Korea-Japan Ⅱ-1

Study on Boundary Mass Transfer Phenomena in Liquid Laminar Flow around Hollow-Fiber Membrane

Toshiyuki KANAMORI and Toshio SHINBO
National Institute of Materials and Chemical Research, Tsukuba, JAPAN

Introduction

To design a membrane device that contacts liquid phase, we have to know the boundary mass transfer coefficient for the liquid phase. For a flat membrane, experimental and/or theoretical approach to obtain a boundary mass transfer coefficient is easy, but for a hollow-fiber membrane, especially for the outside of the membrane, very difficult. In this paper, the methods to observe boundary mass transfer phenomena in liquid phase around a hollow-fiber membrane are presented with discussion about some data.

Theory

Boundary mass transfer phenomena of a solute in laminar flow in a circular tube are theoretically derived as follows on condition that solute concentration at the wall is constant; [1]

$$Sh = 1.62\{ReSc(d/L)\}^{1/3} \tag{1}$$

where Sh ($\equiv kd/D$) is Sherwood number [-], Re ($\equiv ud/\nu$) Reynolds number [-], Sc ($\equiv D/\nu$) Schmidt number [-], d inside diameter of the tube [m], L length of the tube [m], D diffusion coefficient of the solute [m^2/s], u mean fluid velocity [m/s], and ν kinetic viscosity [m^2/s].

For liquid laminar flow in a circular-tube annuli, d in Eq. (1) is generally replaced with hydraulic equivalent diameter, d_h [m] ($\equiv$ [cross-sectional area]/[perimeter]). [2]

Experimental

The Liquid-gas contact

Kanamori *et al.* [3] have reported boundary mass transfer phenomena around a single hollow-fiber membrane for liquid-gas contact using an apparatus shown in **Figure 1**. According to "Theory", **Figure 2** is obtained from the data measured for four hollow-fiber membranes for clinical membrane oxygenator. "Eq. (14)" in the legend is equal to Eq. (1) in this abstract. The slopes of the plots, which are corresponding to the power number of Re in Eq. (1), are nearly 1/3, except the data for PDMS, for which they have pointed out the influence of the vibration of the membranes due to their flexibility.

Liquid-liquid contact

Kanamori *et al.* [4] have revealed that Eq. (1) holds for the outside channel of a single hollow-fiber hemodialysis membrane which is fixed on the axis of a

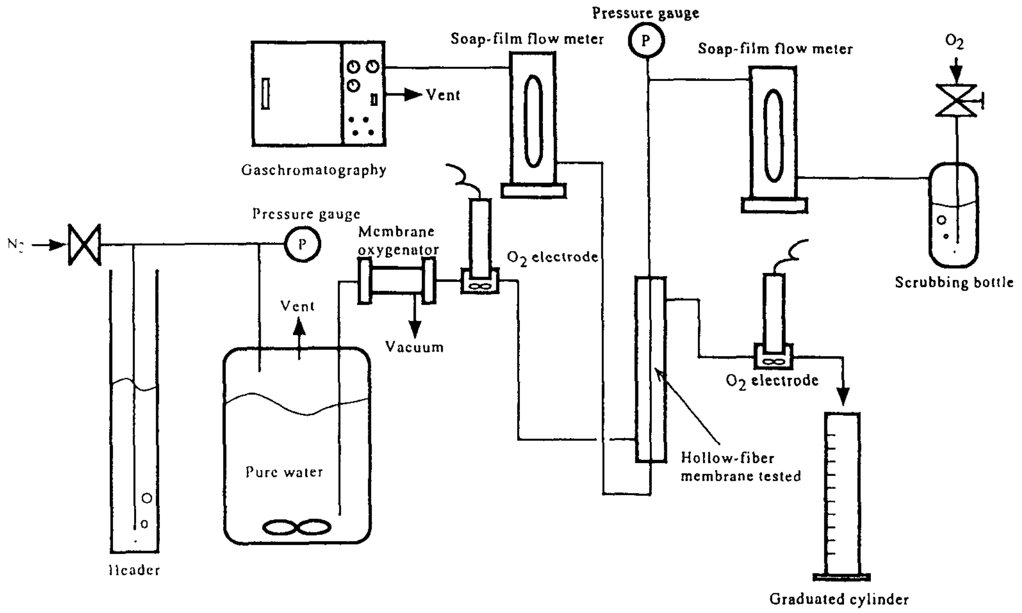


Figure 1 A schematic view of the apparatus for liquid-gas contact.

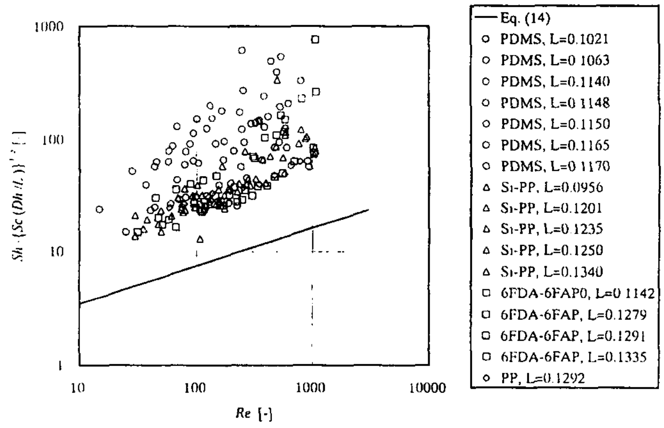


Figure 2 Boundary mass transfer phenomena around a single hollow-fiber membrane for liquid-gas contact.

circular tube and of which the lumen is stagnant. However, Fukuda *et al.* [5] have reported the following equation for shell-side channels of hollow-fiber hemodialyzers with various dimensions by dialysis experiments at a constant flow rate in the lumens and various ones in the shell-side channels;

$$Sh = 1.80 Re Sc^{1/3}(d_h/L)^{1/2}. \tag{2}$$

Accordingly, the authors studied boundary mass transfer phenomena around a single hollow-fiber membrane using a new apparatus shown **Figure 3** to clarify the cause of the disagreement between Eqs. (1) and (2).[6]

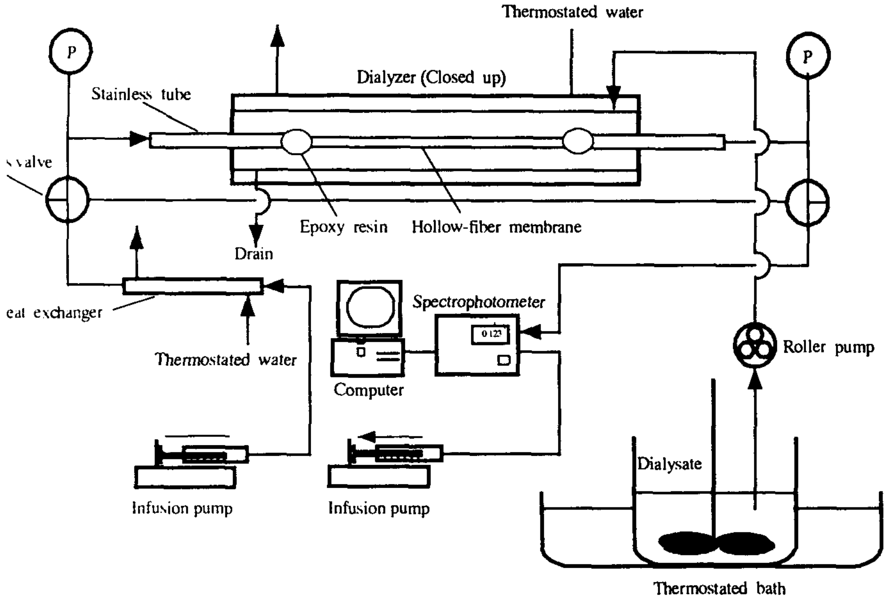
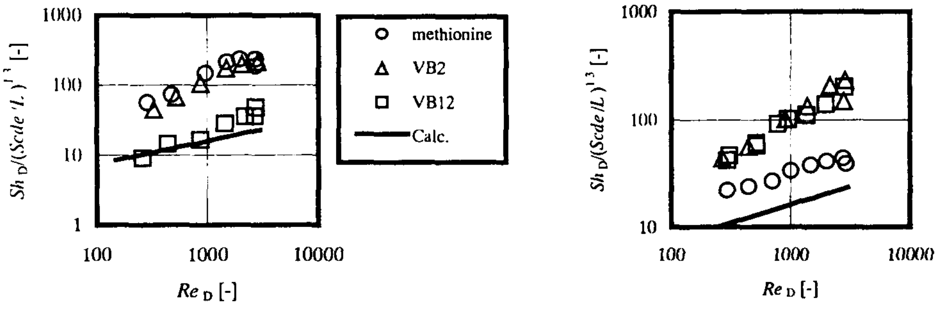


Figure 3 A schematic view of the apparatus for liquid-liquid contact.

Overall mass transfer coefficients were obtained at various outer flow rates and at a constant inner flow rate, and boundary mass transfer coefficients were calculated at each outer flow rate using so-called the Wilson plots.$^{7)}$ **Figures 4** represent the boundary mass transfer phenomena obtained for the hemodialysis membranes with lower (a) and higher (b) water permeabilities, respectively. These results indicate that with increasing water permeability of the membrane and molecular weight of the solute, the power number of Re_D (shell side) increases.



a) AM-SD-L (Asahi Medical) b) APS (Asahi Medical)

Figure 4 Boundary mass transfer phenomena around a single hollow-fiber membrane for liquid-liquid contact.

Discussion

In this study, boundary mass transfer phenomena in liquid laminar flow around hollow-fiber membrane are discussed. For liquid-gas contact which has no influence of convective flow through membrane, the power number of *Re* in the dimensionless equation for the outer boundary mass transfer is almost 1/3 which is theoretically obtained. For liquid-liquid contact on condition that the lumen of a single hollow-fiber membrane is stagnant, the power number is also almost 1/3. The system used for this study is similar to those with which these results have been obtained, however only one point that there is convective flow through membrane is different.

The power number of *Re* obtained in this study is larger than 1/3, meaning the influence of the flow rate is higher. Although the measurements were carried out so as to keep net filtration negligible, the pressure gradients along the membrane corresponding to the inner and outer flow rates caused local convective flux through the membrane. So, the disagreement between Eqs. (1) and (2) in the power number of *Re* is considered to be due to the local convective flux. On the other hand, the disagreement in the power number of (d_h/L) may indicate that hydraulic equivalent diameter, d_h, is not applicable to shell-side channel where many fibers are packed at a high density.

References

1) A.P. Colburn: A method of correlating forced convection heat transfer data and a comparison with fluid friction, *Trans. Am. Inst. Chem. Eng.*, **29** (1933) 174-210.
2) For example, W. Kays, W.E. Crawford: "Convective Heat and Mass Transfer", McGraw-Hill, 1980.
3) T. Kanamori T., M. Niwa, H. Kawakami, *et al.*: An estimate of gas transfer rates of intravascular membrane oxygenator, *ASAIO J.*, **46**, 612-619 (2000).
4) T. Kanamori, K. Sakai, T. Awaka, *et al.*: Mass transfer in laminar flows around single hollow-fiber membranes for hemodialysis, *J. Chem. Eng. Jpn.*, **27**, 830-832 (1994).
5) M. Fukuda, N. Hosoya, T. Kanamori, *et al.*: Determination of optimal fiber density of conventional and high performance dialyzers, *Artif.Organs Today*, **2**, 205-214 (1992).
6) T. Kanamori, T. Shinbo: Mass transfer of a solute by diffusion with convection around a single hollow-fiber membrane for hemodialysis, *Desalination*, **129**, 217-225 (2000).
7) E.E. Wilson: A basis for rational design of heat transfer apparatus, *J Am. Soc. Mech. Eng.*, **37**, 546-551 (1915).