Review of membrane contactors designs and applications of different modules in industry

Miroslav Stanojević
Associate Professor

Bojan Lazarević
Graduate student

Dejan Radić
Assistant

University of Belgrade
Faculty of Mechanical Engineering

New way for applying membrane processes for purification water in different industries is using membrane contactors. Membrane contactor technology has applications in wastewater treatment, pharmaceuticals, fermentation, semiconductor manufacturing, protein extraction, carbonation of beverages, VOC removal from waste gas and so forth. Membrane systems that are designed to form an interface between two components (liquid/liquid, liquid/gas, and gas/gas) are commonly referred to as membrane contactors.

The membrane contactors are devices that achieve gas/liquid or liquid/liquid mass transfer without dispersion of one phase within the other. The membrane is used to accomplish a particular separation and transport of one component more easily than another because of differences in physical and/or chemical properties between the membrane and the permeating components. There are a few advantages to using membrane contactors in contrast to conventional methods. Some of them are no flooding at high flow rates, no unloading at low flow rates, absence of emulsions, no density difference between fluids required, and high interfacial area. The main goal in this paper has been a general review of membrane contactor designs and operations, especially in applying of contactors for removing dissolved oxygen from aqueous solutions by vacuum degassing.

Keywords: *membrane contactor, vacuum degassing, deoxygenating aqueous solutions, hollow fiber membranes*

1. INTRODUCTION

Deoxygenating aqueous solutions has many applications in different production areas where the removal of dissolved oxygen (DO) from an aqueous phase is desired. Removing dissolved oxygen is one of the primary objectives in various industries and environmental engineering applications such as power plants, pharmaceuticals, semiconductor manufacture, foods and biotechnology as well as in oil industry during oil extraction [3].

There are several methods for removing dissolved oxygen from water, such as a thermal and vacuum degassing system as well as the chemical reduction process using sodium bisulfite, then nitrogen bubbling and degassing through a membrane module. It is often difficult to decrease the DO concentrations that are desired values without using very expensive equipment [5].

A number of vacuum degassing processes using a membrane are commercially accessible today. This kind of process uses different types of membranes: microporous (hydrophobic/hydrophilic) or non-porous

(composite/dense). A vacuum is applied to one side of the membrane, and the dissolved oxygen from the feed water will be replaced through it to the other side.

The main challenge of conventional methods for gas/liquid contacting operations is to maximize the mass transfer rate by producing a much interfacial area as possible between the gas and liquid phase.

2. DEFINITION OF A MEMBRANE AND MEMBRANE PROCESSES

The membrane is a main part in all the membrane processes and interphase between the two bulk phases. A membrane can be thick or thin, or may be any one or combination of the following: nonporous solid, microporous or macroporous solid with a fluid in the pores, a liquid phase with or without second phase or a gel. The membrane thickness of hollow fibers is of the order of the dimensions of one of the bulk phase in contrast to the other types of membranes those are thin than the bulk phases.

The membrane phase, which is set between two bulk phases, has ability to control mass transfer between the two bulk phases in a membrane process. The movement of any species across the membrane is a result of one or more driving forces which can be gradients in concentration, pressure, temperature or electrical potential. The flux-force relationship is described by a linear phenomenological equation between flux (J) and the driving force (1), [4]:

$$J = -A \frac{\mathrm{d}X}{\mathrm{d}x}, \qquad (1)$$

where A is called phenomenological coefficient and $(\mathrm{d}X/\mathrm{d}x)$ is the driving force, expressed as the gradient of X (concentration, pressure, temperature) along a coordinate x perpendicular to the transport barrier.

2.1. Driving forces

The basic principle of membrane separation is mainly the same although the membrane can have different structure (porous/non-porous) and may vary in material (organic/inorganic). The separation is achieved via a membrane. Transport through the membrane takes place when a driving force is applied to the compounds in the feed. The driving force is mostly a pressure difference or a concentration (or activity) difference across the membrane.

In Fig. 1 is shown schematic drawing of membrane separation process with different driving forces.
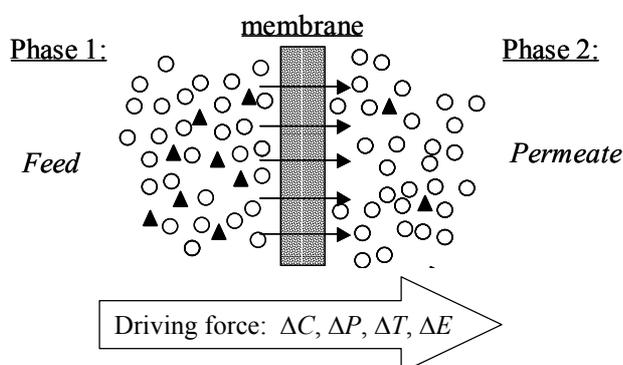
Figure 1. Schematic of membrane separation process with different driving forces that are present [5].

The performance and efficiency of the membrane process is explained by selectivity and flux, *i.e.* by which component is faster transported across the membrane and by flow of the specific component. The selectivity of a membrane is given as a retention factor *(R)*, usually for dilute aqueous solutions, or by a separation factor (α), mainly for gas and organic mixtures. The retention factor is expressed by equation [5]:

$$R = 1 - \frac{C_{permeate}}{C_{feed}}, \qquad (2)$$

where: C is the solute concentration in each phase noted, while the separation factor (3) is given by the respective concentrations in the feed (x_A, x_B) and permeate (y_A, y_B) as [5]:

$$\alpha_{A/B} = \frac{x_B \cdot y_A}{x_A \cdot y_B}. \qquad (3)$$

It should be mentioned that the amount of driving force depends on the gradient in potential through the membrane. The main potential differences in membrane processes are the chemical potential difference ($\Delta\mu$), which include pressure differences across the membrane, concentration gradients between two phases or temperature differences, and the electrical potential

difference (important in electrodialysis).

3. WHAT ARE MEMBRANE CONTACTORS AND HOW DO THEY CARRY OUT A SEPARATION PROCESS?

A new way to accomplish separation processes like gas absorption and liquid-liquid extraction is applying of membrane contactors. A membrane contactor is a device where separation of compounds is accomplished due to a specific driving force through the membrane from the one phase to the other on opposite sides. This module achieves gas/liquid or liquid/liquid mass transfer without dispersion of one phase within another. The common feature in these processes is that the separation performance is determined by the distribution coefficient of a component in two phases. The membrane represents only an interface and can be defined as a permselective barrier between two homogenous phases. The membrane is using to accomplish a particular separation and transport one component more easily than another because of differences in physical and/or chemical properties between the membrane and the permeating components [4]. The contactors have a number of important advantages in contrast to conventional dispersed phase contactors. Some of them are no flooding at high flow rates, no unloading at low flow rates, absence of emulsions, no density difference between fluids required. They reduce the volume of equipment and offer more interfacial area in non-dispersive contact across a membrane, leading to decrease of the height of a transfer unit values (HTU) values. The membrane should be attentively chosen to enable as much as possible higher values of the mass transfer coefficient (k).

Membrane contactors give any wanted shape of fluid-fluid interface in contrast to conventional separation equipment where the shape of the fluid-fluid contact is an accident of nature.

There are different membrane configurations like hollow fiber, flat sheet, rotating annular and spiral wound that have applications in wastewater treatment, VOC removal from waste gas, osmotic distillation, fermentation, pharmaceuticals, carbonation of beverages, protein extraction.

Table 1 gives short review of membrane contactors, characteristics, properties of membrane materials and introduction in membrane contactor applications.

4. REVIEW AND EVALUATION OF CONTACTOR DESIGNS AND OPERATION

In evaluating and describing contactor designs, mass transfer coefficients are very important. For mass transfer equipment in generally and membrane contactors in particular, mass transfer coefficients can be expressed using correlations of the form [3]:

$$\mathrm{Sh} \sim \mathrm{Re}^{\alpha}\,\mathrm{Sc}^{\beta}\,f(geometry). \qquad (4)$$

The functions in equation (4) are changing for different membrane processes and the special values are characteristic for a module design and mode of operation, i.e. feed flow inside or outside tubular

modules, then co-current, counter-current and cross-flow modes and so forth.

Table 1. Summary of membrane contactors [4].

Membranes:	porous (hydrophobic or hydrophilic), nonporous, or composites
Thickness:	20 – 100 μm
Pore size:	nonporous or 0,05 – 1,0 μm
Driving force:	concentration or vapour pressure difference
Separation principle:	distribution coefficient
Membrane material:	hydrophobic (polytetrafluoroethylene, polypropylene, silicone rubber)
Application:	G-L contactors:
	- SO_2, CO_2, CO, NO_x from flue gases
	- CO_2 and H_2S from natural gas
	- O_2 transfer (blood oxygenation, aerobic fermentation)
	- CO_2 transfer (beverages)
	- VOC from offgas
	- NH_3 from air (intensive farmery)
	- saturated/unsaturated (ethane/ethylene)
	L-G contactors
	- volatile bioproducts (alcohols, aroma compaunds
	- O_2 removal from water
	L-L contactors
	- heavy metals
	- fermentation products (citric acid, cetic acid, lactic acid, penicillin)
	- phenolics

There are many examples of correlations that are given for both tube and shell side flow based on equation (4) to estimate the mass transfer coefficient for an appropriate unit design.

In Table 2 is given a review of correlations developed for different membrane module designs and modes of operation. Some of them are mentioned in this report.

4.1. Tube side flow

Using high-speed photography and dye tracer studies, several researchers showed that tube side distribution is often not uniform [3]. They determined that the distribution depends on the inlet manifold type (cylindrical or conical), manifold height, tube length, fiber inner diameter, shell diameter, fiber packing density and Reynolds number. With certain corrections in shell and tube geometry and when was using long manifolds at low Reynolds numbers, a nearly uniform flow was achieved. Now, if the distribution of fiber diameters leads to low flows in some fibers then the mass transfer coefficient will be reduced by polydispersity. This is showed experimentally using microporous polypropylene hollow fibers for stripping oxygen from water into water-saturated nitrogen.

4.2. Shell side flow parallel to the fibers

Shell side flow is not enough investigated in contrast to tube side. There are correlations, that do not give well enough experimental results on mass transfer in

Table 2. Summary of correlations developed for different membrane module configurations and modes of operation [5].

Correlation (Comments)	Reference
Tube side flow:	
$Sh = 1,62 (d^2v/LD)^{1/2}$ General Léveque solution	Léveque, 1928
Shell side parallel flow:	
$Sh = \beta[d_e(1-\varphi)/L]Re^{0,6}Sc^{0,33}$ For $0 < Re < 500$, $0,04 < \varphi < 0,4$ and $\beta=5,8$ or $6,1$	Prased et. al., 1988
$Sh = 1,25 (Red_e/L)^{0,93}Sc^{0,33}$ For $0 < Re < 500$, $\varphi = 0,26$, $0,03$	Yang et. al., 1986
$Sh = 8(Red_e/L)Sc^{0,33}$ Channeling suspected, questionable accuracy	Dahuron et. al., 1988
$Sh = 0,019Gz$ For $Gz < 60$ for close packed fibers	Wickramasinghe, 1992
$Sh = (0,53-0,56\varphi)Re^{0,53}Sc^{0,33}$ For $21 < Re < 324$, $0,32 < \varphi < 0,76$	Costello et. al., 1993
$Sh = 0,18Re^{0,81}Sc^{0,33}$ For $600 < Re < 46000$, $\varphi = 0,01$, $0,03$	Letterman, 1999
Shell side cross-flow:	
$Sh = 0,15Re^{0,8}Sc^{0,33}$ For $Re > 2,5$ (cylindrical, helical wound)	Wickramasinghe, 1992
$Sh = 0,12Re^{0,8}Sc^{0,33}$ For $Re < 2,5$ (cylindrical, helical wound)	Wickramasinghe, 1992
$Sh = 6.0Gz^{0,35}$ For $Gz > 11$ crimped flat membrane	Wickramasinghe, 1992
$Sh = 1,25Gz$ For $Gz < 11$ crimped flat membrane	Wickramasinghe, 1992
$Sh = 1,38Re^{0,34}Sc^{0,33}$ For $1 < Re < 25$, $\varphi = 0,70$	Prased et.al., 1988
$Sh = 0,90Re^{0,40}Sc^{0,33}$ For $1 < Re < 25$, $\varphi = 0,07$	Prased et. al., 1988
$Sh = 0,61Re^{0,363}Sc^{0,333}$ For $0.06 < Re < 49$, $\varphi = 0,003$	Coté et. al., 1989
$Sh = 1,45Re^{0,32}Sc^{0,33}$ Developed for bubbleless aeration	Ahmed et .al., 1996
$Sh = 0,24(Red_e/L)^{0,59}Sc^{0,33}$ Developed for sealed fibers in jet stream	Johnson et. al., 1996
$Sh = 0,39Re^{0,29} \cdot (WeEu)^{0,39}Sc^{0,33}$ Developed for bubbleless surface aeration	Weiss et. al., 1996
$Sh = 0,9Re^{0,5}Sc^{0,33}$ For $1 < Re < 1000$ (rectangular module)	Crespo et. al., 1994

Note: φ is the packing fraction. WeEu=gauge feed pressure * pore diameter/watersurface tension

membrane contactors because of the lack of dependency on geometry [3], but a number of researchers obtained equations very similar to the equation (4) for different operations. In the case of gas absorption and stripping, it was obtained following correlation [3]:

$$Sh = 1,25 \left(Re \cdot d_e / L \right)^{0,93} Sc^{0,33}. \qquad (5)$$

The next correlation is obtained for gas absorption and stripping using close-packed fibers [3]:

$$Sh = 0,019\,Gz\,. \qquad (6)$$

How does the shell side residence time distribution (RTD) influence on mass transfer coefficient? For an ideal contactor, plug flow would be obtained. In real shell side flow, distribution of fluid across the fiber bundle and along it leads to broaden the RTD. Mass transfer is more efficient for fluid parts with a shorter residence time because their concentration driving force is higher than that for fluid particles which spend more time in the shell. Investigators showed that higher local mass transfer coefficients are obtained for fluid elements in cross flow than those in parallel flow to the fibers [3].

The effect of fiber packing density on shell side mass transfer was studied. The mass transfer coefficients were higher for loosely packed fibers in contrast to closely in the absorption of oxygen into water with water flowing on the shell side. Most of the published correlations for the shell side mass transfer coefficient were developed using contactors with low fiber packing densities (3-40 %). The mass transfer coefficient increases steadily with increasing packing density until a maximum is enhanced on value of 65-70%. Then the fibers are very close together and there are "dead zones" which have influence on decline of mass transfer coefficient. There are differences between values which are obtained by theory and experiments. For packing density less than 65 %, experimental coefficients are higher than those based on the theory because the theory assumes the fibers are packed uniformly, with axial laminar flow, whereas in the real systems there is non-uniformity which provides turbulence and consequently higher mass transfer coefficients [3].

4.3. Alternative hollow fiber geometries

A number of investigations led to the development of contactor designs that offer higher mass transfer coefficients than conventional parallel flow. For stripping oxygen from water into nitrogen, investigators used four module designs which were a cylindrical tube bundle, helically wound bundle, a rectangular bed of fibers and a crimped flat membrane, each with water flowing outside and across the microporous polypropylene hollow fibers. Mass transfer coefficients for the first three modules are given as [3]:

$$Sh = 0,15\,Re^{0,8}\,Sc^{0,33} \qquad (Re > 2.5), \qquad (7)$$

$$Sh = 0,12\,Re\,Sc^{0,33} \qquad (Re < 2.5). \qquad (8)$$

Sherwood numbers obtained at flow rates (8) were lower than those, which are calculated by the correlation (7) for high flow rates because of uneven flows caused by polydisperse channels between fibers.

The following correlations are obtained for crimped flat membranes [3]:

$$Sh = 6,0\,Gz^{0,35} \qquad (Gz>11), \qquad (9)$$

$$Sh = 1,25\,Gz \qquad (Gz<11). \qquad (10)$$

Researchers compared features of different cross flow modules as a function of oxygen removal efficiency on the basis of equal flow per unit membrane area and equal flow per unit membrane volume as well. Similar results were found. The rectangular bundle showed the best results, 98 % oxygen was stripped from water, while the cylindrical bundle, helical bundle, and crimped flat plate removed 82%, 86% and 72%, respectively. These designs were more efficient than a parallel flow cylindrical module, with 7 % of removed oxygen from the water [3].

A rectangular design in gas absorption applications with gas flow around and perpendicular to the fibers has a number of advantages like *high mass transfer, low pressure drop, well-defined flow conditions on both sides of membrane, ability to stack modules*. The mass transfer coefficient is higher with fibers arrangement in-line than when they are staggered. There are similar correlations for describing mass transfer coefficients developed in different operations like removal of oxygen or CO_2 from water into nitrogen, oxygenation of water using microporous polypropylene hollow fibers, bubbleless aeration of water using a sealed hollow fiber bundle unconfined in a jet stream. The mass transfer correlation:

$$Sh = 0,24\left(Re \cdot d_e / L\right)^{0,59} Sc^{0,33}, \qquad (11)$$

is obtained using different membrane lengths, jet liquid exit velocities and jet orifice areas [3].

5. HOLLOW FIBER FABRIC

In the prior chapters notice that uneven flow distribution lead to reduction of mass transfer coefficient. Non-uniform fiber spacing causes lower mass transfer coefficients in commercial designs in contrast to hand built laboratory units. It was suggested using fibers woven into a fabric to get more uniform spacing. Modules that contained woven fabric used to strip oxygen or toluene from water into nitrogen and to absorb CO_2 from pure CO_2 and from a CO_2/N_2 mixture into water.

Several of the investigators compared four module configurations in operation of stripping oxygen from water using microporous polypropylene hollow fibers. The first configuration (Fig. 2) was an annular bed of hollow fibers wound helically around a central core.
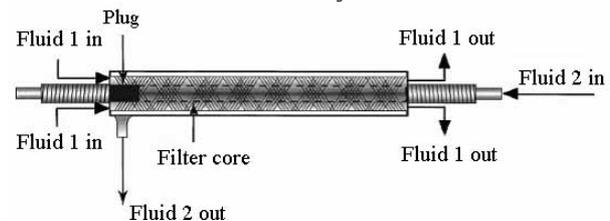
Figure 2. A module containing hollow fibers wound helically around a central core. The plug forces liquid entering the core radially outward so that the flow is perpendicular to the fibers [3].

The second configuration was similar to the first except that the shell contained plugs and O-rings to

provide multiple shell side passes. The next configuration is showed in Fig. 3 and it was made with knitted hollow fiber fabric. The last configuration that is showed in Fig. 4 was mounted diagonally in an open-ended rectangular box, and the liquid entered through a tubular pipe. The first two configurations, with axially wound individual fibers, provided higher mass transfer coefficients for hand-built modules in contrast to commercially manufactured contactors.

Mass transfer coefficients for the axially wound fabric (Fig. 3) were a little bit higher than those obtained with the axially wound were individual fibers. That was because the modules that were containing the fabric had higher uniformity of fiber spacing compared to individual fibers. The mass transfer coefficients for rectangular modules were the highest of the four configurations.
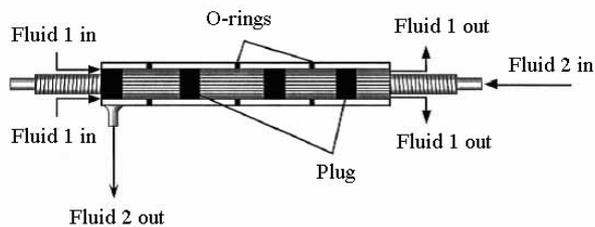
Figure 3. A module containing woven hollow fiber wound helically around a central core. The plug and O-rings provide multiple shell passes [3].
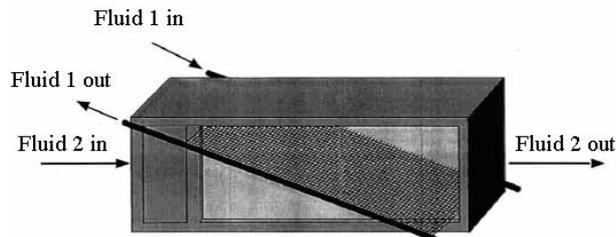
Figure 4. A module containing woven hollow fiber wound mounted diagonally in an open-ended box [3].

Several investigators checked the possibilities of various hand-built modules like the rectangular modules, the axially wound individual fibers, and the axially wound fabric. The results obtaining can be described with average correlation [3]:

$$Sh = 0,82 \, Re^{0,49} \, Sc^{0,33} . \quad (12)$$

Researchers were comparing hollow fiber contactors containing a woven fabric of microporous polypropylene fibers to designs built from individual fibers in gas stripping. The first module design was a conventional parallel flow module, which contained individual fibers. Liquid and gas flowed through the tube and shell, respectively. The second (Fig. 5) and third (Fig. 6) designs had the woven fabric instead of individual fibers. Liquid and gas were placed on the shell and tube sides.

In investigation of commercial oxygenators obtained the Sherwood number correlation for the rectangular module [3]:

$$Sh = 0,18 \, Re^{0,86} \, Sc^{0,33} . \quad (13)$$

Mass transfer coefficients for rectangular modules are lower than coefficients for the cylindrical modules, because the rectangular module contained stagnant liquid zones between adjacent fibers in each layer of fabric.

In absorption of CO_2 from pure CO_2 and from a CO_2/N_2 mixture into water, researchers used a fabric made from microporous polypropylene hollow fibers. The fabric was wound helically around the central core with gas flowing on the tube side. Liquid was forced perpendicular to the fibers by the plug. Data obtained in this operation were similar to the predictions of other correlations described for low Reynolds numbers.
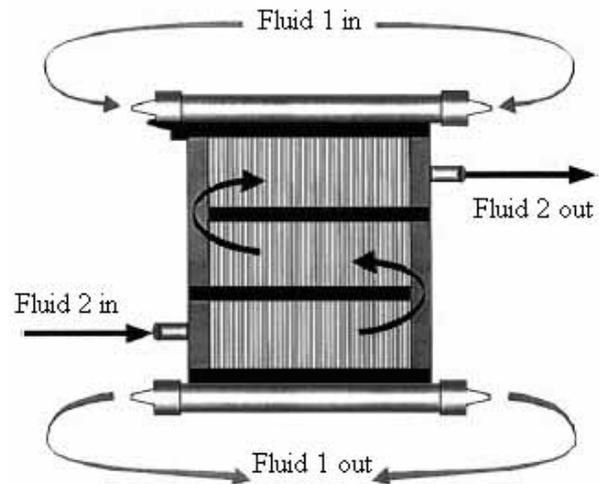
Figure 5. A rectangular module containing two baffles [3].

Figure 6. A fully baffled cylindrical module [3].

6. REVIEW PROCESS DESIGNS FOR MEMBRANE CONTACTORS APPLICATIONS

There are many different designs of membrane contactors because of a large number of applications and module configurations. The module is the central part of a membrane installation and can be defined as separation unit. The main task for every engineer is to arrange the modules that the optimal design is obtained at the lowest product cost.

One of very important question that have to be considered is that of where the feed fluid phase should flow, on the shell side or tube side. In gas stripping, the feed fluid phase is liquid. The feed fluid phase is gaseous in *gas absorption*. After the selection of tube side or shell side flow of the feed fluid phase, it should be choose process design.

In microfiltration is very often applied the concept of dead-end operation (Fig. 7). All the feed is forced through the membrane, which implies that the concentration of rejected components in the feed increases and the quality of the permeate decreases with time because of fouling in dead-end operations.

For industrial applications, a cross-flow operation (Fig. 7) is better because of the lower fouling in contrast to the dead-end mode. In dead-end filtration, the cake grows with time and the flux decreases with time (Fig. 8).
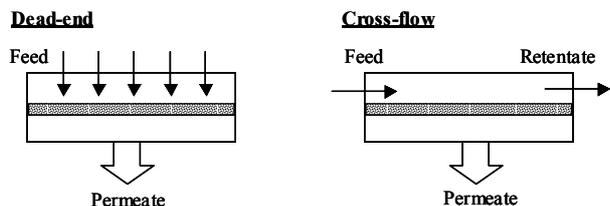
Figure 7. Schematic of the two basic principles of module operation [5].
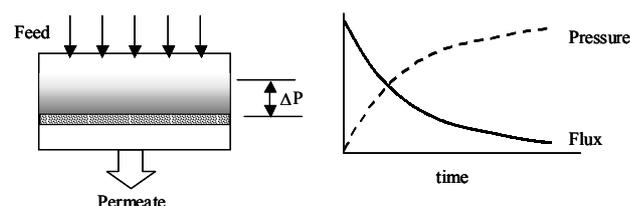
Figure 8. Principle of dead-end operating mode [5].
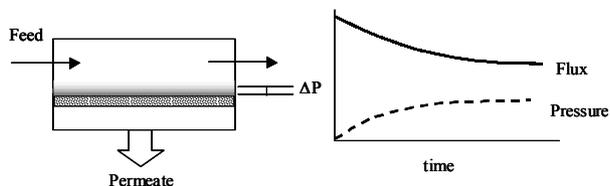
Figure 9. Principle of cross-flow operating mode [5]

a. CO-CURRENT FLOW

b. COUNTER-CURRENT FLOW

c. CROSS-FLOW

d. PERFECT MIXING
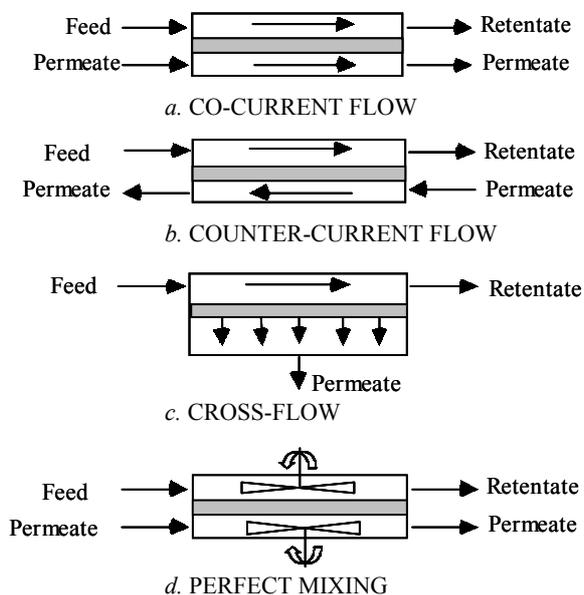
Figure 10. Principle flow patterns used in cross-flow operation [5].

In cross-flow operation, flux decline is smaller and can be adjusted by cross-flow velocity (Fig. 9.).

There are different cross-flow operations (Fig. 10.) like: co-current, counter-current, cross-flow with perfect permeate mixing, perfect mixing.

The contactors are used in the wastewater treatment and for aeration in purification of potable water. For instance, aeration in connection with biological treatment, removal of VOC's and gas stripping.

Some application areas in membrane gas absorption and membrane gas stripping will be described in text bellow. A new application of gas liquid contacting using microporous membranes is an intra vascular oxygenator, wherein the hollow-fiber bundle is plunged through a vein in the neck or the leg into the body's main vein to provide O_2 and remove CO_2.

From acidic wines produced in some unsuccessful fermentation, acetic acid can be removed through a gas membrane into a caustic solution on the other side of a hydrophobic microporous hollow fiber. Several investigators studied removal of ethanol from a fermentation blend through air seated in polytetrafluoroethylene (PTFE) membrane pores into an aqueous solution of ethylene or propylene glycol that does not wet the membrane.

Counter-current flows gives the best results, the next are cross-flow and co-current flow and the worst results are obtained in the perfect permeate mixing [4]. In practice methods are used in a single-stage or multi-stage processes in the form of single pass system and recirculation system. The recirculation system prefers in microfiltration and ultrafiltration to the single-pass system in desalination of water.

It is known the absorption of a different of inert gases in acidic or alkaline medium using a hydrophobic polypropylene hollow fiber device: NH_3 in H_2SO_4; H_2S, CO_2 and SO_2 in NaOH. Researchers reported results for the removal of SO_2 from flue gas in a polysulfone hollow-fiber absorber using an aqueous solution of Na_2SO_3. With using hydrophilic fibers, there is absorption of SO_2 from air into water and the absorption of NH_3 in water [2].

It is very important to describe example of the stripping of O_2 from water using vacuum or sweep gas in hydrophobic polypropylene hollow-fiber devices with either parallel flow or cross flow. This is useful for preparing beverage water and deaeration of boiler feed water. There is an experimental work with air stripping of volatile organic compounds from water in hydrophobic polypropylene hollow-fiber devices with countercurrent flow. There is reported work of dehumidification process using a microporous hydrophobic hollow-fiber module where the moisture from air is absorbed in triethylene glycol (TEG). It is flowing into the fiber lumen with gas-filled pores since TEG does not wet pores [2].

Nowadays, membrane technology is used to using in many environmental, water treatment, chemical, petrochemical, petroleum, pharmaceutical medical, beverage, dairy, food, paper, textile and electronic engineering applications.

7. SOME MORE CONSIDERATIONS IN CONTACTOR DESIGN AND OPERATION – DESIGN APPROACH AND DESIGN OBJECTIVE

A number of design characteristics must be taking into account to obtain the required number of transfer units and capacity. These are tube diameter, wall thickness, porosity, packing density, flow rates, distribution coefficient, fluid physical properties, and inlet concentration. *Module length* is a key design

specification because it is a function of the number of transfer units. Longer modules provide higher efficiency and increasing pressure drop as well. Consequently, the pressure of the no wetting fluid can be lower than that of the wetting fluid, so that bulk flow of the wetting may penetrate into non-wetting. Several investigators described a design procedure, which gives the required number of fibers, length for a existing design problem and module diameter. The design objective in mass transfer with membrane contactors depends on the application. For industrial applications, the objective is to minimize the cost per amount of mass transferred, while in small installation, for example in blood oxygenations, the objective is to maximize the amount of oxygen transferred per unit volume.

8. CONCLUSIONS

This paper gives a wide review of applying of membrane contactors and shows a new way for removal of undesired components from different solutions. Membrane technology offers an alternative method where a non-dispersive interface is created between the two phases. Permanent investigations in separation processes led to improvement results in contrast to conventional ones. Process designs that are described in this paper can more than successfully replace conventional dispersion-based solvent extraction in almost all applications. It is an alternative technology that provides many advantages in contrast to traditional fluid/fluid contactors. They reduce the volume of equipment, and with much more interfacial area the membrane can ensure higher values of the mass transfer coefficient (k). All of these advantages enable development of commercial applications and a number of laboratory investigations prove why the membrane contactor technology is the best way for applying of membrane processes.

LIST OF SYMBOLS

A — phenomenological coefficient,
C — solute concentration in each phase,
c_p — specific heat at constant pressure,
D — liquid diffusion coefficient of the component,
d_e — hydraulic diametar or effective diameter,
f — function of geometry,
J — flux volume through the membrane,
k — mass transfer coefficient,
k_L — liquid-film mass transfer coefficient,
R — retention factor,
x_A, x_B — concentration in the feed,
y_A, y_B — concentration in the permeate,
DO — dissolved oxygen,
HTU — height of a transfer unit value,
PTFE — polytetrafluoroethylene,
RTD — residence time distribution,
TEG — triethylene glucol,
VOC — volatile organic compounds,
α — separation factor,
φ — packing fraction,

v — kinematic viscosity of the liquid,
v_L — liquid velocity past the membrane,
λ — thermal conductivity,
μ — viscosity,
$\Delta\mu$ — chemical potential difference,
ΔC — concentration difference across the membrane,
ΔE — electrical potential difference across the membrane,
ΔP — pressure difference across the membrane,
ΔT — temperature difference across the membrane,
$Gz = Re \cdot Pr \cdot d_e/L$ — Graetz number,
$Pr = c_p \cdot \mu/\lambda$ — Prandtl number,
$Re = v_L \cdot d_e/v$ — Reynolds number,
$Sc = v/D$ — Schmidt number,
$Sh = k_L \cdot d_e/D$ — Sherwood number.

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ПРЕГЛЕД КОНСТРУКЦИЈА МЕМБРАНСКИХ КОНТАКТОРА И ПРИМЕНА РАЗЛИЧИТИХ МОДУЛА У ИНДУСТРИЈИ

Мирослав Станојевић, Бојан Лазаревић, Дејан Радић

Нов начин примене мембранских процеса у пречишћавању вода из различитих индустрија је коришћење мембранских контактора. Технологија мембранских контактора има примене у третману отпадних вода, фармацеутској индустрији, ферме-нтацији, производњи полупроводника, екстракцији протеина, карбонизацији пића, уклањању испарљи-вих органских компонената (VOC) из отпадног гаса и тако даље. Мембрански системи пројектовани да

формирају контакт између две компоненте (течно / течно, течно/гас и гас/гас) су заједнички дефинисани као мембрански контактори.

Мембрански контактори су уређаји који постижу пренос материје у систему гас/течност или течност/течност без дисперзије једне фазе унутар друге. Мембрана се користи за сепарацију и транспорт радне компоненте много лакше у односу на друге услед разлика у физичким и/или хемијским карактеристикама између мембране и компонената. Постоји неколико предности при коришћењу мембранских контактора у односу на конвенционалне методе. Неке од њих су: не постоји плављење при високим протоцима, задржавање радних карактеристика при ниским протоцима, одсуство емулзије, нема разлике густина тражених флуида и велика површина. Главни циљ овог рада је био преглед карактеристика и примене мембранских контактора, посебно примене контактора за издвајање раствореног кисеоника из водених раствора уз помоћ вакуума.