the aqueous phase due to the intermolecular

repulsion between water and benzene. On the other hand, phenol molecules might stay in the palisades of the micelles and in the bulk phase of the solution instead of in the hydrophobic core of the micelle.

MEUF Using Cellulose Acetate Membranes

Cellulose acetate membranes were tested for their applications to the MEUF process. $C_{16}E_8$ was added at a concentration of 1.0 mM to the solution that contains each organic at 0.2 mM. As shown in Fig. 1, benzene was removed up to 90% while phenol was removed less than 40%. The trends of the permeate flux and surfactant rejection examined with cellulose acetate membranes in the previous work^[24] indicated that micelles formed in aqueous solution can be eliminated by filtration using a membrane having a pore diameter smaller than the micelle diameter, i.e., the surfactant rejections increased with decreasing membrane pore size and with increasing operating pressure. It was also observed that the surfactant rejections increased with increase in hydrophobicity of a nonionic surfactant, which can be controlled

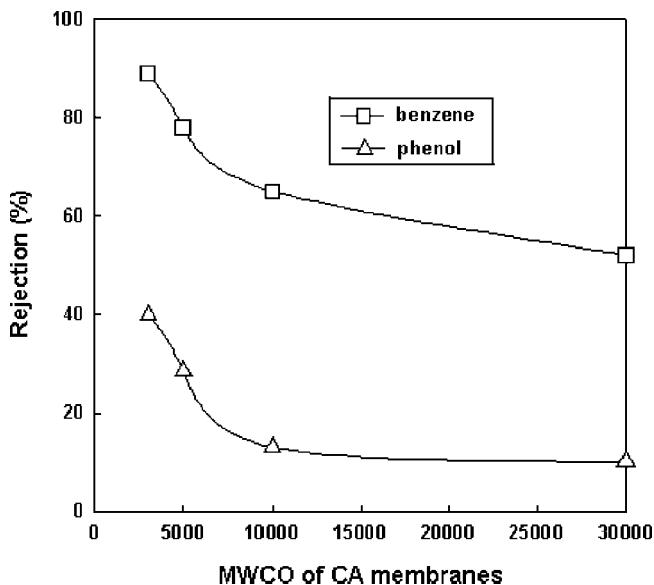


Figure 1. Rejections of benzene, and phenol examined with CA membranes at the operating pressure of 3 bar where concentration of $C_{12}E_8$ was 1 mM.

by varying the number of methylene group and oxyethylene group. Since the surfactant aggregated in the micelle remained in the retentate solution during the MEUF process, the rejection percent in the case of benzene that was solubilized in the core of the micelles was higher than that in the case of phenol that stayed in the palisades of the micelles and in the bulk phase of the solution.

In order to investigate the effects of the alkyl chain length and concentration of a surfactant on the membrane performance, $C_{16}E_8$ and $C_{12}E_8$ were used at different concentrations. With increasing number (n) of methylene groups, the size of the micelle increased but the CMC decreased. That is, $C_{16}E_8$ more easily formed the micelle with greater size at lower concentration than $C_{12}E_8$. Therefore, $C_{16}E_8$ was expected to be more effective in the MEUF process than $C_{12}E_8$. However, as shown in Fig. 2, at the concentration of 100 times of CMC, $C_{12}E_8$ was more effective than $C_{16}E_8$ for both phenol and benzene removal via the MEUF process. These results might come from the difference in the absolute concentrations of the surfactant. Absolute concentration of 100 times of CMC for $C_{12}E_8$ was about 70 times greater than that for $C_{16}E_8$. Therefore,

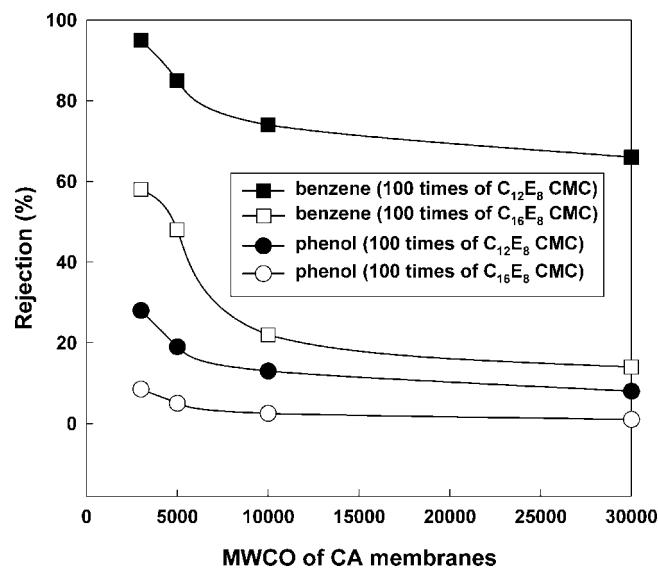


Figure 2. Benzene and phenol rejections examined with CA membranes at the operating pressure of 3 bar where 100 times of CMC of each surfactant was added to the feed solution.

$C_{16}E_8$ surfactant at the concentration of 100 times of CMC was not sufficient enough to solubilize the organics, and showed the poor performance in removing organics. However, as shown in Fig. 3, when each surfactant was added at the same concentration of 1.0 mM, $C_{16}E_8$ was more effective than $C_{12}E_8$. In the MEUF process, absolute concentration of the surfactant was more important in solubilizing the organics in the micelles rather than the relative concentration based on the CMC. In these results, benzene rejections were much greater than those of phenol due to the differences in solubilization behavior of phenol and benzene in the micelle. That is, molecules of benzene are located deeper in the micelle, i.e., more deeply in the palisade layer and in the core of the micelle, than the molecules of phenol.

The rejection of organics was examined with PLBC (MWCO = 3000) by changing systematically the numbers (n) of the hydrophobic alkyl group and those (m) of the hydrophilic oxyethylene group in C_nE_m . As shown in Figs. 4 and 5, the rejection of organics increased with increasing the number (n) of the hydrophobic alkyl group and with decreasing the hydrophilic oxyethylene group (m) when each surfactant was added at the same concentration of 1.0 mM. These results indicated that the rejection of

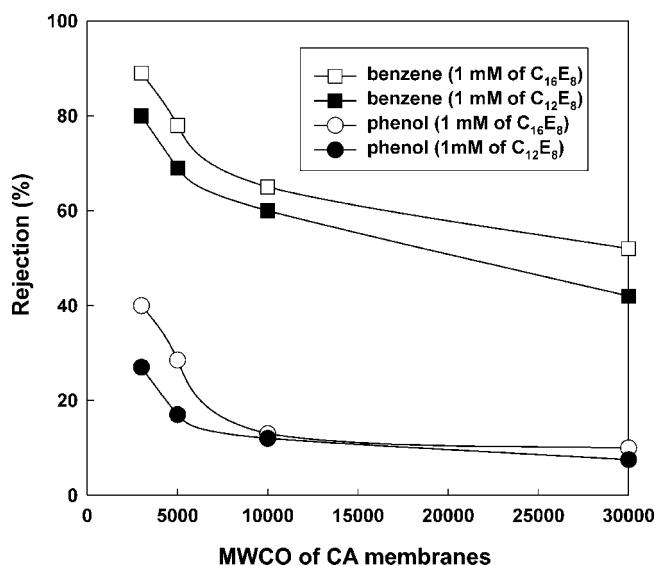


Figure 3. Benzene and phenol rejections examined with CA membranes at the operating pressure of 3 bar where 1 mM of surfactant was added to the feed solution.

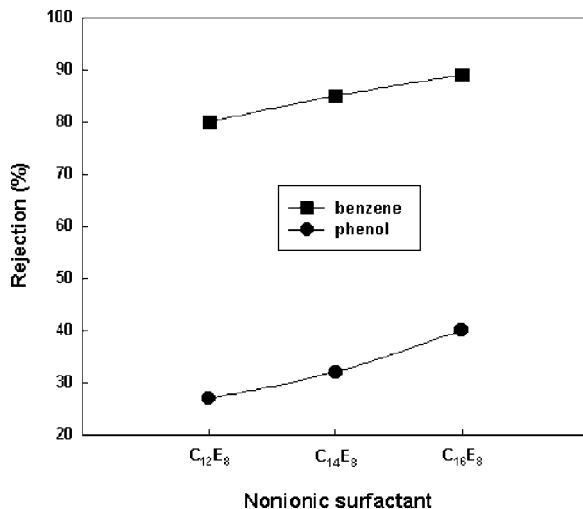


Figure 4. Benzene and phenol rejections examined with PLBC (MWCO = 3000) at the operating pressure of 3 bar where the concentration of each surfactant having different number of methylene groups was fixed at 1 mM.

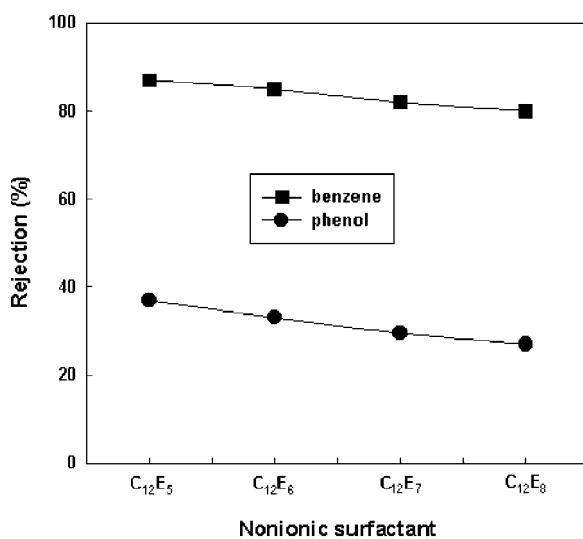


Figure 5. Benzene and phenol rejections examined with PLBC (MWCO = 3000) at the operating pressure of 3 bar where the concentration of each surfactant having different number of ethylene oxide groups was fixed at 1 mM.



organics increased with an increase in hydrophobicity of a nonionic surfactant. It is also noticeable that both rejections of benzene and phenol are more affected by an increase in the number (n) of the hydrophobic alkyl group than by a decrease in the hydrophilic oxyethylene group (m). It is mainly due to the fact that the CMC value decreases more rapidly with an increase in the number (n) of the hydrophobic alkyl group than with a decrease in the hydrophilic oxyethylene group (m). As shown in Table 2, the CMC values of nonionic surfactants increase about 10 - fold per decrease of two methylene groups in the hydrophobic part of a surfactant, whereas a change from eight to five oxyethylene units in the hydrophilic part of a surfactant caused only a slight increase in CMC. On the other hand, the average micelle size increases with an increase in the alkyl chain length (n) of a surfactant, while it decreases with an increase in the oxyethylene chain length (m) of a surfactant. The trends found with the rejection of organics is in agreement with those found with the surfactant rejection in the absence of an organic.^[24]

Effects of the operating pressure on the organic removal were examined for cellulose acetate membranes. A nonionic surfactant C₁₆E₈ was added at a concentration of 1.0 mM to a solution that contains each organic at 0.2 mM. In the ultrafiltration of a very dilute solution, or when using an ultrafiltration membrane with small enough pore sizes, the permeate flux is a linear function of a pressure difference across a membrane and is only slightly dependent on concentration in the lower concentration region. As the retentate becomes more concentrated, or the applied pressure difference is increased, concentration polarization becomes significant due to accumulation of a solute inside the pores and on the membrane surface, and thus the flux reaches a plateau region.^[2,28-30] As shown in Fig. 6, rejection of both organics increased with increasing the operating pressure. The increase of rejection with the operating pressure is usually observed in traditional ultrafiltration and reverse osmosis processes mainly due to the water flux increase.^[28-30] It has also been shown that surfactant rejections examined with cellulose acetate membranes increased with operating pressure.^[24] On the other hand, surfactant rejections with polysulfone membranes decreased with operating pressure due to strong attractive forces between membrane material and a solute, which will be discussed more in detail later. From Fig. 6, the trend of the organic and surfactant rejection indicates that surfactant aggregate containing organic can be eliminated by filtration using a membrane having pore diameter smaller than the micelle diameter.

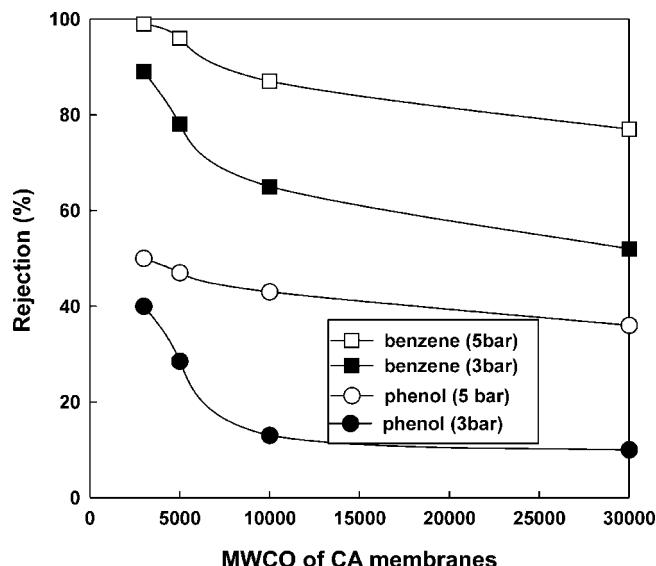


Figure 6. Benzene and phenol rejections examined with CA membranes at the two operating pressures of 3 and 5 bar where 1 mM of $C_{16}E_8$ surfactant was added to the feed solution.

MEUF Using Polysulfone Membranes

Two types of membranes were prepared from the solutions in different solvents, i.e., DMF and NMP. The membranes from DMF solution (D-type) formed lacy structures, and those from NMP solution (N-type) formed fingerlike structures depending on the precipitation rate in a nonsolvent.^[25] The rejection of C_nE_m surfactants by polysulfone membranes with the wt% of the polymer in the casting solution increases with an increase in the number (n) of the hydrophobic alkyl group at constant number (m) of the hydrophilic oxyethylene group, and also with an increase in the number (m) of the hydrophilic oxyethylene group at constant number (n) of the hydrophobic alkyl group.^[24] It indicates that the pore size in the polysulfone membrane decreases with an increase in polysulfone content of the casting solution used to make the membrane. It has also been found that the surfactant rejection behavior for the polysulfone membrane is totally different from that for the cellulose acetate membrane.^[24] Surfactant rejections decrease with increasing operating pressure and molecular weight of a surfactant, while those increase

with increasing pore size of a membrane and hydrophobicity of a nonionic surfactant. The results obtained with polysulfone membranes could be explained with the adsorption characteristics of surfactant on the membrane surface and the pores.^[13–23]

As shown in Figs. 7 and 8, the permeate flux decline for polysulfone membranes was remarkable, while that for the cellulose acetate membranes was not serious when aqueous solution containing the same surfactant and organic was used as the feed solution in place of water. It is known that the hydrophilic/hydrophobic properties of the membrane material have an important influence on the membrane flux reduction when treating solutions containing hydrophobic solutes.^[21] The permeate flux of a hydrophilic membrane such as cellulose acetate membrane is only marginally reduced, whereas the flux reduction of a hydrophobic membrane such as polysulfone membrane is significant due to hydrophobic interaction between membrane and surfactant.^[21–24] The hydrophobic interactions are mainly determined by hydrophobic properties of membrane materials and by the properties of both the hydrophilic and hydrophobic parts of the surfactant. In the case of a homologous series of nonionic surfactants, the extent of surfactant adsorption decreases with an increase of the number (m) of oxyethylene group and increases with an increase of the alkyl chain length (n). Interaction forces increase with an increase of the numbers of alkyl chains

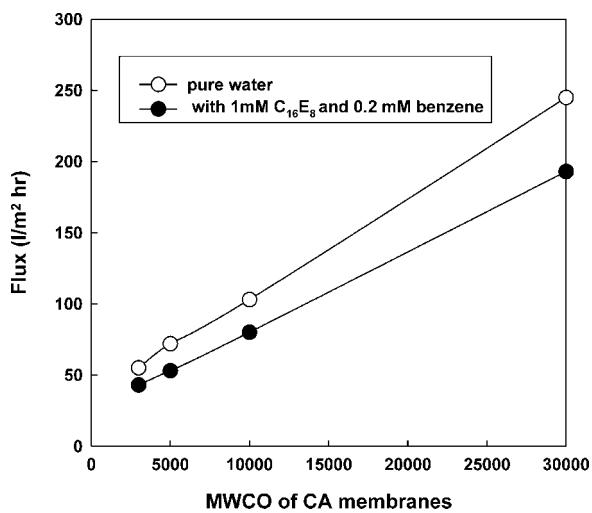


Figure 7. Flow rate through CA membranes at the operating pressure of 3 bar.

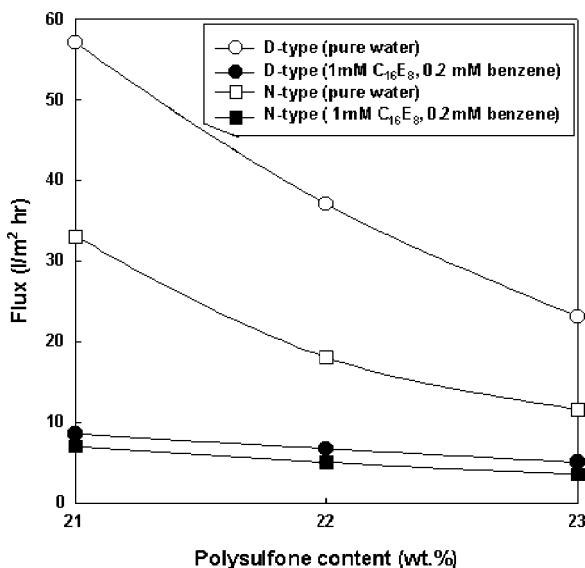


Figure 8. Flow rate through polysulfone membranes at the operating pressure of 3 bar.

while interaction forces slightly decrease with an increase of the numbers of oxyethylene group. Molecular weight of the surfactant molecule also plays an important role, i.e., the longer chain length the higher shear force is needed to go through the membranes. Therefore, the absolute amounts of water and surfactant to go through the membrane pores decrease with an increase in interaction forces and the chain length.

The rejection of benzene examined with polysulfone membranes exhibited a decrease with an increase in polysulfone content of the casting solution, and surfactant rejection also exhibited trends similar to those of benzene (Fig. 9), which is contrary to the expectations based on the MWCO of the membranes. The serious decline in the permeate flux and the apparent abnormal behavior of benzene rejection might be explained on the basis of surfactant adsorption on the membrane surface and the pores caused by hydrophobic interactions. The benzene molecules stayed in the hydrophobic cores of the micelle directed to the hydrophobic surface and pores of membrane, together with the hydrophobic part of the surfactant caused by the destruction of the micelles. Therefore, benzene molecules remaining within the gel layer might be adsorbed on the membrane surface and pores and then entrained with the stream through the membranes.

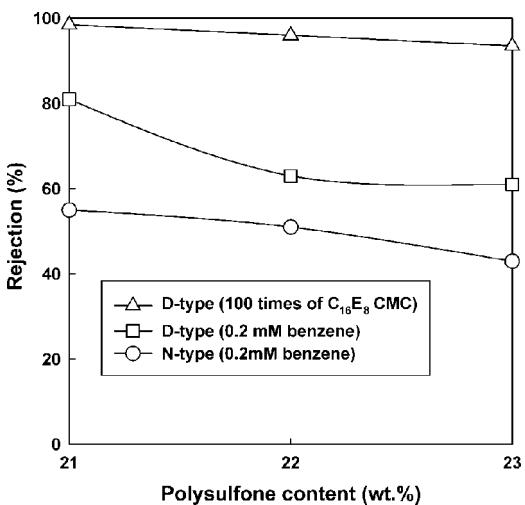


Figure 9. Rejections of surfactant and benzene examined with polysulfone membranes at the operating pressure of 3 bar where the concentrations of surfactant and benzene were 100 times of CMC and 0.2 mM, respectively.

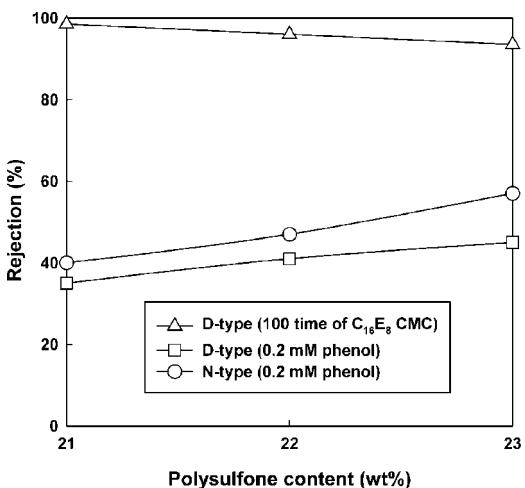


Figure 10. Rejections of surfactant and phenol examined with polysulfone membranes at the operating pressure of 3 bar where the concentration of surfactant was 100 times of CMC.



An increase of the polymer content in the casting solution causes a decrease in pore size of a membrane and the solution flux decreased. Thus the concentrations of benzene and surfactant in permeate should be increased to result in the rejection decrease. However, as shown in Fig. 10, rejection of phenol increased with an increase in polysulfone content. A gel layer formed on the high-pressure side of the membrane enabled the filtration of phenol molecules that stayed in the palisades of the micelle and in the bulk phase of the aqueous solution. The rejection of organics was examined with the polysulfone membranes fabricated using two different types of casting solution, i.e., polysulfone solutions in NMP and those in DMF. As shown in Fig. 9, the rejection of benzene examined with the D-type membranes was always greater than that examined with the N-type membranes when polysulfone content in the casting solution was the same. However, the phenol rejection examined with the D-type membranes was smaller than that examined with the N-type membranes (Fig. 10). The water flux of the D-type membrane was always greater than that of the N-type membrane while the MWCO based on the PEG rejection showed the opposite trend. It means that the pore size in the N-type membrane is smaller than that in the D-type membrane when the casting solution contains the same amount of polysulfone. As exhibited with the membranes fabricated from the casting solution containing different amounts of polysulfone, the decrease in pore size in the polysulfone membrane resulted in increase of the phenol rejection and decrease of the benzene rejection.

The rejection of organics was examined with D-type membranes by changing systematically the hydrophobicity and hydrophilicity of a surfactant i.e., changing n and m in C_nE_m . As shown in Figs. 11 and 12, the rejection of organics increased with increasing the number (n) of a hydrophobic alkyl group and with decreasing the number (m) of a hydrophilic oxyethylene group when each surfactant was added at the same concentration of 1.0 mM. It means that the rejection of organics examined with polysulfone membranes increased with an increase in the hydrophobicity of a nonionic surfactant.

When the operating pressure was increased from 3 bar to 5 bar, phenol rejection increased with pressure, but benzene rejection decreased with pressure as shown in Fig. 13. The increase in rejection with operating pressure is usually observed in the ultrafiltration process mainly due to the water flux increase. Since phenol molecules mainly exist in aqueous phase and in the hydrophilic part of the gel layer, the rejection of phenol increases with operating pressure. In the previous work,^[24] the decline of surfactant rejection with an increase in operating pressure caused by the strong hydrophobic interactions between membrane material and surfactant was

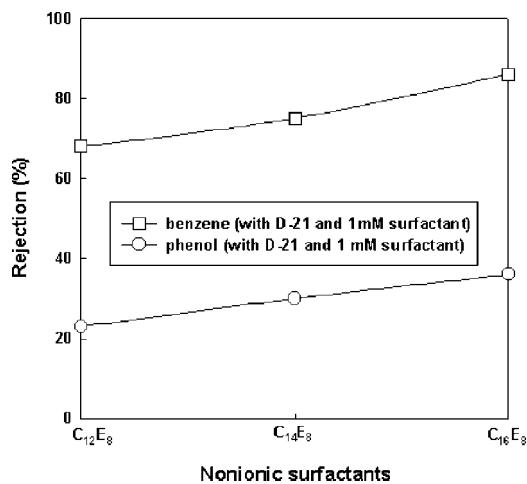


Figure 11. Benzene and phenol rejections examined with D-21 membrane at the operating pressure of 3 bar where the concentration of each surfactant having different numbers of methylene groups was fixed at 1 mM.

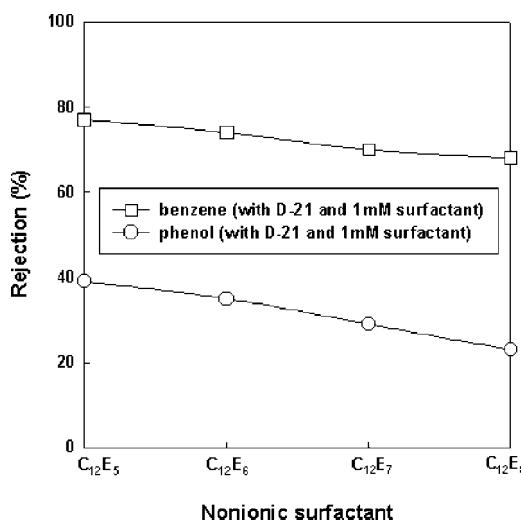


Figure 12. Benzene and phenol rejections examined with D-21 membrane at the operating pressure of 3 bar where the concentration of each surfactant having different numbers of ethylene oxide groups was fixed at 1 mM.

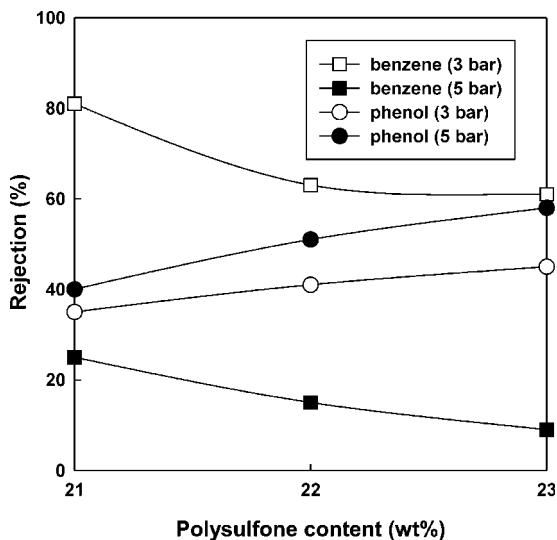


Figure 13. Benzene and phenol rejections examined with polysulfone membranes (D-type) at the two operating pressures of 3 and 5 bar where 100 times of CMC for C₁₆E₈ surfactant was added to the feed solution. Note that surfactant rejections were examined with cellulose acetate.

observed. On one hand, since benzene molecules went along with surfactant during the MEUF process, the absolute amount of benzene going through the membrane pores rapidly increases when the operating pressure is high enough to break hydrophobic interactions.

CONCLUSIONS

The micellar-enhanced ultrafiltration (MEUF) process for obtaining pure water from aqueous solutions containing small amounts of phenol and benzene, has been studied. A homologous series of polyethyleneglycol alkylether nonionic surfactants having different numbers of oxyethylene groups and lengths of hydrocarbon chains was used. Cellulose acetate membranes and polysulfone membranes having different molecular weight cut-offs (MWCO) were used as hydrophilic and hydrophobic membranes, respectively. The performance of the MEUF process in removing organics was shown to depend on the membrane characteristics, surfactant characteristics, organic characteristics, and operating pressure. The decline



in the permeate flux for the polysulfone membranes was serious, while that for the cellulose acetate membranes was not remarkable. The rejection of organics and surfactants for cellulose acetate membranes increased with decreasing membrane pore size and with increasing operating pressure. The performance for cellulose acetate membranes was similar to that observed in the traditional ultrafiltration. The rejection behavior of phenol for polysulfone membranes was also similar to that for cellulose acetate membranes. However, benzene rejection for polysulfone membranes was totally different from that for the cellulose acetate membranes. Benzene rejection for polysulfone membranes decreased with increasing operating pressure and with decreasing pore size of a membrane. The rejections of organics increased with increasing hydrophobicity of a nonionic surfactant when feed solution contained the same amounts of surfactant. The results relating to the solubilization of organics indicated that most of the benzene molecules remained in the hydrophobic cores of the micelles, while phenol molecules might remain in the palisades of the micelles and in the bulk phase of the solution. Therefore, benzene was more effectively removed than phenol via the MEUF process.

ACKNOWLEDGMENT

This work was supported by the Dongguk University Research Fund.

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Received July 2002

Revised November 2002