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# A novel process for oxygen absorption from air using hollow fiber gas-liquid membrane contactor

H. Banazadeh, S.M. Mousavi*

*Chemical Engineering Department, Faculty of Engineering, Ferdowsi University of Mashhad, Mashhad, Iran*

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ABSTRACT

In this study, the absorption of oxygen from air flowing through polypropylene hollow fiber membrane contactor was investigated using slaughterhouse wastewater, including about 90% (v/v) blood, as an absorbent. The effect of operating parameters on process performance was examined in two modes of absorbent flowing through both the lumen and shell of the membrane contactor. In addition, some experiments were carried out to examine the long term performance of the system. Removal efficiency and absorption flux were determined for investigation of the process performance. Results showed decrease in gas flow rate and increase in liquid flow rate resulted in higher removal efficiency, respectively. Moreover, absorption flux was increased by augmenting both gas and liquid flow rate. Furthermore, the removal efficiency of near 78% was obtained for mode of wastewater flowing through the lumen side. No considerable variations in removal efficiency were observable for long term operation.

## 1. Introduction

The air almost consists of oxygen (21%), nitrogen (78%), and some other gases (1%) [1]. In view of increasing applications of both the abovementioned gases as pure components in industrial and medical usages, the need for proper separation processes seems inevitable. The most common method of pure oxygen and nitrogen production is air separation [1]. Methods of extracting pure oxygen and nitrogen from air can be divided into three major categories: cryogenic method, adsorptive separation, and membrane permeation [1,2]. Cryogenic method is generally believed to be able to produce all main products with high purity. However, this method needs air feed compressors that have high energy consumption. Furthermore, investment cost of cryogenic method is significant [3]. On the other hand, in membrane permeation and adsorptive separation, the purity of products (especially oxygen) is lower [4,5]. Advantages and drawbacks of each abovementioned method along with their application domains are available in literature [6,7].

Membrane absorption of gases in membrane contactors as a novel approach of contacting liquid and gas possesses major advantages in comparison with absorption columns. Membrane contactors don't have limitations of absorption columns such as foaming, channeling, flooding, and entrainment of the liquid [8–10]. In addition, they have lower investment cost compared to absorption columns [9]. Hollow fiber membrane contactors can economize on weight of the set-up and required space due to their compactness and high surface to volume ratio [11]. In fact, the advantages of absorption process and membrane method have been combined in membrane gas absorption (MGA) [12]. This process is completely different from membrane gas separation owing to the fact that, in MGA, the membrane just acts as a barrier between two phases and liquid is responsible for selectivity [8,13]. However, in membrane gas separation, with respect to applying different membranes, permeability usually decreases with increase in selectivity, and vice versa [14]. Based on the aforementioned reasons, the flux can be higher in MGA [14].

Taking into account the advantages of MGA compared to other separation methods, membrane contactor can be exploited for separation of air into its components if a suitable absorbent is used. Blood can be considered as a proper absorbent for separation of oxygen. Nearly all oxygen carried in blood of animals, is attached to hemoglobin in erythrocytes (red blood cells) [15]. Hemoglobin in red blood cells transports oxygen [16]. Indeed, hemoglobin binds oxygen in lungs and releases it in tissues because of oxygen partial pressure changes between lungs and tissues [15].

The production of enriched nitrogen by removal of oxygen from air using a hollow fiber gas-liquid membrane contactor is the objective and novelty of this research. In the present study, blood was considered as an absorbent for the first time to transfer oxygen by mimicking living species which use blood to transport oxygen to tissues. Therefore, the slaughterhouse wastewater, including almost 90% (v/v) blood, was

* Corresponding author.
*E-mail address:* mmousavi@um.ac.ir (S.M. Mousavi).

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**Table 1**
Membrane and module specifications.

| Item | Description | Reference |
|---|---|---|
| Membrane material | Hydrophobic PP | Supplier |
| Contact angle (°) | 117.7 | [17] |
| Outer diameter (mm) | 0.45 | Supplier |
| Inner diameter (mm) | 0.22 | Supplier |
| Membrane length (m) | 0.4 | Measured |
| Membrane pore size (nm) | 100–200 | Supplier |
| Outside fiber area ($m^2$) | 1 | Supplier |
| Inside shell diameter (m) | 0.06 | Measured |
| Effective contactor length (m) | 0.35 | Measured |
| Membrane porosity | 0.5 | Supplier |

used as the absorbent in order to absorb oxygen from air in membrane contactors. Experiments were conducted in two operating conditions i.e. wastewater flowing through the lumen of hollow fibers (the first mode) and the shell (the second mode). The impact of membrane contactor key parameters, including liquid and gas flow rates, was examined on absorption flux and removal efficiency in both operating conditions. In addition, performance of the system was assessed in long-term operation. Furthermore, wastewater saturation was studied using used and fresh wastewater.

## 2. Materials and methods

### 2.1. Materials

The polypropylene hollow fiber membranes used in this study was prepared from Parsian Pishro Sanat Polymer Co. (Iran). Specifications of the hollow fiber membrane and module are summarized in Table 1. Sodium citrate (industrial grade) and drinking water were also used for anti-coagulant preparation.

### 2.2. Wastewater preparation

For preparation of an applicable wastewater for utilization in membrane contactor, clotting must be precluded. Accordingly, the exertion of sufficient anti-coagulants is needed. Sodium citrate 4% (w/w) was applied as anti-coagulant. An approximate volume of 100 mL of this solution was adequate for preventing coagulation in 1200 mL wastewater. A local poultry slaughterhouse was selected as the source of wastewater. The collecting container was filled with approximately 600 mL anti-coagulant prior to placing in the slaughter line. The collecting container was withdrawn from the line after that the volume of wastewater was reached roughly 7L. Then all collected wastewater was filtered two times using a mesh 35 (0.5 mm) to remove suspended solid particles.

### 2.3. Experimental set-up and procedure

Absorption experiments in membrane contactors were conducted in two different modes. In the first operating mode, wastewater was flowed through the shell while the air was moved through hollow fibers. Fig. 1 presents the system configuration. The ambient air was sent to the humidifier with atmospheric pressure using a small blower. Oxygen content of inlet air was subsequently analyzed by an oxygen analyzer (Oxyme 120, MPSP). Afterward, wet air was passed through a rotameter (Azmoon Mottamem, LZB 1000) and entered the hollow fibers. Second oxygen analyzer was responsible for continuous measurement of oxygen discharging the membrane contactor. Wastewater also counter-currently entered the shell side of the membrane contactor using a centrifugal pump (SP2500III, BOYU). Scaled cylinder and timer were used to measure wastewater flow rate of the output stream into the storage tank.

In order to ensure the minimum wettability, input liquid pressure should be kept under breakthrough pressure. Young-Laplace equation was used to determine breakthrough pressure [12,18]:

$$\Delta P_{br} = \frac{-2\gamma_l \cos\theta}{r} \tag{1}$$

where $\Delta P_{br}$ is the breakthrough pressure, $\gamma_l$ is the liquid surface tension, $\theta$ is the contact angle between liquid and membrane, and $r$ is the radius of pores in the membrane.

Considering the fact that wastewater is consisted of about 90% (v/v) blood and operating temperature of 25 °C, surface tension of wastewater is calculated from the equation presented in literature [19] to be 59.7 mN/m. Finally, breakthrough pressure was calculated as 3.65 bar according to the value of contact angle presented in Table 1. Operating pressure of input wastewater was fixed at 0.1 bar to be sufficiently lower than breakthrough pressure.

In the second operation mode, wastewater was passed within the hollow fibers while the air was moved through the shell. The dashed lines in Fig. 1 represent the operating condition. Moreover, streams of wastewater and air were in counter-current manner.

### 2.4. Determination of removal efficiency and absorption flux

To study the effect of various parameters on the absorption process, removal efficiency and absorption flux were calculated from Eqs. (2) and (3), respectively [20,21]:

$$\eta(\%) = \frac{Q_{g-in}y_{in} - Q_{g-out}y_{out}}{Q_{g-in}y_{in}} \times 100 \tag{2}$$

$$J_{O_2} = \frac{P(Q_{g-in}y_{in} - Q_{g-out}y_{out})}{RTA_m} \tag{3}$$

where $\eta$ is the removal efficiency, $Q_{g\text{-}in}$ and $Q_{g\text{-}out}$ are the volumetric gas flow rates in the inlet and outlet, respectively, $y_{in}$ and $y_{out}$ are the oxygen mole fractions in the inlet and outlet gas, respectively, $J_{O2}$ is the oxygen absorption flux, $P$ is the total absolute pressure of gas, $R$ is the gas constant, $T$ is the absolute temperature of gas, and $A_m$ is the total effective membrane area (interfacial area).

It can be assumed that changes in gas flow rate during absorption process in membrane contactors are negligible; thus, input and output flow rates have been considered equal [22]. This assumption is applicable for systems with little change between concentrations of inlet and outlet gas phase. For systems operating with low gas flow rates and relatively high concentration of removable component, in which almost major of this component is absorbed to liquid, the changes in the flow rate is considerable. Based on the fact that air is mostly composed of oxygen and nitrogen and by taking into account the negligible absorption of nitrogen by hemoglobin of the wastewater, a mass balance for membrane contactor can be written for other components except oxygen:

$$(1-y_{in})Q_{g-in} = (1-y_{out})Q_{g-out} \tag{4}$$

Eqs. (5) and (6) are obtained by substituting Eq. (4) in Eqs. (2) and (3):

$$\eta(\%) = \left(1 - \frac{(1-y_{in})y_{out}}{(1-y_{out})y_{in}}\right) \times 100 \tag{5}$$

$$J_{O_2} = \frac{P_t Q_{g-in}y_{in}}{RTA_m}\left(1 - \frac{(1-y_{in})y_{out}}{(1-y_{out})y_{in}}\right) = \frac{P_t Q_{g-in}y_{in}\eta}{RTA_m 100} \tag{6}$$

## 3. Results and discussion

### 3.1. Effect of air flow rate

#### 3.1.1. Part 1: wastewater in shell side

Fig. 2 shows the removal efficiency variations versus input air flow