



# Performance study of pervaporation in a microfluidic system for the removal of acetone from water

Yali Zhang<sup>a</sup>, Nieck E. Benes<sup>b</sup>, Rob G.H. Lammertink<sup>a,\*</sup>

<sup>a</sup>Soft Matter, Fluidics and Interfaces, MESA+ Institute for Nanotechnology, Faculty of Science and Technology, University of Twente, Enschede, The Netherlands

<sup>b</sup>Films in Fluids/Inorganic Membranes, MESA+ Institute for Nanotechnology, Faculty of Science and Technology, University of Twente, Enschede, The Netherlands

## HIGHLIGHTS

- We report an efficient  $\mu$ -PV device to separate acetone from water.
- 81% acetone is removed within just 3 min at room temperature.
- Our microfluidic device provides insight in the mass transport limitations.
- A design criterion is derived to characterise and optimise the PV process.
- Promising potential as a universal tool to remove VOCs from water in microscale.

## ARTICLE INFO

### Article history:

Received 28 July 2015

Received in revised form 21 September 2015

Accepted 24 September 2015

### Keywords:

Pervaporation  
Microfluidic  
Mass transfer  
Modelling  
VOCs

## ABSTRACT

Separation of organic compounds from aqueous streams presents many challenges regarding materials and separation conditions. Such separations become increasingly important with the development of bio-mass related processes. Pervaporation is a promising membrane process capable of isolating organic species from aqueous feeds. Typically, volatile organic compounds (VOCs) removal from water suffers from mass transport limitations due to depletion of the minor component at the membrane surface. Understanding of such mass transport limitations is crucial for the development of novel pervaporation membranes and methods. In this work, we present a performance study on the removal of trace amount of acetone from water via pervaporation to provide insight on mass transport limitations. We used glass microfluidics containing a thin polydimethylsiloxane (PDMS) membrane that allows very fast removal of acetone from water. Via modelling and experiments, we quantitatively investigate the mass transfer coefficients of acetone through the liquid boundary layer ( $k_l$ ) and that of the membrane ( $k_m$ ) by varying membrane thicknesses and feed flow rates. High acetone removal efficiency of 81% is achieved for just 3 min residence time at room temperature for a 35  $\mu$ m thin membrane. A design criterion based on intrinsic system parameters is derived to engineer the pervaporation system for both micro- and macro-scales. Our micro-PV device shows promising potential regarding the characterisation of pervaporation processes and materials for the removal of VOCs from water.

© 2015 Elsevier B.V. All rights reserved.

## 1. Introduction

The broad ranges of functionality and versatility of microchemical systems has promoted their transformation from simple devices, like micro-reactors [1–3], micro-mixers [4,5], and micro-separators [6,7], to complex multi-step integrated networks [8–11]. Developing a continuous multi-step microchemical synthesis is of particular interests nowadays. Moreover, such systems

provides fundamental insight regarding the mass transport kinetics.

Separating immiscible liquids in microdevices has been intensively investigated exploiting capillary phenomena which become stronger at smaller length scales [12,13]. Separating miscible liquids requires different approaches. Trace removal of volatile organic compounds (VOCs) from water inherently suffers from mass transport limitations posing challenges regarding fast and complete purification. Few studies have attempted to accomplish microfluidic separation by implementing membrane technology [14,15]. Zhang et al. [14] reported membrane distillation in a microfluidic system to separate water-methanol mixtures. By

\* Corresponding author.

E-mail address: [r.g.h.lammertink@utwente.nl](mailto:r.g.h.lammertink@utwente.nl) (R.G.H. Lammertink).

generating a temperature gradient in a stacked microdevice, methanol vapour was separated from water and collected in a cooling channel. Kaufman et al. [15] fabricated a high pressure microfluidic cell for Nanofiltration/Reverse Osmosis separation. They have investigated the performance of the device via both experiments and simulation and concluded that a shallower channel is beneficial for minimising concentration polarisation. In addition to these membrane technologies in microdevices, pervaporation (PV) seems another interesting but relatively unexplored candidate.

PV is an efficient membrane process to separate minor components from liquid mixtures by partial vapourisation and permeation. Such process is performed by bringing a liquid mixture in contact with one side of a membrane while a vacuum or a sweeping gas is applied to the other side. Species with higher affinities for the membrane, diffuse preferentially through the membrane and vapourise at the other side of the membrane. The created concentration gradient or the partial pressure difference across the membrane is the driving force for the separation process. The advantages of PV, regarding energy requirements and simple process control, allow for competitive applications like separating VOCs from water, aqueous acrylic latex, dehydrating organic solvents, and organic-organic solvent separation [16–20]. The study of VOC pervaporation using microfluidic devices is of particular interest due to the notorious concentration polarisation, or depletion, resulting in severe mass transport limitations.

Implementing pervaporation into microfluidic devices has been accomplished in some examples [21–24]. Transport of water through a polydimethylsiloxane (PDMS) layer was used to investigate concentration profiles and phase diagrams of the retained solute [22,25,26]. Ziemecka has recently reported progress on concentrating hydrogen peroxide by pervaporation in a microfluidic device by varying the process temperatures. The experimental results closely resembled their 1D modelling work. No investigation on the mass transport resistance was reported in their study [24]. Among these studies, PDMS membranes are commonly selected as a results of their properties including optical transparency, ease of integration into microdevices and low-cost.

The mass transport mechanisms of PV systems can be described in various models according to the selection of dense or porous membranes [27–30]. The resistance-in-series model is widely accredited in describing the mass transport for dense membrane pervaporation systems under steady state. Three serial mass transfer resistances are defined in this model (Eq. (1) and (2)); the resistance in the feed liquid ( $1/k_l$ ), that across the membrane ( $1/k_m$ ) and that in the membrane permeate ( $1/k_p$ ). The  $1/k_p$  is normally neglected due to relatively fast transport in the gas phase. The permeation flux  $J_m$  of the migrating species in the system can be defined as

$$J_m = k_{ov}(c_l - c_p) = k_l(c_l - c_{l,m}) = k_m(c_{l,m} - c_{m,p}) \quad (1)$$

where  $c_l$ ,  $c_p$ ,  $c_{l,m}$  and  $c_{m,p}$  ( $\text{mole m}^{-3}$ ) are the species concentrations in the feed bulk, in the permeate phase, at the feed-membrane interface and at the membrane-permeate interface, respectively.  $k_{ov}$  ( $\text{m s}^{-1}$ ) is the overall mass transfer coefficient. The inverse of a mass transfer coefficient is the respective resistance:

$$\frac{1}{k_{ov}} = \frac{1}{k_l} + \frac{1}{k_m} = \frac{l}{D} + \frac{\delta}{D_m} \quad (2)$$

where  $\delta$  is the membrane thickness,  $D_m$  is the species diffusion coefficient in the membrane,  $D$  is its diffusion coefficient in the solvent, and  $l$  is the thickness of the concentration boundary layer in the liquid feed.

The values of  $k_m$  and  $k_l$  allow comparisons of process performances, as well as evaluations of mass transfer efficiency for differ-

ent configurations. It is important to notice that  $k_l$  varies with the dynamics of the feed solution and  $k_m$  depends on the intrinsic membrane characteristics. Côté and Lipski [31,32] are among the first to propose that the mass transfer of a PV system is particularly limited by diffusion of the solute in the boundary layer. The reason lies in the long diffusion length or low concentration gradient between the bulk to the membrane boundary which cause strong concentration polarisation. Depletion in the boundary layer can dominate the performance [33]. In particular, Wijmans shows that concentration polarisation already dominates at very low Peclet ( $Pe$ ) numbers for the removal of trace compounds by PV [34]. In such a case, membrane selection is less critical. Relative thick rubber membranes are sufficient and preferable over thinner composite materials due to the advantages in low-cost and low water permeability. Li et al. [35] have investigated operation parameters on the PV performance using a composite PDMS membrane to separate a variety of organic solvents from water. Their results have shown a high dependence of the dominant resistance region on the solvent properties, particularly in its partition coefficient. In their investigated flow rate range, methanol transfer is limited by the  $k_m$  whereas acetone transfer is determined by both  $k_m$  and  $k_l$ .

In this study, we aim to conduct a performance study for the removal of acetone from water to provide the insights on the mass transport mechanisms. The used microfluidic format provides excellent mass transport in the boundary layer, which allows adequate membrane performance assessment. A thin layer of PDMS membrane was selected for its high selectivity for VOCs in a low concentration range [36,37]. Via modelling and experiments, we quantitatively investigated the local mass transfer coefficients of acetone through the liquid boundary layer ( $k_l$ ) and the membrane ( $k_m$ ) by varying membrane thicknesses and feed flow rates. An optimisation based on the intrinsic system parameters is proposed to identify the rate limiting region and engineer the design for both micro- and macro-scale pervaporation.

## 2. Experimental

### 2.1. Microchips preparation

**Glass slides.** The microchannels for liquid flow (L-channel) and gas flow (G-channel) were fabricated on separate borofloat glass slides by standard photolithography followed by wet etching (Micronit B.V.). The depth ( $H$ ) and length ( $L$ ) of both channels were 50  $\mu\text{m}$  and 0.26 m, respectively. The width of the L-channel was 350  $\mu\text{m}$  and the G-channel was 600  $\mu\text{m}$  to facilitate channel alignment during manual assembly (Fig. 1). The glass slides were diced in the size of  $1.5 \times 4.5$  cm for bonding.

**PDMS membrane.** The flat-sheet PDMS membranes were prepared by mixing the polymer and the crosslinking agent (TRV 615 A+B, Momentive, Columbus, Ohio) in 10:1 weight ratio [38]. The mixture was first degassed in a desiccator and then cast onto a polished aluminium plate at controlled thickness. The films were cured at 80° for 2 h in a nitrogen-flushed oven and then placed in a nitrogen box overnight. The resulting membrane thicknesses were measured by a Micrometer (Coolant Proof) at multiple spots of the membranes before bonding and varied between  $35\text{--}270 \pm 5$   $\mu\text{m}$ .

**Membrane integration.** A combined oxygen plasma and thermal-bonding method was employed to create leakage-free bonding between PDMS membrane and glass slides [39]. Two glass slides and a PDMS membrane were firstly cleaned and activated by oxygen plasma at 60 W, 40 s (Femto, Diener Electronic). The PDMS membrane was immediately contacted with one glass slide first and then to the other with manual alignment. The pre-bonded chip was clamped and placed in an oven to enhance the bonding strength at 80° for 2 h. The bonded chip was enclosed in a Micronit

Download English Version:

<https://daneshyari.com/en/article/146038>

Download Persian Version:

<https://daneshyari.com/article/146038>

[Daneshyari.com](https://daneshyari.com)