A study of catalytic *p*-cyclodextrin carbonate membrane reactor performance in PNPA hydrolysis

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Abstract

A catalytic cyclodextrin membrane reactor system is a promising tool for the production of chemicals of potential interest. To investigate the *application* of membrane immobilized carbonate derivative β-cyclodextrin (β-CD) for the *p*-nitrophenylacetate (PNPA) hydrolysis, the effect of different average degree of β-CD carbonate substitution (DS), the amount of immobilized β-CD carbonate and operating conditions such as pH and temperature have been examined under a constant substrate concentration. The initial reaction rate as a function of immobilized β-CD carbonate concentration resulted in an increase of the *p*-nitrophenol (PNP) production rate. A complete hydrolysis of PNPA was reached after 3 h of operation by using the β-CD carbonate with DS equal to 7. These data suggest the conditions under which the β-CD carbonate membrane reactor with 2.5 wt% to 7.5 wt% of β-CD carbonate (DS 5 and 7) can operate with high productivity and low cost: a reaction temperature of 20°C, a pH of 8.4, low permeation rate and transmembrane pressure.

Keywords: Catalytic membrane reactor; β-cyclodextrin carbonate

1. Introduction

In a previous study we investigated preparation, structure and catalytic properties of a membrane in which O-octyloxycarbonyl-β-cyclodextrin has been immobilized, using the hydrolysis of *p*-nitrophenylacetate (PNPA) as a model reaction to characterize the *catalytic* pathway and reactor productivity [1]. In this study the influence of some *parameters* on the catalytic performance of the β-CD carbonate membrane reactor, such as: amount of immobilized cyclodextrin, degree of carbonate substitution of cyclodextrin, reaction pH and temperature, have been examined.

In aqueous basic solutions cyclodextrins cleave phenyl acetates by acyl transfer from the ester to an ionized hydroxyl group of the cyclodextrin. The reaction takes place with an inclusion complex in which the phenyl group of the ester stays in the hydrophobic cavity of the CD [2]. The efficiency of the ester cleavage is enhanced in the presence of immobilized mem-

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brane cyclodextrin since the PNPA orients its phenyl group into the CD cavity in geometries that are suitable for the acyl transfer [1]. Catalytic activity of β-CD carbonate is a function of DS and of the strength of the alkaline medium. In homogeneous system the catalytic action of CD derivatives has been found to decrease with increasing of the substitution degree [3,10]. Moreover the β-CD acyclic carbonate derivatives are not stable because of the hydrolysis of carbonate at basic pH, whereas the rate constant for the CD-catalyzed reaction is maximal at a pH of $12 \div 13$ [2,8].

We have found that the β-CD acyclic carbonate derivative seems to be an effective nucleophilic catalyst when incorporated in the PEEKWC membrane [1]. It seems to possess a high nucleophilicity towards the reagent p-nitrophenylacetate leading to the formation of the product by a large rate acceleration.

In the present study we have prepared membranes based on PEEKWC and β-CD acyclic carbonate with DS 5 and 7. Different amounts of CD derivative 2.5 wt%, 5 wt%, 7.5 wt% have been immobilized. The CD derivative density and DS may help to understand how the cyclodextrinic catalytic properties could depend on the change in the geometry of the active site and on the inclusion complex in the membrane structure. This study shows the performance of a novel design of catalytic membrane reaction, in which the specific properties of a non conventional catalyst immobilized in a polymeric membrane can promote and extend new applications of these systems.

2. Experimental

2.1. Materials

PEEK-WC, poly(oxa-p-phenylene-3,3-phthalido-p-phenylenxoxa-p-phenylenenexoxi-p-phenylene) was supplied from the Chanchung Institute of Applied Chemistry, Academia Sinica. The polymer powder was washed with

methanol at room temperature and then dried in a vacuum oven before membrane preparation.

β-cyclodextrin (β-CD) was a gift of Roquette Italia (Cassano Spinola-ltaly). Its O-octyloxy-carbonyl derivative was synthesized according to the literature and the average degree of substitution (DS 5 and 7) was determined via quantitative FT-IR analysis [4].

p-nitrophenylacetate (PNPA) and p-nitrophenol (PNP) were purchased from commercial sources (Fluka Chemicals) and were used without purification.

2.2. Methods

2.2.1. Membrane preparation and characterization

The membranes were prepared following the traditional phase inversion process [5] which permits the production of membranes with an asymmetric pore structure. The PEEK-WC polymer and O-octyloxycarbonyl-β-CD (DS 5 and 7) were dissolved in N,N-dimethylformamide (DMF). The casting solution was centrifuged for 15 min at 4000 rpm in order to remove macroscopic impurities present in the PEEK-WC powder.

The flat membranes were cast on a glass plate at 28°C with a gardner knife gap of 250 μm in atmospheric air (humidity relative 50–60%). The solvent was allowed to evaporate 45 s. The cast film was then immersed in a coagulation bath containing distilled water at 27°C; the cast films were kept in water for 10 min and then transferred to fresh distilled water for 2 h. All membranes were stored in water. The operational conditions for membrane preparation are listed in Table 1.

The hydraulic permeability coefficient (Lh) was calculated from measurement at 20°C of the mass flux obtained at various average transmembrane pressure differences. The membrane morphology was determined with a scanning electron microscopy (JEOL T330). Cross sections of membrane were obtained by freeze fracturing of the sample in liquid nitrogen.

Table 1
Conditions of asymmetric PEEK-WC/O-cyclodextrin carbonate membranes (AM) preparation

| Membrane | Polymer solution (% w/w) | β-cyclodextrin acetate (% w/w) | | Solvent, DMF (% w/w) |
		DS = 7	DS = 5	
AM-1	15.00	2.5	–	82.50
AM-2	15.00	5.0	–	80.0
AM-3	15.00	7.5	–	77.50
AM-4	15.00	–	2.5	82.50
AM-5	15.00	–	5.0	80.0

2.2.2. Reactor equipment

The membrane reactor configuration has been described by Drioli et al. [1]. A simple Millipore stirred cell device was used at 500 rpm. The membrane area was 13.2 cm^2. The volume of reactor was 50 ml. The solution of PNPA (10^{-4} M) was continuously ultrafiltered across the membrane with a permeate flux of 4.5 l/h · m^2. A source of nitrogen was connected to the top of the stirred cell and the pressure value was adjusted to obtain the same permeate flux through each membrane.

2.2.3. Reactor operation and analytical methods

A standard solution of PNPA 0.02 M in acetonitrile was prepared. In the typical experiment, 50 ml of phosphate buffer (pH 7.0, 7.8, 8.4, 10.0) were placed in the CD-membrane reactor carbonate and 0.25 ml of the standard solution of PNPA was added. The final ester concentration was equal to 10^{-4} M and the acetonitrile concentration was 0.5%.

During the reaction, samples (3 ml) of permeate and retentate were collected and concentrations of PNP were determined. The permeate samples were returned into the feed cell and recirculated through the membrane after each sampling and spectrophotometric monitoring. The total concentration of the PNP produced in the membrane reactor was calculated from the equation:

$$C_{Tot} = \frac{C_{Perm} \cdot v_{Perm} + C_{Ret} \cdot v_{Ret}}{v_{Perm} + v_{Ret}}$$

where C_{Perm} and C_{Ret} are the concentrations of PNP in permeate and retentate, respectively and

v_{Perm} and v_{Ret} are the volumes of permeate and retentate, respectively.

p-Nitrophenol concentration was determined spectrophotometrically at 401 nm using a 1 cm quartz cell and a Shimadzu UV-160A UV-VIS recording spectrophotometer, at room temperature. The reference compartment contained a phosphate buffer. A calibration curve for pH in the phosphate buffer was made in the concentration range 10^{-6}–10^{-4} M and the curve was approximated with a linear function.

Because hydrolysis of esters occurs spontaneously in alkaline solutions, the hydrolysis of PNPA (10^{-4}) has been studied at four pH values (7,0, 7.8, 8.4 and 10.0) applying the AM-3 membrane. The influence of different operating temperatures (20, 40, 50 and 60°C) on the productivity of the CD-membrane (AM-3) reactor was determined.

3. Results and discussion

3.1. Membranes

The different structures of phase inversion membranes are related to the polymer and CD concentrations in the casting solution [6]. The actual membrane formation process is usually a diffusion induced phase separation (DIPS) process.

The membrane forming system is composed of PEEKWC, O-octyloxycarbonyl β-CD derivative, DMF as solvent and water as non solvent. All components are only miscible in a concentration range between 15 wt% PEEKWC/2.5 wt% O-octyloxycarbonyl β-CD derivative and
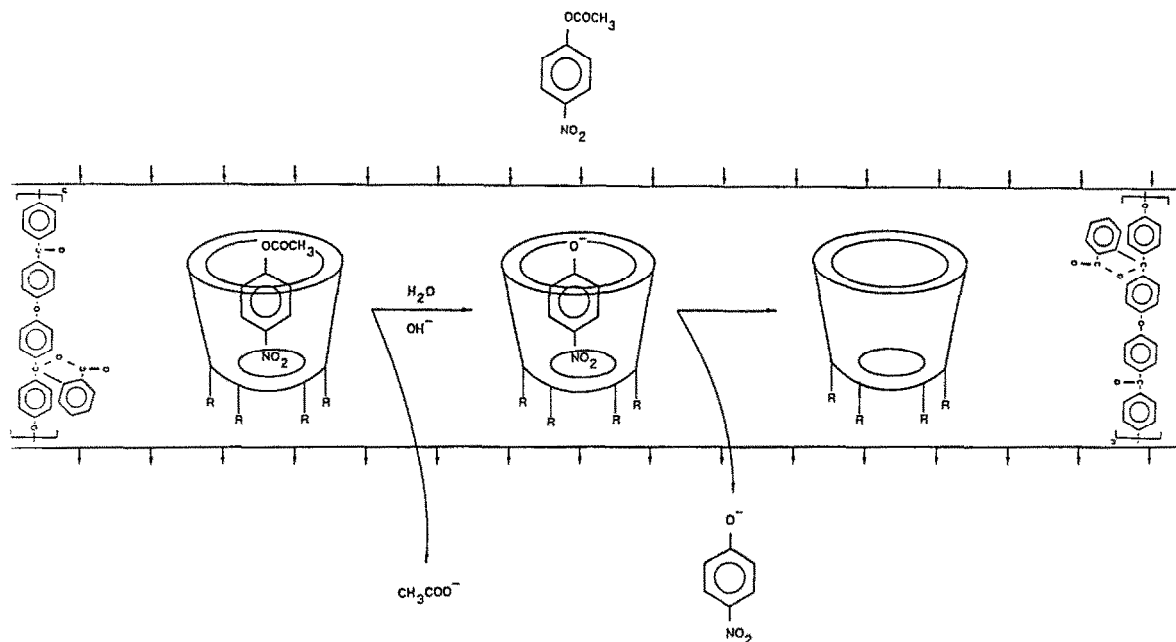
Fig. 1. Scheme of p-nitrophenylacetate (PNPA) hydrolysis reaction on octyloxycarbonyl cyclodextrin membrane. R = $OCOO(CH_2)_7$–CH_3.

15 wt% PEEKWC/7.5 wt% O-octyloxy-carbonyl β-CD derivative. At high CD concentrations, i.e. equal or more than 10 wt%, a homogeneous casting solution cannot be obtained. The different membrane structure, porosity and permeability properties, mainly depend upon diffusivities and the ratio of solvent and non solvent exchange that are influenced by components concentration.

Figs. 2–4 show the characteristic morphologies observed in this study. Scanning electron

microscopy (SEM) photomicrograph of cross section of all membranes show a typical skinned-structure in which a porous skin layer is integrated in the thick porous substructure. The SEM micrograph of AM-1, in Fig. 2, shows the structure composed of voids, fingerlike in shape, with a porous thin skin at the air–polymer interface according to Strathmann's study [5] in which he found a correlation between the membrane structure and the precipitation rate. Systems with rapid precipitation rate tend to form
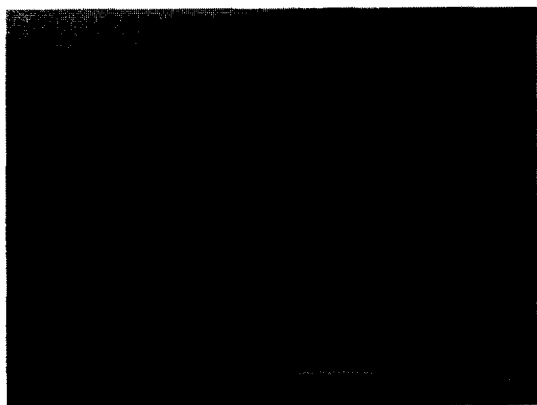

Fig. 2. Scanning electron micrograph of cross-section of AM-1.

Fig. 3. Scanning electron micrograph of cross-section of AM-2.

Fig. 4. Scanning electron micrograph of cross-section of AM-3.

AM-1 AM-2 AM-3 AM-4 AM-5

Fig. 5. PNPA hydrolysis versus time carried in O-octyloxy-carbonyl-β-CD in a stirred membrane reactor as a function of CD-loading of the membrane.

fingerlike structure whereas systems with slow precipitation rates result in a sponge-type structure. The Fig. 3 shows a sponge-type structure of AM-2 and the Fig. 4 shows a combination of tear dropped in shape and sponge-type structure.

All membranes show a linear dependence of water flux on the applied pressure gradient, at constant temperatures Increasing the CD content, a decrease of the hydraulic permeability is observed related to a overall lower porosity of the skin and also to the average lower pore size (see Table 2).

3.2. Hydrolysis Of PNPA in the β-cyclodextrin carbonate membrane reactor

PNPA hydrolysis reaction is an ideal model reaction for its simple mechanism, widely investigated to obtain information on the catalytic and selectivity properties of CDs [7–9]; an improved reaction rate and productivity has been

already observed when the reaction was carried out in the catalyzed β-CD carbonate membrane reactor in comparison to the alkaline batch reactor [1].

3.3. Effect of CD amount and substitution degree (DS) on the membrane reactor productive efficiency

Fig. 5 and Table 3 show the reaction rate and productivity obtained for the five membrane reactors. Results exhibit that the initial reaction

Table 2
Flux water and hydraulic permeability measurements of AM at P = 0.8 bar

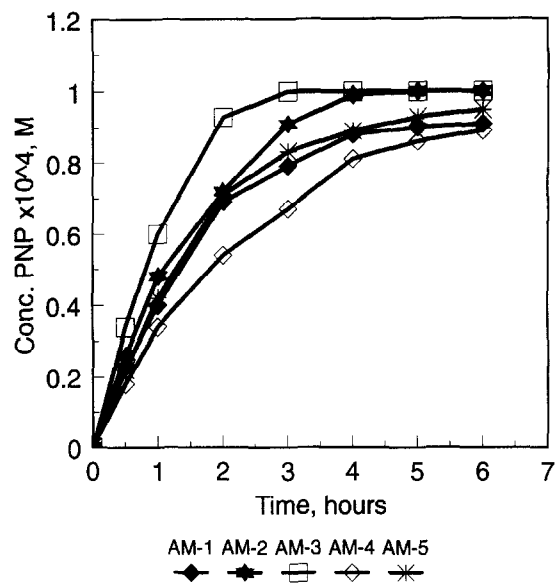| Membrane	Flux water (1/m² · h)	Hydraulic permeability (1/m² · h · bar)
AM-1	154.60	193.20
AM-2	50.0	62.50
AM-3	31.80	38.60
AM-4	143.20	179.70
AM-5	45.50	56.80

Table 3
Initial reaction rate, productivity and conversion degree of membrane reactors

Membrane	Reaction rate (mmol/ml · h)	Productivity [a] (mmol/h)	Conversion degree [b] (%)
AM-1	0.45	4.62	77.00
AM-2	0.58	5.46	91.00
AM-3	0.74	6.00	100.00
AM-4	0.40	4.02	67.00
AM-5	0.50	4.98	83.00

[a] Productivity was calculated from following expression: productivity = permeate flow rate × PNP concentration, after 3 h.
[b] Conversion degree was calculated after 3 h.

rate and productivity are higher for AM-1, AM-2 and AM-3 containing β-cyclodextrin-O-octyloxycarbonyl derivative with DS 7. The investigation of DS parameter has been carried out by correlating the CDs derivatives activity with their structural morphology when immobilized in the polymeric PEEKWC membrane. It is widely reported that the phenyl ester hydrolysis involves in complex formation of the substrate with cyclodextrin and the phenyl portion of the substrate is included in the cyclodextrin cavity from the secondary hydroxyl group side. The catalysis by cyclodextrin, consisting in cleavage of phenyl esters, is carried out by nucleophilic attack of a secondary group, in the ionic state, on the carbonyl carbon atom of substrate [2,3,10]. The higher activities of the membrane-loaded CD derivative with DS 7 in comparison to the membrane-loaded CD derivative with DS 5, suggest that the catalytic *activity* is not affected by a moderate increasing in the substitution degree of the acyclic chains (*from 5 to 7*). This should mean that the acyclic carbonate chains are bonded preferentially to the primary hydroxyls side of the parent β-CD thus forming bonds with PEEK polymer so that the hydrophobic cavity is free and oriented in the membrane structure in a geometry able to include and cleave the phenyl acetate. This result agrees with the previous experimental data [1,4]. A schematic representation of this mechanism is shown in Fig. 1.

We have been using three concentration of CD derivative: 2.5 wt%, 5 wt% and 7.5 wt% for CD with DS 7 and two concentration of CD derivative: 2.5 wt% and 5 wt% for CD with DS 5 (higher concentrations lead to formation of a non homogeneous casting solution). In all cases the reaction rate was measured from the quantity of PNP produced. The hydrolytic activity of the immobilized CD derivatives was linearly correlated with the increasing of CD density in the membrane, confirming a real catalytic activity of CD derivatives when entrapped in the membrane. The AM-3 had the highest catalytic activity; it was chosen to investigate the effects
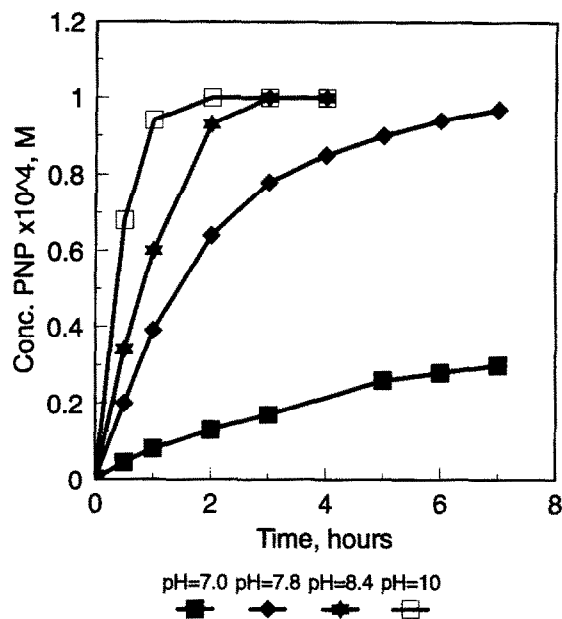

Fig. 6. PNPA hydrolysis versus time carried in O-octyloxycarbonyl-β-CD in a stirred membrane reactor as a function of pH values.

of pH and temperature on the ester hydrolysis and on the reactor productivity. pH and temperature stability was improved by immobilization.

3.4. pH dependence of the membrane reactor productive efficiency

The AM-3 has been tested at different pH with PNPA solution. Fig. 6 shows that the catalytic activity of AM-3 increases with increasing of pH, as expected. However, also by working at moderate pH values, i.e. 8.4 and 7.8, the reaction reach a 100% of conversion after three hours and after seven hours, respectively.

This modified cyclodextrin entrapped in the membrane may really display enzyme-like behavior by utilizing the orientation effect and fast hydrolysis in moderate basic pH region, whereas the reaction rate for the free cyclodextrin catalyzed hydrolysis is maximal at pH 12 ÷ 13 [8].Table 4 indicates the results of reaction rate and productivity as a function of pH.

The acyclic carbonates of β-CDs can be hydrolysed by the alkaline medium giving the

soluble parent cyclodextrin [4]. We have found that the acyclic carbonate derivative of β-CDS, when dispersed in the polymeric membrane, have shown a significant stability: the permeation of hydroxyl ions through the membrane does not hydrolyze the carbonate at basic pH under these operating conditions. All runs have been repeated at least three times without any lost of catalytic activity thus testing the data reproducibility and the stability of the membrane. Moreover, no detectable amount of β-CD in the feed solution was checked by TLC analysis [4].

3.5. Temperature dependence of the membrane reactor productive efficiency

The effect of temperature *on the CD catalyzed-activity* of AM-3 has been studied, as showed in the Fig. 7. Noticeable, the membrane does not show any loss of activity also by working at 60°C thus demonstrating *a good thermal* stability of the *n*-octyl carbonate of β-CD when entrapped in PEEKWC membrane.

In order to measure the activation energy of the reaction, the Arrhenius equation was used. Assuming that the reaction order does not change with the temperatures E_{att} value of 8.5 kcal/mol is obtained. This low value is in accordance to the previously reported data [11] thus confirming the catalytic system membrane reactor performance. Probably the interaction of the alkyl chain of the carbonate derivatives of β-CD with the polymer chain lead to a decreasing of the degrees of freedom of the carbonate

Table 4
Initial reaction rate, productivity and conversion degree of membrane (AM-3)

pH	Reaction rate (mmol/ml · h)	Productivity [a] (mmol/h)	Conversion degree [b] (%)
7.0	0.08	1.08	17.00
7.80	0.38	4.68	78.00
8.40	0.74	6.00	100.00
10.0	1.43	6.00	100.00

[a] Productivity was calculated from following expression: productivity permeate flow rate × PNP concentration, after 3 h.
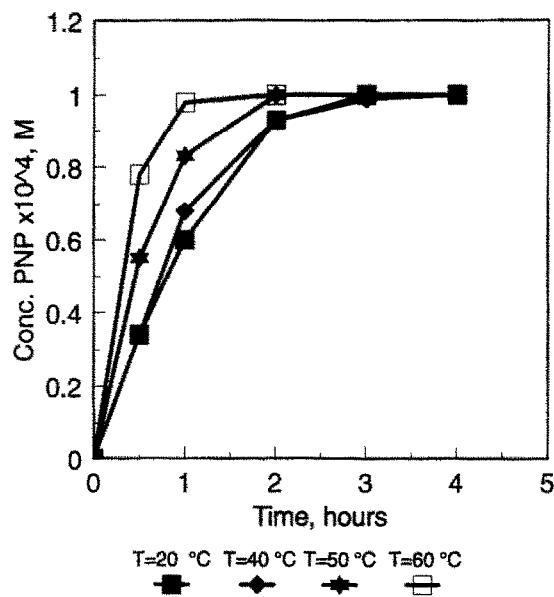[b] Conversion degree was calculated after 3 h.

Fig. 7. PNPA hydrolysis versus time carried in O-octyloxy-carbonyl-β-CD in a stirred membrane reactor as a function of operating temperatures.

of β-CD. This allows the positioning of the reagents in a suitable geometry around the cavity of the β-CD carbonate that highly facilitate the formation of the required inclusion compound with the substrate.

4. Conclusions

Immobilization in the polymeric PEEKWC membrane of CD derivatives with three different concentration (2.5 wt%, 5 wt% and 7.5 wt%) and two different DS (5 and 7) has been performed. The AM-3 membrane with CD concentration of 7.5 wt% and DS 7 shows the higher reaction rate in the hydrolysis of PNPA. The cleavage of *p*-nitrophenylacetate by PEEKWC membrane immobilized β-cyclodextrin-O-octyloxy carbonyl derivative has been found to be sensitive to the substitution degree of the acyclic carbonate. The hydrolytic activities of the PEEKWC membrane immobilized β-cyclodextrin-O-octyloxy carbonyl derivative has been investigated as a function of pH and temperature. Mild operating conditions in terms of pH and temperature were obtained. Fast hy-

drolysis in moderate basic pH region, $7.8 \div 8.4$, and temperature of 20°C may be used. In the membrane, the CD carbonate derivatives shows to have more stability because of their chemical resistance to alkaline attack. The entrapment of CD in the polymeric membrane optimizes the interaction with the substrate, increases the chemical stability of the catalyst, allows the reuse of the catalytic membrane.

Acknowledgements

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