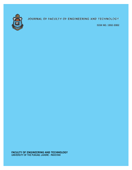
JFET 19 (2012) 17-25

Journal of Faculty of Engineering & Technology

journal homepage: www.pu.edu.pk/journals/index.php/jfet/index



HOLLOW FIBER MEMBRANE CONTACTORS: A NOVEL SEPARATION TECHNOLOGY FOR VALUE ADDED PRODUCT INDUSTRY

M. Younas, B. Bibi, H. Nasim*
Department of Chemical Engineering, University of Engineering and Technology,
Peshawar, Pakistan.

Abstract

In the current study, theoretical behavior of commercially available hollow fiber membrane contactor (HFMC) modules has been presented to investigate the extraction efficiency and mass transfer solute flux. It was aimed to separate the selected aroma compounds from aqueous streams with an organic solvent, hexane at ambient temperature. It was found from the results that distribution affinity of the solute with the solvent, diffusivity of solute and the hydrodynamics strongly affect the flux and extraction efficiency. Moreover, the geometry of the hollow fiber membrane contactor also plays an important role in the recovery of the solute from aqueous solution.

Keywords: Hollow fiber membrane contactor, Aroma compounds, Modelling and simulation

---

* Corresponding Author e-mail:engr_unas@nwfpuet.edu.pk
Phone Off: 091 9218180

1. Introduction

Scarcity of water, cost of energy, purity in separation industry and industrial economic growth motivate chemical engineers to use membrane technology as an alternative for traditional separation processes. Membrane contactors emerged tremendously, during the past few decades, as an exciting research domain for chemical engineers to make it distinguish from conventional separation technology. Hollow fiber membrane contactors (HFMC) offer a number of advantages over conventional separation processes like absence of emulsions, no flooding, no need of density differences between the fluids, simple handling, low organic solvent load, high solute capacity and high interfacial area [1,2].

The effluents from the manufacturing processes in food, agricultural and pharmaceutical industries contains the value added products which on one side, threatens the aquatic media by producing the odour and toxicity but on the other side, these compounds can be used as a flavorants, if recovered. Value added natural products are becoming backbone to boost the economy due to their vast applications among the society [3-5]. In Pakistan where food is found in rich quantity, value added products need more attention to elaborate them as key role player in country's economy. Food industry to grow efficiently, the extraction process of these compounds should be compact, economical and fast in contest of quality and hygiene. Although membrane contactors have been studied for a variety of application however, limited work is available on the theoretical investigation of aroma compounds in order to study the performance of different kinds of hollow fiber membrane contactors. Moreover, the theoretical study is inevitable to design of a robust, compact and efficient membrane contactor module for the scale up in food industry.

2. Experimental

In the current study, different aroma compounds like ethyl hexanoate, 2-heptanone, cis-3-Hexenol and 2,5-Dimethylpyrazine have been selected for the liquid-liquid extraction. The physical properties of these compounds are enlisted in Table 1. Two different HFMC modules have been used for the theoretical investigation of mass flux and extraction efficiency of aroma compounds with the help of an organic solvent. These modules, shown in Figure 1 are modelled under steady state and dynamic conditions and have been validated with the experimental data in previous work [6,7]. The details of the modules can be found elsewhere [7,8]. Here simulation will be performed to analyse the modules quantitatively and qualitatively.

Table 1. Physical properties of aroma compounds [9]

Aroma compound	Odor	Molecular weight, g/mol	Diffusion coefficient in water at 25 ^{0}C	Diffusion coefficient in hexane at 25 ^{0}C	Partition coefficient Water-hexane
2,5-Dimethylpyrazine	Chocolate	108.1	8.8×10^{-10}	3.6×10^{-9}	1.9
2-Heptanone	Fruity, soapy	114.2	7.8×10^{-10}	3.2×10^{-9}	113
cis-3-Hexenol	Leaf-like	100.2	8.6×10^{-10}	3.5×10^{-9}	10
Ethyl hexanoate	Fruity, pineapple	144.2	7.1×10^{-10}	2.9×10^{-10}	1193

3.1. Figure 1. Schematic drawings of HFMC modules ; (a) parallel flow (b) single baffled cross flow.

4. Theory and principle

Membrane contactor is a concentration driven device which provides only the contact surface separating the two immiscible fluid phases (A and B) without dispersion where separation of solute is accomplished. Thus solute is transferred from one phase (aqueous solution) on one side of membrane to the other phase (organic solvent) on the other side of membrane. Figure 2 shows the simple working diagram where solute from phase A transfers to permeate side which is actually the fluid phase B. The relationship between the flux (J) and driving force (dC) has been described by the following Fickian equation,

$$J = -D\frac{dC}{dx} \tag{1}$$

where C and x denote the solute concentration and membrane thickness, respectively. The pores are wetted and filled with organic fluid phase, as far as the membrane used is hydrophobic.

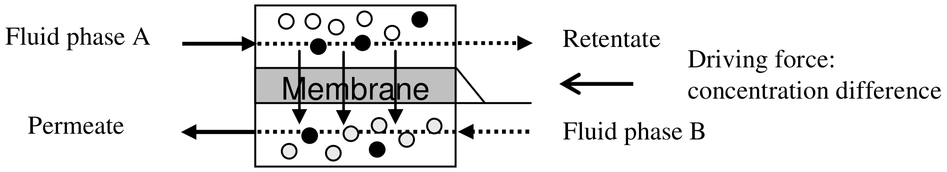


Figure 2. Schematic of membrane contactor separation process.

A small but positive transmembrane differential pressure is guaranteed to keep the interface immobilised at the extremity of membrane pores and not inside the pores. This restricts the fluid phase which wets the pores from penetrating into the fluid phase on the other side of the membrane. A steady-state mass transfer model is developed which consists of a coupled set of algebraic equations originated from resistance in series model and mass balance equations of solute across the module.

The expressions for overall mass transfer coefficients without chemical reaction or with instantaneous chemical reaction at the interface and for fluid-fluid interface as shown the flowing equation,

$$\frac{1}{K_{aq}d_{ext}} = \frac{1}{k_{aq}d_{ext}} + \frac{1}{Pk_{mb}d_{lm}} + \frac{1}{Pk_{org}d_{int}} \tag{2}$$

d_{int} and d_{ext} are denoted for internal and external diameter of the fiber, respectively while d_{lm} is the logarithmic mean diameter. P is the partition coefficient defined as the ratio of solute concentration in organic phase to that in aqueous phase at equilibrium.

5. Results and discussion

5.1. Effect of hydrodynamics and type of molecule

Simulation was performed for once through dispersion-free extraction of selected aroma compounds with hexane in both the modules for mass transfer efficiency and solute flux through the pores of the membrane from one side in aqueous solution to the other side in organic solvent. Extraction efficiency has been determined and compared for the recovery of aroma compounds in both the modules.

It was observed that an increase in aqueous phase flow rate decreases the extraction efficiency as seen in Figure 3. In fact, when the flow rate of aqueous solution is increased, the retention time of the fluid decreases. Thus less time is available for the aroma molecule to interact with the solvent in the pores of the membrane which causes less molecules to be extracted from aqueous solution. But on the other hand, solute flux increases with the increase of the flow rate of the aqueous solution as observed in Figure 4. As mass transfer rate is depended on the concentration difference across the membrane so high flow rates cause the increase in concentration difference and therefore flux increases.

It can also be noted from Figure 3 and 4 that extraction efficiency and mass transfer flux is not same for each aroma compound at the same. A little difference is found in extraction efficiency and mass transfer flux at low flow rates for the molecules. However, the difference is notable at high flow rates. While studying the physical properties of these aroma compounds in Table 1, it can be inferred that diffusion coefficient and partition coefficient influence the extraction efficiency and solute flux. For example for 2,5-Dimethylpyrazine which possesses the low value of partition coefficient, exhibits the low values of extraction efficiency and solute flux as compared to the rest of aroma compounds. Nevertheless, 2-Heptanone and ethyl hexanoate achieves almost the same extraction efficiency and flux. It can also be observed from previous work [6] while studying the extraction of other aroma compounds with heptane as an organic solvent that the transport characteristics and values of partition coefficient influence the performance of the membrane contactors.

Likewise similar behaviour can also be found while performing the simulation in the module X 50 under the same conditions of hydrodynamics and molecules but with different quantities. However the results have not been shown here.

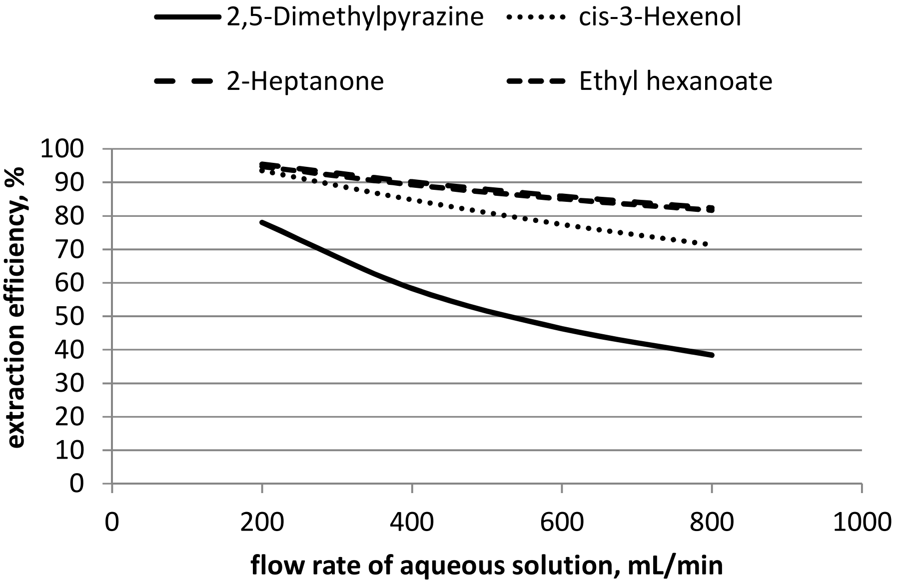


Figure 3. Effect of flow rate of aqueous solution on extraction efficiency; Q_{org}=400 mL/min

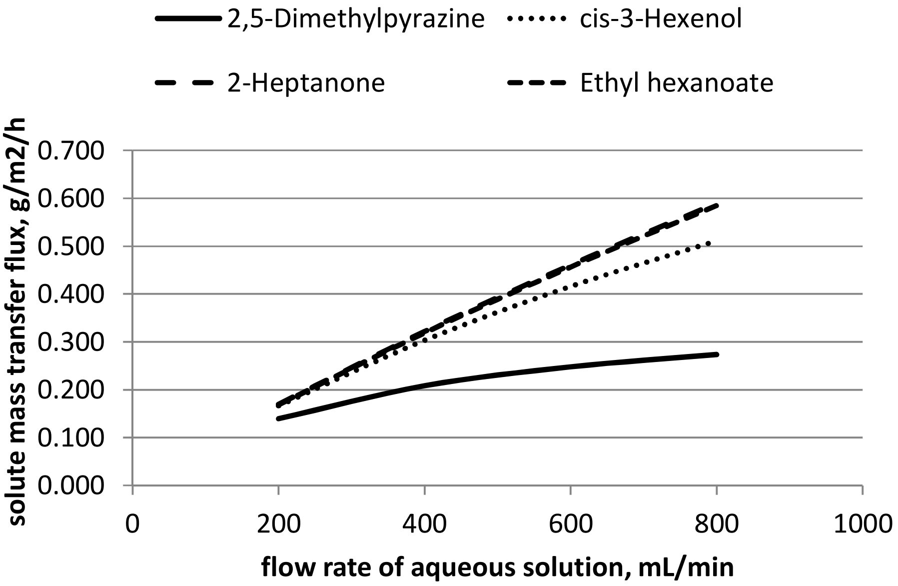


Figure 4. Effect of flow rate of aqueous solution on solute mass transfer flux; Q_{org}=400 mL/min

5.2. 1-D axial profile of membrane contactor module

The mathematical model developed for the liquid-liquid extraction is also capable to analyse the flux and concentration profile along the length of the module at any particular time during the continuous extraction. For example consider the extraction of cis-3-Hexenol with hexane as organic solvent in X 50 hollow fiber membrane contactor module for the same flow rate of aqueous and organic solutions at the start of the extraction. In Figures 5 and 6, where solute mass flux and concentration is plotted along the length of the module, it is observed that solute flux and concentration changes linearly along the axis of the reactor.

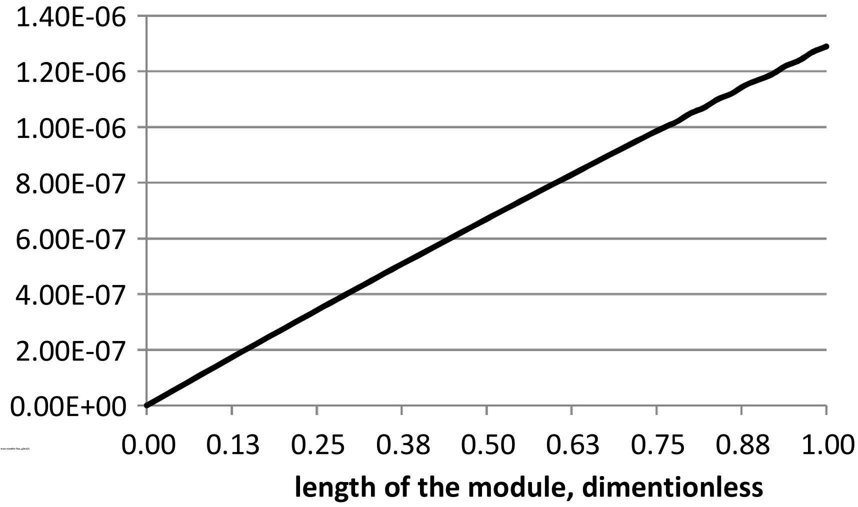


Figure 5. Axial flux profile, $Q_{aq}=Q_{org}=50$ mL/min ; X 50 Module, cis-3-Hexenol

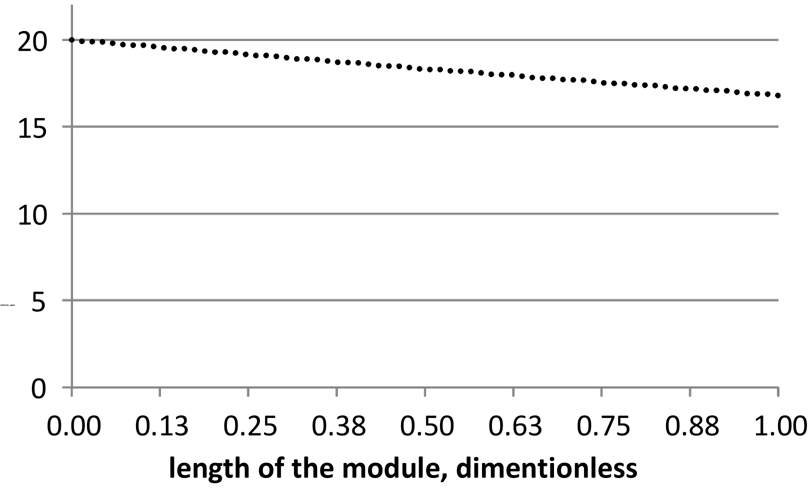


Figure 6. Axial concentration profile, $Q_{aq}=Q_{org}=50$ mL/min ; X 50 Module, cis-3-Hexenol

5.3. Influence of Module geometry, type of molecule and hydrodynamics on mass transfer coefficient

Overall mass transfer coefficient was calculated from the sum of the individual mass transfer resistances in the boundary layers of membrane in both sides of the membrane and mass transfer coefficient within the pores of the membrane. It is found from the literature [10,11] that membrane characteristics like porosity and thickness of the membrane, physical properties of the molecules and hydrodynamics affect the overall mass transfer coefficient. Similar effects can also be observed as found in Table 2. It can be seen that type of the molecule and geometry of the module have the paramount effects on the overall mass transfer coefficients. In fact, for X 40 hollow fiber membrane contactor module, which contains the baffle and a distribution tube in the middle of the module, results in high values of overall mass transfer coefficients as compared to the module X 50 because, the transport characteristics of the molecules and the geometry of the module influence the dimensionless numbers like Reynolds number, Sherwood number and Greatz number upon which the overall mass transfer coefficient is greatly depended.

Table 2. Overall mass transfer coefficient values $\times 10^6$, m/s: $Q_{org}=400$ mL/min

	2,5-Dimethylpyrazine		cis-3-Hexenol		2-Heptanone		Ethyl hexanoate	
Q_{aq}, mL/min	Module X 40	Module X 50	Module X 40	Module X 50	Module X 40	Module X 50	Module X 40	Module X 50
200	4.25	0.392	6.74	0.372	7.27	0.395	6.91	0.350
400	5.20	0.585	9.57	0.564	11.0	0.597	10.5	0.530
600	5.73	0.737	11.6	0.719	14.0	0.760	13.5	0.676
800	6.09	0.876	13.2	0.855	16.6	0.901	16.1	0.803

6. Conclusion

This work discusses the theory, principles of operation and mass transfer modelling of HFMCs for the recovery of aroma compounds from aqueous streams in an effort to give a better understanding of the technology for the food industry.

It is found that the solute molecule which possesses high values of partition coefficient and diffusion coefficient with the organic solvent achieves higher extraction efficiency and flux. The hollow fiber membrane contactor module X 40 is found to be more efficient as compared to baffleless modules X 50. However, pressure drop should also be calculated for both the modules. Furthermore, other organic solvent should be searched out which gives high values of partition coefficient and diffusion coefficient for the molecules like 2,5-Dimethylpyrazine.

Acknowledgement

The current work is the part of a postgraduate research project approved by Board of Advanced Studies and Research (BOASAR) at UET Peshawar.

References

[1] A. Gabelman, D.T. Hwang, Hollow fiber membrane contactors. J. Membr. Sci. 159 (1999) 61-106.

[2] S.R. Wickramasinghe, M.J. Semmens, E.L. Cussler, Hollow fiber modules with hollow fiber fabric, J. of Membr. Sci. 84(1993) 1-15.

[3] A. Baudot, J. Floury, H.E. Smorenburg, Liquid-liquid extraction of aroma compounds with hollow fiber contactor, AIChE J. 47 (2001) 1780-1793.

[4] F.X. Pierre, I. Souchon, M. Marin, Recovery of sulphur aroma compounds using membrane-based solvent extraction, J. Membr. Sci. 187 (2001) 239-253.

[5] K.K. Sirkar, Membrane separations: Newer concepts and applications for the food industry, in R.K. Singh and S.S. Rizvi, (Eds), Biosepration processes in food, New York: Marcel Dekker (1998), 353-356.

[6] M. Younas, S. Druon-Bocquet, J. Sanchez J. Extraction of aroma compounds in a HFMC: Dynamic modelling and simulation. J Membr Sci. 323 (2008) 386-394.

[7] M. Younas, S. Druon-Bocquet and J. Sanchez, Kinetic and dynamic study of liquid-liquid extraction of copper in a HFMC: Experimentation, modelling and simulation. AIChE J. 56, 6 (2010) 1469-1480.

[8] S. Bocquet, F.G. Viladomat, C.M. Nova, J. Sanchez, V. Athes, I. Souchon, Membrane-based solvent extraction of aroma compounds: choice of

configurations of hollow fiber modules based on experiments and simulation. J Membr Sci. 281 (2006) 358-368.

[9] F.G. Viladomat, I. Souchon, F.X. Pierre, M. Marin, Liquid-liquid and liquid-gas extraction of aroma compounds with hollow fibers. AIChE J. 52 (2006) 2079-2088.

[10] E. Drioli, A. Criscuoli, E. Curcio, Membrane contactors: Fundamentals, Applications and potentials, Elsevier, The Netherlands, 2006

[11] A.K Pabby, A.M. Sastre, Hollow fiber membrane-based separation technology; Performance and design perspectives. In: M. Aguilar Solvent extraction and liquid membranes. New York: Taylor & Francis Group, LLC. 2008:91-140.