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On Gas Separation by Permeation with One-Side Mixing

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NOTE

On Gas Separation by Permeation with One-Side Mixing

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Abstract

A calculation method for gas separation by permeation with one-side mixing is proposed. Five types of stage flow patterns (one-side mixing, countercurrent flow, cross flow, cocurrent flow, and perfect mixing) are compared with reference to separation of oxygen from air. The calculation results regarding one-side mixing differ from those reported previously.

INTRODUCTION

There are several models for a membrane module of gas permeation, and depending on the flow patterns and operating conditions, these models are classified as (*1*, *2*): countercurrent flow, cocurrent flow, cross flow, perfect mixing, and one-side mixing. In a shell-and-tube type membrane module where the length of the shell is much shorter than that of the bundle of hollow fibers, the phase of the shell-side is likely to be perfectly mixed when both the longitudinal and normal velocity components are small. However, the phase of the tube-side is likely to be in plug flow. Such a case is called one-side mixing.

There are few reports on one-side mixing. Oishi et al. (*2*) mentioned that the enrichment obtained in one-side mixing lies in between those in countercurrent flow and perfect mixing. Kammermeyer et al. (*1*) carried out computations for the oxygen enrichment of air when a silicone-rubber membrane was used as a barrier. They showed that the mole fraction of oxygen in permeate decreased in the order: countercurrent flow, cross flow, cocurrent flow, one-side mixing, and perfect mixing. In this paper the five types of stage flow patterns mentioned above are compared with reference to the separation of oxygen from air. The calculation results regarding one-side mixing differ from those by Kammermeyer et al. (*1*).

METHOD OF CALCULATION

The assumptions utilized in this study are as follows.

(1) The permeability of each gas component is the same as that of the pure gas, and is independent of pressure.
(2) The effective membrane thickness is constant along the length of the permeator.
(3) The concentration gradients in the permeation direction are negligible.
(4) The pressure drops of the feed and permeate gas streams are negligible.
(5) A plug flow situation exists in the feed and permeate streams except, of course, in mixed flow and in the permeate streams in cross flow.

The calculation methods used in this paper for the flow patterns, except for one-side mixing, are similar to those developed by previous investigators (*1–6*). The calculation method for one-side mixing is described below.

Figure 1 shows the permeation stage in a one-side mixing pattern. Taking component and total balances over the differential area dA, one can obtain the following equations:

$$-d(xF) = dAQ_1(P_h x - P_l y_p)/\delta \tag{1}$$

$$-dF = -d(xF) + dAQ_2\{P_h(1 - x) - P_l(1 - y_p)\}/\delta \tag{2}$$

where F is the flow rate on the feed (high pressure) stream; Q_1 and Q_2 are the permeabilities of oxygen and nitrogen, respectively; P_h and P_l are the pressure on the feed side and the permeate side, respectively; x and y_p (constant) are the mole fractions of oxygen on the feed stream and the permeate side, respectively; and δ is the membrane thickness. Dividing

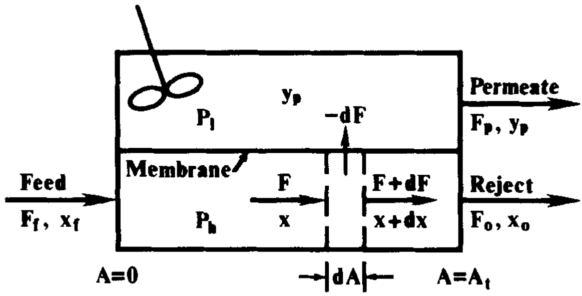

FIG. 1. Diagram of single permeation stage with one-side mixing.

Eq. (1) by Eq. (2) and integrating from the inlet point to the outlet point, by noticing that $x_f = (1 - \theta)x_o + \theta y_p$ and $F_f = F_o + F_p$, yields

$$1 - \theta = \left(\frac{-2a_1 \dfrac{x_f - \theta y_p}{1 - \theta} + a_1 - a_2 + a_4 + 1}{-2a_1 x_f + a_1 - a_2 + a_4 + 1} \right)^{a_5} \times \left(\frac{-2a_1 \dfrac{x_f - \theta y_p}{1 - \theta} + a_1 - a_2 - a_4 + 1}{-2a_1 x_f + a_1 - a_2 - a_4 + 1} \right)^{a_6} \quad (3)$$

where

$$a_1 = \alpha^* - 1 \quad (4)$$

$$a_2 = 1 - \gamma + \gamma y_p - \alpha^* \gamma y_p \quad (5)$$

$$a_3 = -\alpha^* \gamma y_p \quad (6)$$

$$a_4 = \{(a_1 - a_2 + 1)^2 + 4a_1 a_3\}^{1/2} \quad (7)$$

$$a_5 = -(a_1 + a_2 + a_4 + 1)/(2a_4) \quad (8)$$

$$a_6 = (a_1 + a_2 - a_4 + 1)/(2a_4) \quad (9)$$

α^*, γ, and θ are defined as

$$\alpha^* = Q_1/Q_2 \quad (10)$$

$$\gamma = P_l/P_h \tag{11}$$

$$\theta = F_p/F_f \tag{12}$$

When the values of α^*, γ, θ, and x_f are given, the solution of Eq. (3) gives the value of y_p.

RESULTS AND DISCUSSION

The effect of stage cut θ on the oxygen mole fractions y_p and x_o in the five flow patterns are presented in Figs. 2 and 3 with an ideal separation factor of 2.05 and a pressure ratio of 0.359. These operating conditions are the same as those employed by Kammermeyer et al. (*1*). In comparing the effectiveness of the five flow patterns examined, it is seen that the separation performance with one-side mixing is between those with cross flow and cocurrent flow.

Direct numerical integration of Eqs. (1) and (2) with an appropriate iteration scheme, of course, gives the same value as is obtained from Eq. (3). The calculation results for one-side mixing shown in Figs. 2 and 3 differ from those by Kammermeyer et al. (*1*). It is inferred that their derivation of an analytical solution (*2*) for one-side mixing or their calculation (*2*) may contain some errors.

SYMBOLS

A	membrane area (m^2)
a_1	constant defined by Eq. (4) (dimensionless)
a_2	constant defined by Eq. (5) (dimensionless)
a_3	constant defined by Eq. (6) (dimensionless)
a_4	constant defined by Eq. (7) (dimensionless)
a_5	constant defined by Eq. (8) (dimensionless)
a_6	constant defined by Eq. (9) (dimensionless)
F	variable flow rate on feed stream (mol/s)
F_f	feed flow rate (mol/s)
F_o	reject flow rate (mol/s)
F_p	permeate flow rate (mol/s)
P_h	pressure on the feed side (Pa)
P_l	pressure on the permeate side (Pa)
Q_1	permeability of oxygen (mol/s · m · Pa)
Q_2	permeability of nitrogen (mol/s · m · Pa)

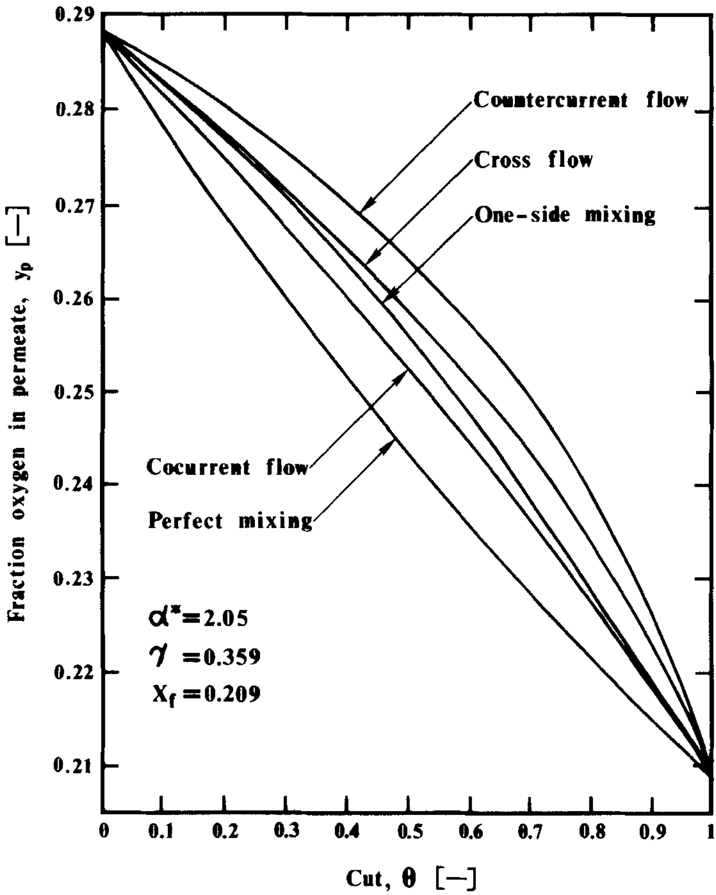

FIG. 2. Comparison of various cases for air separation, y_p vs θ.

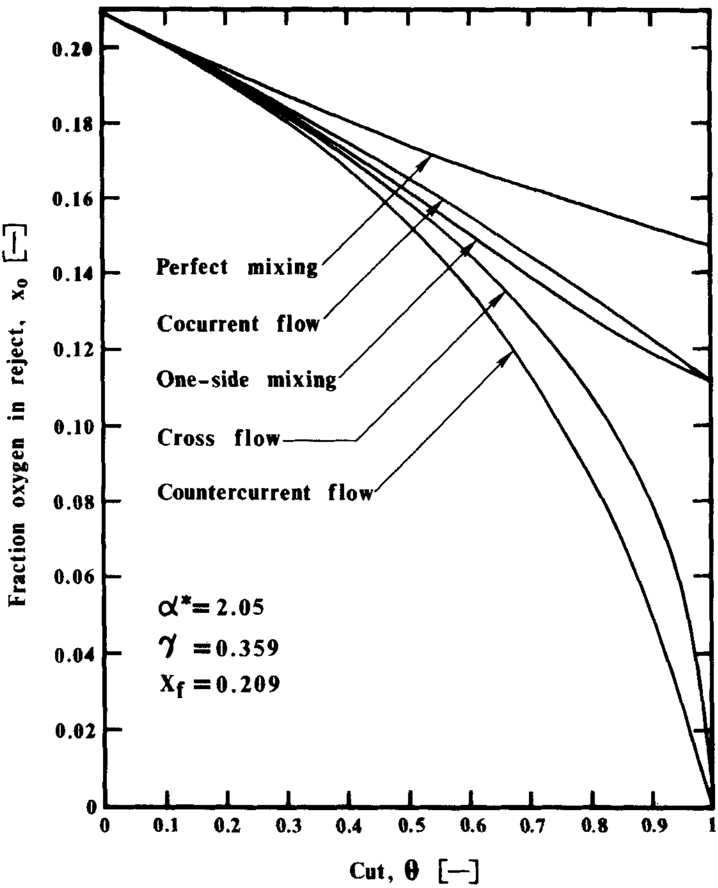

FIG. 3. Comparison of various cases for air separation, x_o vs θ.

x variable mole fraction of oxygen on the feed stream (dimensionless)
x_f mole fraction of oxygen on the feed stream at the inlet (dimensionless)
x_o mole fraction of oxygen on the feed stream at the outlet (dimensionless)
y_p mole fraction of oxygen on the permeate side (dimensionless)

Greek Letters

α^* ideal separation factor defined by Eq. (10) (dimensionless)
γ pressure ratio defined by Eq. (11) (dimensionless)
δ membrane thickness (dimensionless)
θ stage cut defined by Eq. (12) (dimensionless)

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