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Changing the microstructure of membranes using intense electric fields: Dielectric strength studies

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ABSTRACT

Electric breakdown studies using a range of membranes made of various polymers showed that, in principle, electrical poling can be applied to most membranes types. The results showed that the electric breakdown behavior of membranes was affected by their material type. The microstructure of the membranes was the most important factor in determining their dielectric strength. It was found that anisotropic membranes with layered structures had the lowest electric breakdown strength. The sample size and temperature also affected the electric breakdown of membranes. The former is probably due to a probabilistic presence of defects.

1. Introduction

Controlling the microstructure of membranes is one of the key objectives in membrane manufacturing and sophisticated methods have been developed to control the pore size and surface topography of membranes [1–4]. Recently, we developed a method using an intense electric field to change the properties of prefabricated PVDF membranes [5–9]. Although the main purpose of electrical poling was to impart piezoelectric properties to the PVDF microfiltration membranes, further experiments showed that treatment in an intense electric field changed the electrical properties, microstructure [7] and filtration properties of these membranes [10]. Filtration experiments showed that electrically treated PVDF microfiltration membranes had different fouling mechanism, lower initial flux but higher rejection. The improvement in rejection was more significant than the decline in the flux [10].

Filtration experiments performed to evaluate the effect of treatment in an intense electric field on the separation performance of a selection of other microfiltration, ultrafiltration, nanofiltration and reverse osmosis membranes were presented elsewhere [11]. It was found that treatment in an intense electric field can generally increase the rejection of membranes at a cost of relatively less significant flux decline. Characterizing the microstructure of the membranes before and after treatment in an intense electric field showed that the electrically treated membranes generally had smoother surfaces and tighter microstructure [11].

This suggested that the same technique can be used to alter the microstructure of other *pre-fabricated* membranes. Sometimes it is required to modify pre-formed membranes to enhance their overall performance. The typical objectives are to eliminate membrane defects, control pore size and improve the fouling resistance, flux or selectivity of membranes [12]. The techniques used successfully are solvent treatment [13], surface coating [14] and chemical treatment [15] including but not limited to fluorination [16], cross-linking [17] and pyrolysis [18].

Alternative (AC) electric fields have been used also to decrease the number of structural defects *during* the fabrication of membranes [19–24]. However, intense DC electric field has not been used to change the microstructure of pre-fabricated commercial membranes. In the present study, the possibility of using a DC electric field to alter the microstructure of various membranes is investigated. To do this, it was necessary first to investigate the electric breakdown behavior of the membranes.

The main types of instability that lead to the failure of polymers in electric fields are thermal degradation, electromechanical forces, ionization and super-heating. Thermal degradation is the most universal instability and it is believed that the conductivity growth leads to an increase in joule thermal power dissipation that, due to the limited heat conduction of polymers, causes temperature increases that eventually lead to local melting and the formation of discharge channels [25,26]. Mechanical instabilities are reported

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to develop due to the electromechanical forces generated by interaction of free and fixed charges. These electromechanical forces may result in weak points, such as micro-cracks [26,27]. Ionization instabilities are thought to be related to charge carrier generation resulting from electrostatic or shock ionization. Charge carrier heating in dielectrics can result in super-heating, which is followed by a substantial localized growth in conductivity [26,28]. Thermal and electromechanical instabilities are the most common theories used to explain the electric breakdown of bulk dielectrics. However, all of these instabilities can coexist, convert to other forms or strengthen each other synergistically [25–31]. Electrical breakdown behavior of a wide range of membranes is investigated in the present study.

2. Materials and methods

To achieve conclusive results, we examined a wide range of membranes made of different materials that varied in their microstructure. The membranes used in this study are listed in Table 1.

2.1. Electric breakdown analysis

To evaluate the electric strength, a $20 \times 20\ \text{mm}^2$ rectangular specimen of each membrane was sandwiched between two electrodes. In order to prevent electrical arcing, the top electrode was $10 \times 10\ \text{mm}^2$ whilst the bottom electrode was $30 \times 30\ \text{mm}^2$. The set-up was located on the surface of a hot plate and a temperature controller was used to control the temperature of the system. The output current flow was measured to an accuracy of 1 μA using the built-in meters.

To investigate the pre-breakdown behavior of the membranes and measure their electric breakdown voltage, the DC voltage was gradually increased from zero at a rate of 100 V/min and the current was recorded every minute until the point of electrical failure. The average of three tests on each sample was recorded. For safety reasons, the experiment was stopped if the breakdown

Table 1
Characteristics of the membranes used to evaluate the feasibility of electrical poling on various membranes. MF: Microfiltration, UF: Ultrafiltration, NF: Nanofiltration, RO: Reverse osmosis and FO: Forward osmosis membranes.

Code	Material	Pore size (μm)	/MWCO	Description
MF-1	Polyvinylidene fluoride	0.2	–	–
MF-2	Polyethersulfone	0.2	–	–
MF-3	Polyethersulfone	0.1	–	–
MF-4	Nylon	0.2	–	–
MF-5	Nylon	0.1	–	–
MF-6	Poly propylene	0.2	–	–
MF-7	Poly propylene	0.1	–	–
MF-8	Polyester	0.2	–	–
MF-9	Cellulose acetate	0.2	–	–
MF-10	Poly carbonate	1	–	–
MF-11	Poly carbonate	0.8	–	–
MF-12	Poly carbonate	0.6	–	–
MF-13	Poly carbonate	0.4	–	–
MF-14	Poly carbonate	0.2	–	–
MF-15	Teflon	0.2	–	Un-laminated
UF-1	Polyamide/polysulfone* [19]	–	4000	GE Osmonics UF GM
UF-2	Composite polyamide	–	1000	GE Osmonics
UF-3	Cellulose acetate	–	20,000	GE Osmonics UF CQ
UF-4	Polyethersulfone	0.03	–	–
UF-5	Polystyrene [20]	–	60,000	GE Osmonics UF EW
UF-6	Polyethersulfone	–	5000	PT GE Osmonics UF
UF-7	Polyvinylidene fluoride	–	100,000	Koch HFM-180
UF-8	Polyvinylidene fluoride	–	50,000	Koch HFM-100
UF-9	Polyvinylidene fluoride	–	30,000	GE Osmonics UF JW
UF-10	Polyvinylidene fluoride	–	20000	Alfa laval ETNA 01-PP
UF-11	Polyvinylidene fluoride	–	10,000	Alfa laval FS61-PP
UF-12	Polyvinylidene fluoride	–	1000	Alfa laval ETNA 01-PP
UF-13	Ultrafilic*	–	100,000	GE Osmonics UF MW
UF-14	Acid resistance* [21]	–	1000	Koch SelRO, MFP-36
NF-1	Thin film polyamide	0	190 [20]	GE Osmonics NF HL
NF-2	Thin film polyamide	0	260 [20]	GE Osmonics NF DL
NF-3	Thin film polyamide	0	190 [20]	GE Osmonics NF DK
NF-4	Composite polyamide	–	200	Koch, TFC-SR3
NF-5	Cellulose acetate	0	150 [20]	GE Osmonics NF K
NF-6	Solvent resistance* [22]	–	200	Koch SelRO, MFP-44
NF-7	Composite polymeric* [23]	–	300–400 [23]	Koch, TFC-SR2
NF-8	Acid resistance* [21]	–	200	Koch SelRO, MFP-34
RO-1	Polyamide	0	0	RO Toray, 80LB
RO-2	Polyamide	0	0	RO Toray, 80B
RO-3	Polyamide	0	0	RO Toray, 70UB
RO-4	Polyamide	0	0	RO Toray, 70B
RO-5	Polyamide	0	0	GE Osmonics RO AG
RO-6	Thin film polyamide	0	0	GE Osmonics RO SE
RO-7	Polyamide	0	0	GE Osmonics RO AD
RO-8	Polyamide	0	0	GE Osmonics RO AK
RO-9	Cellulose acetate	0	0	GE Osmonics RO CE
FO-1	Polyamide*	0	0	–

* Exact composition not known.