Electronic Supplementary Information

Vacuum membrane distillation on a microfluidic chip

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Materials and instruments

Tris(2-acryloyloxyethyl)isocyanurate (M315) and bis(acryloxyethyl)hydroxyethy isocyanurate (M215) were obtained from Toagosei Chemical Industry Co., Ltd. (Tokyo, Japan). A moderate molecular weight, urethane linkage-containing triacrylate (V4263, M_n, ca. 2,000) was obtained from DIC Inc. (Tokyo, Japan). 1,6-Hexanediol diacrylate (HDDA) was obtained from Dai-ichi Kogyo Seiyaku Co., Ltd. (Kyoto, Japan). 1-Hydroxycyclohexylphenyl ketone (Irgacure 184) was obtained from Ciba Geigy Corp. (Hawthorn, NY). Methanol and 2,4-diphenyl-4-methyl-1-pentene (DPMP) were obtained from Wako Pure Chemical Industries, Ltd. (Osaka, Japan). Micro-porous Teflon® membranes (0.2 μm pore diameter, 74% porosity) were obtained from Toyo Roshi Kaisha, Ltd. (Tokyo, Japan).

A syringe pump (KDS210P, KD Scientific, USA) outfitted with a 1 mL gastight syringe (Hamilton, USA) were used for our experiments. The downstream pressure was measured by using a digital pressure sensor (AP-11S, Keyence, Japan). The temperature at the top surface of the chip was measured by using a digital radiation temperature sensor (FT-50, Keyence, Japan). The compositions of the methanol aqueous solutions were analyzed by a Fourier transform infrared spectrophotometer (FT/IR-660 Plus, Japan Spectroscopic, Japan) equipped with a single reflection ATR accessory MIRacle (Shimadzu, Japan).

Chip layer fabrication and assembly

Precursor 1 was spin-coated onto a 25×95 mm acrylic plate (layer 7 in Fig. 1a) and irradiated with a 120 W cm^{-1} medium-pressure mercury lamp at 792 mW cm^{-2}. The precursor was spin-coated again and then partially cured in a UV curing system fitted with a 250 W high pressure mercury lamp at 70 mW cm^{-2} for 165 s through a photomask. Layer 6 on substrate 7 was obtained after washing away the unreacted precursor with ethanol.

For the fabrication of the membrane layer 5 (Fig. 1a), the ethanol pre-wet PTFE membrane.was immersed in precursor 1 to fill the pores of the membrane, and then sandwiched between two biaxial oriented polypropylene (OPP) films. The excessive precursor was pressed out manually on a glass plate by using a bar coater with a 127 μm gap. The channel pattern was transferred onto the membrane by UV exposure as preparing layer 6. The unreacted precursor in the membrane pores was then washed away with acetone. By using this method, the PTFE membrane except the channel part was filled with the precursor and partially cured. The self-adhesive surfaces make it possible to be bonded with layers 6 and 4 at later steps.

Layers 4 and 2 (Fig. 1a) were prepared on two OPP films by using the essentially similar procedure as layer 6. To fabricate the self-adhesive cover layers 3 and 1, precursor 2 was bar-coated on OPP films and then partially UV-cured.

After the assembly of the multilayer stack, access holes were drilled mechanically at the designated inlet and outlet positions. Finally, N-333 ports obtained from Upchurch Scientific Inc. (Oak Harbor, WA) were secured at these positions with UV curable precursor 1.

Determination of theoretical plates from Vapor-Liquid Equilibrium (VLE) diagrams

Theoretical plate was defined as one that produces a perfect simple distillation, that is the same difference in composition as exists at equilibrium between a liquid mixture and its vapor. When the compositions of distillate ($y_{1,\mathrm{v}}$) and feed ($x_{1,\mathrm{f}}$) are known, the L-V composition diagram may be used to step off the number of theoretical plates in the rectifying section (n_r) as shown in Fig. 1s.[1] The plate number in the stripping section (n_s) is obtained by carrying out the similar stepwise construction by starting with the feed composition ($x_{1,\mathrm{f}}$) and working toward the "heavier" liquid composition ($x_{1,\mathrm{l}}$). Thus the total theoretical plate number (n_t) can be obtained from the following equation:

$$n_\mathrm{t} = n_\mathrm{r} + n_\mathrm{s}. \qquad (1)$$

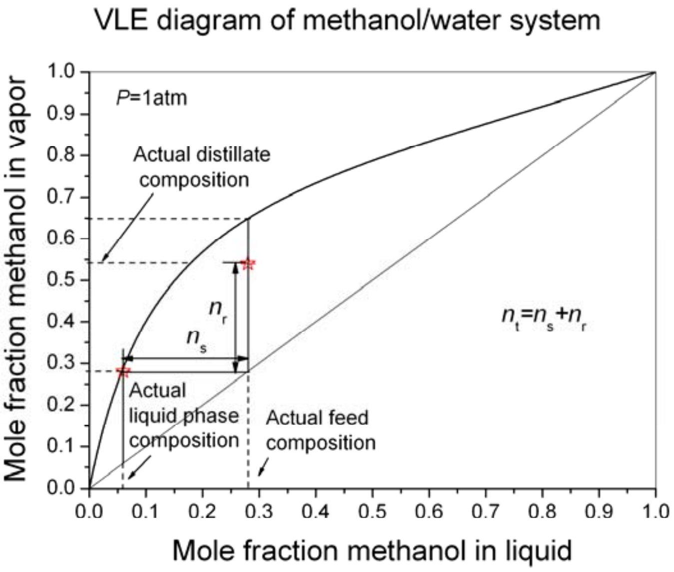

Fig. 1s Stepping-off procedure to determine the total theoretical plates**.**

Minimization of concentration polarization

A higher feed flow rate can improve the separation efficiency because of the better mixing condition at higher feed flow velocities, which decrease the effect of the concentration polarization in the boundary layer. In our microchannel which can be thought as a slit die, the calculated shear rate ($\dot{\gamma}$) at the interface is about 96 s^{-1} ($\dot{\gamma} = \frac{6Q}{WH^2}$, where flow rate, Q, is 5 µL/min, channel thickness, H, is 0.072 mm, and channel width, W, is 1 mm)[2]. The large shear rate can contribute to the reduction of the boundary layer.

In addition to this, we think that fast diffusion in the micro channel can also reduce the thickness of the boundary layer due to improved mixing. The reason is shown as below. Pressure driven flow in microchannels is generally laminar, since the Reynolds numbers (Re) are proportional to the channel diameter and small (under 100). In the microfluidic channel, the only means by which solvent, solutes and suspended particles move in a direction transverse to the direction of flow is by diffusion. The root mean square distance traveled by a molecule in a time interval, t, is described by the Einstein relation for molecular diffusion in solution[3]

$$x_{rms} = \sqrt{2Dt} \qquad (2)$$

where D is the molecular diffusion coefficient. Since the diffusion coefficient of methanol[4] in water (25 °C, mole fraction methanol=0.28) is 1.014×10^{-9} m^2s^{-1}, and channel depth is 72 μm, the obtained diffusion time for methanol from the upper surface of the liquid channel to the membrane/solution interface is less than 3 s. However, the retention time of liquid flowing in the channel is about 224 s (feed flow rate=5 μL/min, channel length=260 mm, channel width=1 mm, channel depth=0.072 mm), which is much larger than the diffusion time of methanol. This implies the methanol/water solution can be well mixed by fast diffusion in the liquid channel. Therefore, the concentration polarization can be minimized in the microchannel.

References:

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