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Characterization of Microfluidic Hollow Fibre for Urea Separation

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ABSTRACT

A microfluidic device with a hollow fibre membrane is presented in this research paper. The device was fabricated using polydimethylsiloxane (PDMS) and tested by performing measurement using syringe pump and characterization using Zetasizer in order to determine the overall mass transfer coefficient, K_0. The urea concentration was varied at four different concentrations of 60, 90, 120 and 150 mM accordingly due to the range of pathophysiology. From the measurement and Debye plot graph and formulas, it was observed that there is separation process occurs and mass transfer coefficient was calculated which is 0.00177 cm/min. This study aims to fabricate a simple microfluidic device with high performance efficiency. Therefore, there is still room for improvement in order to come out with higher mass transfer coefficient for microfluidic hollow fibre device for future wearable artificial kidney device.

Keywords: Hollow Fibre, Microfluidic, PDMS, Separation, Urea.

1. INTRODUCTION

Nowadays, around 10% of the population worldwide is affected by kidney failure and millions of them die every year due to fail in getting proper treatment [1]. Usually, most of them are depending on dialysis treatment and have to spend for 3 to 5 hours 3 times a week in dialysis centre but they still facing side effect such as infections and cardiovascular disease. Meanwhile, extensive dialysis treatment for 6 to 8 hours daily was introduced to get better results but this will limit the patient daily routine activities.

In consequent, technology to miniaturize dialysis machine towards wearable and implantable artificial kidney is needed to solve the problems so that the kidney failure patients can carry out their activities while undergo extended dialysis treatment [2]. Therefore, one of the aims of this study is to fabricate a simple microfluidic hollow fibre device with high performance efficiency for future wearable and implantable artificial kidney.

Recently, miniaturization of analytical and clinical instruments has been comprehensively studied due to its promising advantages such as inexpensive mass production and low reagent consumption. Lab on chip is one of the examples of a single substrate parallel processing which involves integration and analytical functionalities such as extraction, reaction, detection, mixing and separation [3].

Microfluidic is one of the potential technologies to be applied in order to miniaturize analytical instrument which involves either gases or liquids that flow in the scale of micro meter length. It is also can be easily operated at a low cost [4,5].

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Microfluidic chip is built by bonding a mold polymer to any flat surface such as silicon, glass or polymer itself [6]. Polymer-polymer is one the most favourable pair to be used in building a microfluidic device due to high durability factor and require a low cost [7,8]. Consequently, polydimethylsiloxane (PDMS) is an example of polymer that can be chosen to build a microfluidic device. J. Alvankarian reported that PDMS is chosen to be one of the most favourable polymer to be used in process of fabrication due to its promised advantages that is require a low-cost material and an it is ideal elastomeric polymer for the rapid prototyping of microfluidic devices [9].

There are various types of filter/ membrane that have been used for various applications, such as weir- like, comb-like and mesh-like silicon [10]. Hollow fibre is one of favourable artificial membrane that contains semipermeable filters along small tubes. The advantage of hollow fibre membrane is can provide high packing density with multiple of shell-and-tube module [11]. Typically, a hollow fibre can be found in bundles and is used in several applications, such as reverse osmosis, microfiltration, ultrafiltration for protein purification, gas separation, extraction, pervaporation and hemodialysis [11,12].

Based on previous studies, there are several studies reported using flat membranes in between two substrates containing microfluidic channels. However, these devices are challenging to be fabricated while microfluidic with insertion of hollow fibre offer easier way to be fabricated and advantages, such as enhances mass transfer, higher active surface area per unit volume and simpler design [13].

On the other hand, urea is one of the nitrogenous waste products of metabolism which is produced from the breakdown of protein. It is eliminated from the body by an organ called kidney through urine. Over 150 years, concentration of urea is measured for clinical application at two different stages which is first in urine and later in blood [14]. Urea was varied at four different concentrations which were 60, 90, 120 and 150 mM. This range of concentration was chosen due to the range of pathophysiology [15].

In this work, a PDMS to PDMS microfluidic device is developed using conventional hollow fibre polyethersulfone, Smartflux which functioned as a urea separation membrane for urea. The mass transfer coefficients, K for microfluidic hollow fibre device was studied.

2. METHODOLOGY

In this study, there are two main parts methodology of the experiment which is preparation of microfluidic device, experimental set-up and data analysis.

2.1 Preparation of Microfluidic Device

The mold pattern was designed using Autodesk commercial-computer aided design (AutoCAD 2007) software. Then, the acrylic with thickness of 10 mm was engraved according to previous designed using a computer numerical control (CNC) machine equipped with solution ready platform (SRP) player, Roland MDX 40. The acrylic mold size is 41 x 80 x 10 mm while the microfluidic channel was design at dimension of 1 x 1 x 40 mm.

Then, PDMS was prepared by mixing silicon elastomer, Sylgard 184 with its curing agent at ratio of 10 to 1, respectively. The mixture was stirred well until visible bubble as shown in Figure 1(a). Then, the mixture was poured onto the pre-cleaned acyclic mold and petri dish for microchannel and sealing layer, respectively as shown in Figure 1(b).

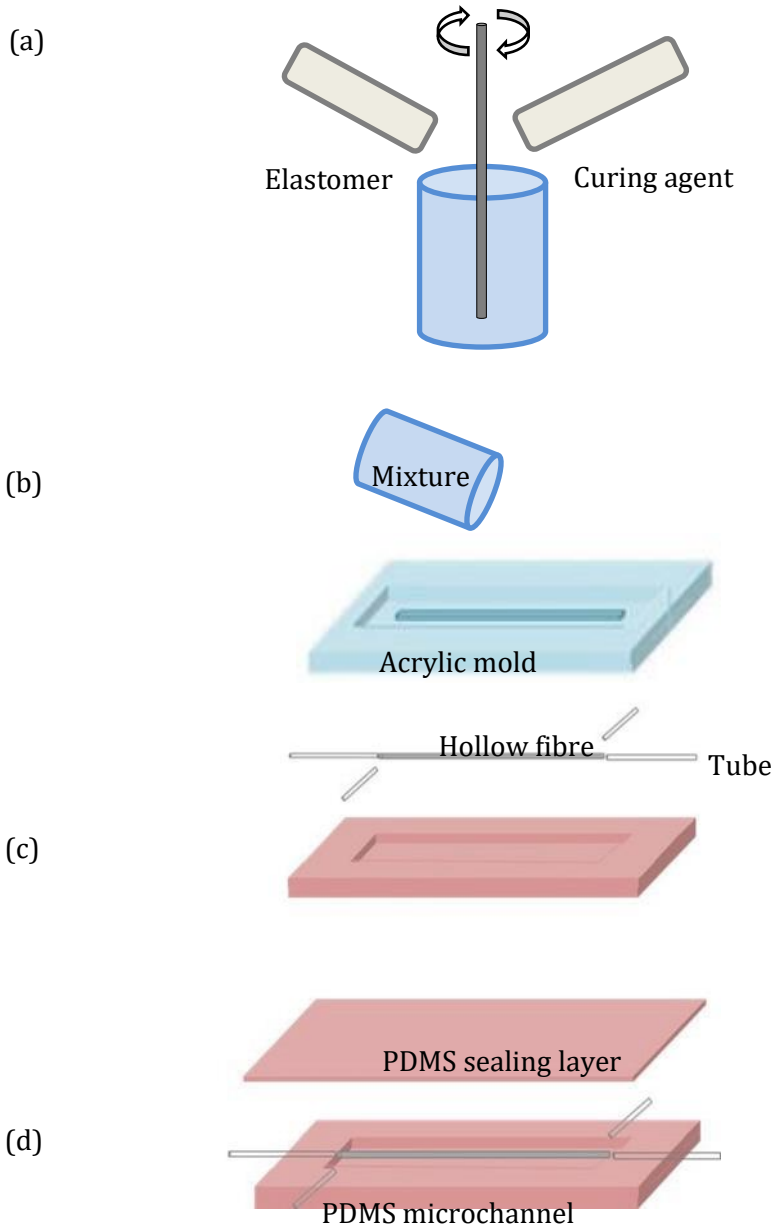

Figure 1. Simplified process of microfluidic device preparation made from PMDS. (a) Elastomer and curing agent mixing, (b) dispensing the mixture onto a pre-cleaned acrylic mold, (c) hollow fibre insertion and connection of the inlet and outlet, and (d) sealing layer and microchannel sealing with hollow fibre insertion as a sandwich structure.

Both of them were then being placed inside a vacuum chamber for 40 mins to undergo degassing process to remove trapped bubbles. This is to avoid leakage at both layers of PDMS during liquid flow later. The PDMS were then being placed in an oven and pre-baked at temperature of 90°C for 1 hour.

Once the PDMS was hardened, they were peeled off from the mold and petri dish using tweezers. Then, the inlet outlet and hollow fiber with effective length of 4 cm was prepared and being inserted into the PDMS microchannel as shown in Figure 1(c). Tygon tube (0.025 in. i.d., 0.047 in. o.d., Dow corning) was used to connect end of hollow fiber to the main tubing of polytetrafluoroethylene (PTFE, 1/32 in. i.d., 3/32 in. o.d., ColeParmer) that was directly attached to the syringe needle.

The sealing layer was then being treated using oxygen plasma at 300 mTorr for 45 s at 1 cm from the surface. Finally, it will being bonded to the microchannel with a pre-inserted 6 cm polyethersulfone (PES) hollow fibre (LFP110, Purema, Smartflux) as a sandwich between them as shown in Figure 1(d).

On the other hand, hollow fibre was coated with gold using a quick coater (Electron Microscopy Sciences (EMS), 105 RES) with a thickness of 5 nm in order able to be characterized using a Scanning Electron Microscope (SEM, JEOL-JSM 6510 LV). This is to ensure that both ends of the hollow fiber lumens were opened after being cut.

Figure 2 shows the SEM cross-section image of hollow fibre lumen. From the SEM image, it shows that the inner diameter of hollow fiber lumen is ~200μm which is same as stated in the product specification of hollow fiber. Besides, from the SEM cross-sectional image, the average wall thickness of the hollow fiber is 35μm which is also as stated in product details.

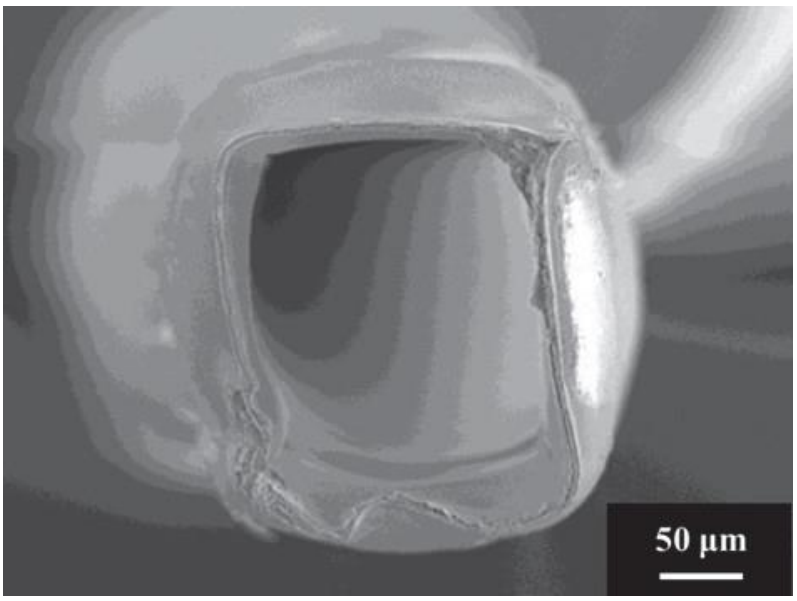

Figure 2. SEM cross-sectional image of hollow fibre lumen.

2.2 Experimental Set-Up

Firstly, the microfluidic channel was tested by flowing dye-coloured liquid and then flush back with De-Ionised (DI) water through the hollow fibre. This is to ensure that there is no leaking throughout the actual experiment. Figure 3 shows the experimental setup of fabricated microfluidic device connected to the syringe pump system (Longerpump, TS- 2A/L0107-2A).

Then, urea with four different concentrations of 60, 90,120 and 150 mM was being prepared by diluting urea powder (CH_4N_2O, Merck) inside DI water. These four solutions were then being characterized using Zetasizer (Zs, Malvern Nano-ZS) as the standard solution in order to produce graphical presentation called Debye plot.

There are two inlets and two outlets involve in this experiment and labelled as draw and feed solutions which are in counter flow configuration. Draw solution is the liquid that flows inside the hollow fibre while feed solution is the liquid that flows outside of the hollow fibre.

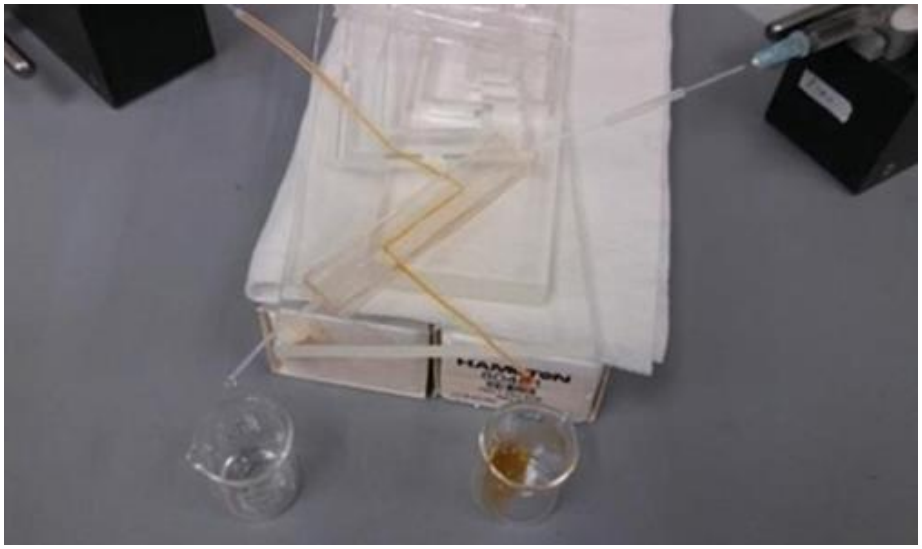

Figure 3. Photograph of the microfluidic device measurement system set-up.

In order to imitate actual dialysis process, four different concentrations of urea were set to flow through the draw solution while DI water was set to flow through the feed solution. The urea concentration were set to varied at concentration of 60, 90, 120 and 150 mM while the input for both draw and feed solutions was set to be constant at 6 μL/min. This exact flow rate is chosen due to actual comparison with dialysis process using a dialyzer. The flow rate of actual in dialysis was lower than 400 mL/min, which each dialyser contains approximately 10,000 pieces of 20 cm hollow fibre membrane in length [16]. The output solution from both draw and feed outlet ports was then collected, where output 1 refers to the excess of draw solution and output 2 refers to the excess feed solution.

Then, all collected of output draw solutions for four different concentration was being characterized again using Zetasizer. From the measurement, a Debye plot graph for output solution was plotted and being compared to the initially measure and plotted Debye plot graph for input solutions. In this measurement, the technique is very sensitive to dirt and dust. Therefore, the solution and cuvettes must be prepared with great care. A set number of concentrations of the solution must be prepared for both input and output in order to get Debye plot graph.

From the Debye plot graph, we will observe two lines of intensity of scattered light which refer to input and output solutions. It is expected that for each urea concentration, the intensity for the output solution is higher than input solutions. This is to prove that there is separation process occur throughout the experiment. Besides, from the Debye plot graph, mass transfer coefficient, K can be calculated.

3. RESULTS AND DISCUSSION

Figure 4 shows the cross sectional image of a hollow fibre membrane used throughout this work captured using SEM. From the SEM image, it has been measured and the average diameter of hollow fibre pores is ~1.8 μm.

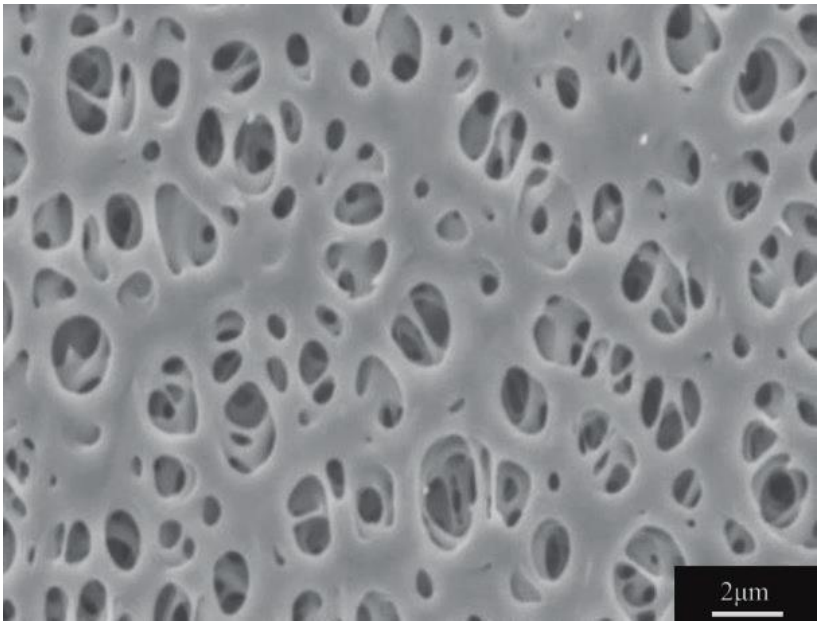

Figure 4. SEM image of cross-section of hollow fibre membrane.

Figure 5 shows Debye plot graph for both input and output solutions plotted at various urea concentration. The blue and red line shows the plotted graph for input and output solutions, respectively. The Debye plot is the intensity of scattered light that a particle produces is proportional to the product of the weight-average molecular weight and the concentration of particles. As mentioned earlier in experimental part of the experiment, the concentration of the output solution can be calculated based on the red line after being compared and calculated based on the reference input blue line.

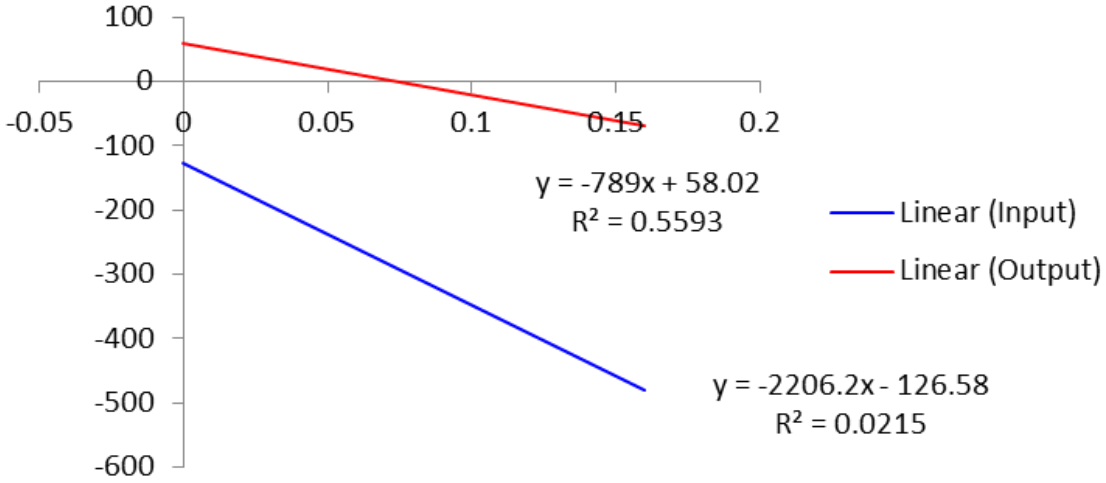

Figure 5. Graph of Debye plot of input and output solution at various concentrations.

The plotted graph shows as estimated where the plotted graph for input is lower than plotted graph for output. It means that there is separation occurs throughout the experiments. In general, there are two common way to identify the performance of mass transfer device which is fractional removal and mass transfer coefficient, K_o. Higher fractional removal and K_o means higher efficiency of the device performance. Hence, in the field of hemodialysis, there is room of improvement towards less membrane used, smaller dialyzers unit and cheaper devices which is useful for future wearable artificial kidney device [17].

However, fractional removal is rarely reported in open literature, thus it is difficult to find this mass transfer characteristic for commercially available hollow fibre hemodialyzer. In contrary to fractional removal, overall K_o, is more often reported in studies. It is largely insensitive to the length of hollow fibre and initial input concentration. So, it is reliable to be chosen to compare the mass transfer efficiency in hemodialyzer devices specifically hollow fibre [17].

Both mass transfer coefficient and fractional removal of urea were also calculated using the urea output concentrations. The equation of mass transfer coefficient, K_o is as shown in equation 1:

$$K_O = \frac{\dot{N}}{\frac{(\Delta C_{inlet} - \Delta C_{outlet})}{\ln(\frac{\Delta C_{inlet}}{\Delta C_{outlet}})}} \quad (1)$$

$$\dot{N} = \frac{m_{trans}}{A \cdot \Delta t} \quad (2)$$

In equation 1 and 2, $\dot{N}$ is the average mass flux and m_{trans} is the urea transferred to the dialysate, delta t is the mean residence time of the fluid in a microchannel, A is the surface area available for transfer process to occur, C is the concentration of urea, and K_0 is the overall mass transfer coefficient with units (cm/min) [17].

From this experiment as shown in figure 5, the overall mass transfer coefficient was calculated based on the equations above. The calculated K_0 for this device is ~0.00177 cm/min. However, the commercial hollow fiber dialyzers show the value for K_0 is at the range of 0.049 to 0.051 cm/min while from other studies reported that their device of flat-plate hemodialyzer perform at mass transfer coefficient range of 0.068 to 0.14 cm/min [17-19].

4. CONCLUSION

In conclusion, this study presented the simple and easy fabrication process of developing a microfluidic hollow fibre device. The prepared input concentration was being characterized using Zetasizer in order to be the reference graph to for future measurement. After the experiment of liquid flow using syringe pump, the output solutions from various urea concentrations were collected and being characterized again with Zetasizer in order to plot Debye graph. From Debye graph and several equations, output concentration can be calculated. It shows that there is separation process occur at rate mass transfer coefficient of 0.00177 cm/min. However, there is still room for improvements that need to take into account in term of microfluidic design and hollow fiber effective length in order to get higher value of K_0 which contribute to higher device performance.

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