

Designing Better Hollow Fiber Oxygenators

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Abstract

Mass transfer is central in designing hollow fiber oxygenators. A model system of oxygen transfer to water is developed as a basis for discussion. Previously developed mass transfer correlations are then successfully used to predict experimentally observed oxygen transfer rates. For hollow fiber devices with the same type hydrophobic membrane and membrane area, these correlations allow a comparison of different geometries. The extension of these concepts to oxygen transfer to blood is discussed.

Introduction

The goal of this paper is to show how better hollow fiber modules can be designed using correlations already available in the literature. In writing this paper, we have had a choice between two writing styles, an informal, rather conversational style and a more exact scientific type. We have chosen the informal style. In a sense, this returns to the scientific conversations of the 18th century, when groups of persons interested in a common subject got together and talked over their ideas. The second more formal style began in the 19th century universities, when professional scientists became dominant. We have decided not to use the formal style because it is the norm in the published work to which we will refer. We want to use the informal style because it aids entry into this published work.

The design of hollow fiber modules depends upon the concept of mass transfer. Mass transfer is one of the intellectual triumphs of engineering. Unlike many disciplines, engineering conceals its intellectual accomplishments. Ideas that are useful in many fields, such as the ideas behind dimensionless groups, lie buried well in the engineering curriculum. This is because every engineering student is assumed to be a candidate for the entire curriculum. Thus, if one is not trained in engineering, he or she may have trouble finding these engineering ideas.

Mass transfer is one of these useful, but concealed ideas. It deals with diffusion across interfaces. It is useful to engineers because it is basic to the performance of separation processes.

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These processes usually require more than half the investment in a chemical plant.

Mass transfer is also a useful idea in perfusion, because it frequently controls the design of perfusion modules. This mass transfer is most commonly expressed in terms of an oxygen transfer rate, J .

$$J=kaV \Delta c$$

In this equation, the rate J is proportional to a module volume V and a concentration difference Δc . If this volume or concentration difference is doubled, then the rate will double. The proportionality constant involves two parts: the mass transfer coefficient k and the surface area per volume a . The mass transfer coefficient commonly has the dimensions of velocity and the surface area per volume of reciprocal length.

This product of the mass transfer coefficient and the area per volume has the dimensions of reciprocal time. It is thus like a first order reaction rate constant. However, it is not like a chemical reaction rate constant because it is not a direct function of the chemistry but of the physics. In other words, it is not a function of the periodic table or of the valence or of reactivity. It is a function of quantities like the diffusion coefficient and the viscosity of the solution.

In many cases, the mass transfer coefficient can be estimated if the specific physics of the problem is known. These estimates come both from theory and from experimental correlations. The theoretical estimates are commonly restricted to laminar flow. This is a major restriction. However, flow in most hollow fiber devices is laminar, so this theoretical source is sometimes what we want.

The best correlations for mass transfer come from experiments with the hollow fibers themselves. Originally, there were few of these correlations. However, in the past five years, a wide variety have become available, and their number is escalating dramatically (1). Still, they are limited because the applications of this type of analysis to this type of hollow modules are so new.

Other sources of mass transfer coefficients come from heat transfer, from gas absorption and from liquid-liquid extraction. The mass transfer coefficients which come from heat transfer tend to be the most valuable, because they are developed for

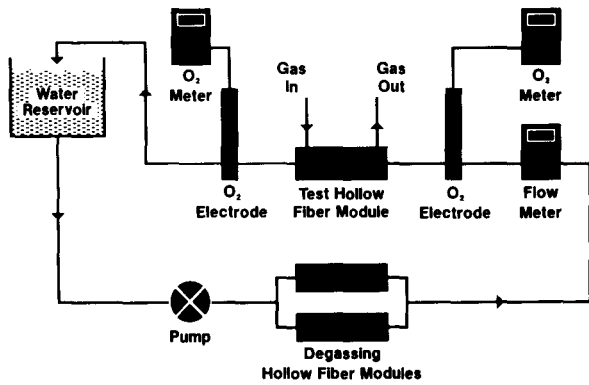
interfaces between a solid and a fluid. This solid fluid interface is what exists in hollow fiber modules, where typical interfaces are between a fluid and a membrane. Mass transfer correlations from gas absorption and liquid-liquid extraction are often less useful. Those based on liquid-liquid extraction imply a liquid-liquid interface. As a result, these are less directly applicable to hollow fiber membrane devices.

In the work below, previously developed mass transfer correlations are used to predict oxygen transfer rates in hollow fiber devices. From the work, the importance of mass transfer concepts in designing hollow fiber devices should be more clear.

Materials and Methods

Oxygen delivery capabilities measured with Cel-Life™ modules containing Celgard (copyright) microporous hollow fiber (a) used the test stand set up shown in Figure 1. Although not constructed for blood oxygenation, Cel-Life™ modules are intended for use in a variety of gas exchange processes such as oxygenation of cell culture media. Oxygen concentrations on the circulating distilled water were determined using Ingold oxygen electrodes (#40180-01 19 mm x 150 mm, flange

FIGURE 1



mounting) and a Model 1240 Dissolved Oxygen Amplifier and Analyzer (b). House air was used as the feed. For a measurement at a given water flow rate, water from the reservoir was first routed through the degassing modules (also Cel-Life™ modules) where nitrogen was used to strip dissolved oxygen from the water. By varying the nitrogen flow rate, the concentration of dissolved oxygen entering the test module could be tuned to achieve a desired overall oxygen concentration difference in the test module. The oxygen content of the water exiting the test module was then recorded and the oxygen transfer rate calculated from

$$J = \delta c Q / \Delta c$$

δc - Oxygen concentration at module outlet minus that at module

a. Hoechst Celanese Corporation, Charlotte, NC

b. Ingold Electrodes, Inc., Wilmington, MA

inlet (mmoles/liter)

Q - Water flow rate (liters/hr)

Δc - Oxygen concentration in gassing air minus oxygen concentration in water at module inlet (mm oxygen)

Oxygen transfer rates were found to be independent of oxygen concentration differences and gassing rates over the ranges measured (83 to 138 mm oxygen and 6 to 120 l/hr, respectively). These rates did vary with the water flow, as discussed in the next section.

Results and Discussion

Before turning to the experiments, we first consider how the oxygen transfer rates can be estimated. This in turn requires choosing a mass transfer correlation.

One good example of these mass transfer correlations occurs for oxygenation of water which is flowing inside the lumen of hollow fibers. In this case, the mass transfer coefficient k is given by

$$\frac{kd}{D} = 1.62 \left[\frac{d^2 v}{DL} \right]^{1/3} \quad (2)$$

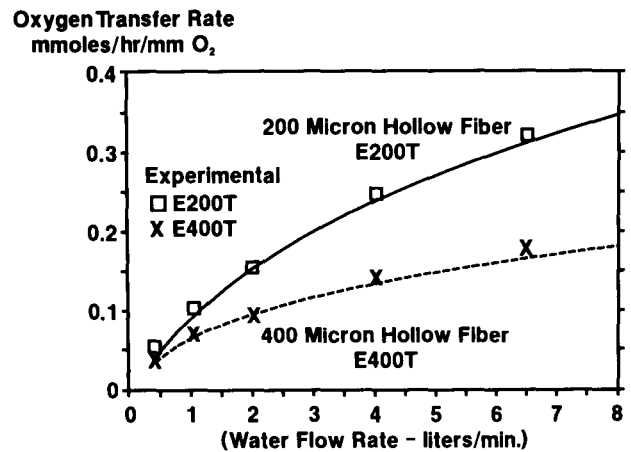
where D is the diffusion coefficient, v is the water velocity, d is the fiber diameter and L is the fiber length. In the same sense, the area per volume a in this situation is given by

$$a = \frac{4\varepsilon}{d} \quad (3)$$

where ε is the fraction of the module which is filled with hollow fibers. The relations, first predicted theoretically for heat transfer by Graetz and by Leveque, are in close agreement with experiment. Equations 2 and 3 suggest that oxygenation will be fastest for small hollow fibers. Obviously, from Equations 2, the mass transfer coefficient increases as the fiber diameter becomes small. In the same sense, the area per volume increases as the fiber diameter becomes small.

These expectations are supported by the data in Figure 2. The continuous solid and dashed lines are the predicted oxygen

FIGURE 2



transfer rates using Equation 2. The experimentally obtained results are consistent with the predictions.

Other mass transfer correlations have been developed for different flow geometries (2). For water flow on the outside of the hollow fibers:

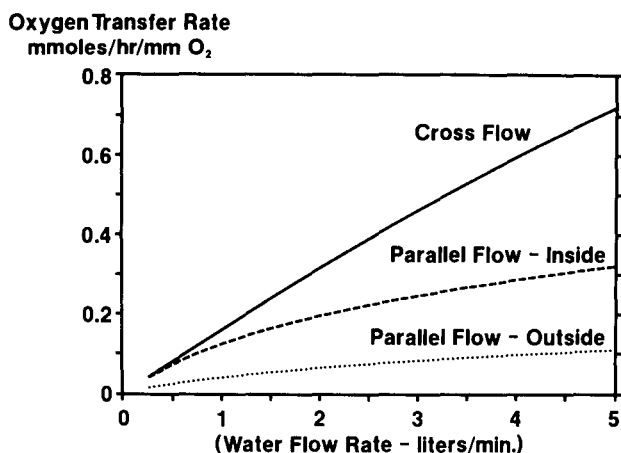
$$\frac{kd}{D} = 1.2 \left[\frac{d^2 \vartheta}{\vartheta L} \right] \left[\frac{\vartheta}{D} \right]^{1/3} \quad (4)$$

in which ϑ is the kinematic viscosity of the fluid, that is, the ordinary viscosity divided by the density. For water flow on the outside, flowing perpendicular to the gas flow,

$$\frac{kd}{D} = 1.38 \left[\frac{d \vartheta}{\vartheta} \right]^{1/3} \left[\frac{\vartheta}{D} \right]^{1/3}$$

The most important implication of Equations 2, 3, 4 and 5 is that similar hollow fiber devices can have significantly different oxygenation capabilities. An example of this observation is given in Figure 3. Each device contains the same mass of identical hollow fiber packed to the same degree of available volume in the modules. The oxygenation rates, however, are distinctly different due to the differing flow geometries utilized by each device. The observation is consistent with that found by others. (3)

FIGURE 3



We should recognize that the mass transfer coefficient for the oxygenation of water is unusually simple. It is simple because the major resistance to mass transfer results from diffusion of oxygen in the water. Diffusion of oxygen across the membrane is rapid and hence does not affect the oxygen transfer rate. Hence, modest changes in membrane characteristics (e.g., porosity, pore size, thickness) would impact oxygenation rates marginally. In the same way, diffusion of oxygen into the surrounding gas is rapid and so does not affect the oxygen transfer rate.

In general, we will not be able to expect such a simplification. We will expect that there will be resistances to solute transport

in the liquid, the membrane, and the gas. These resistances will be additive, just like resistances in electrical circuits. Indeed, one may show that the overall resistance is the reciprocal of the mass transfer coefficient in Equation 1. This resistance is the sum of the resistances in the other phases.

$$\frac{1}{k} = \frac{1}{k_{\text{liquid}}} + \frac{1}{k_{\text{membrane}}} + \frac{1}{k_{\text{gas}}}$$

In the above, we have actually been discussing only the mass transfer coefficient in the liquid k_{liquid} . We have been ignoring the mass transfer coefficients in the membrane k_{membrane} and in the gas, k_{gas} .

The mass transfer coefficient in the gas is given by same kinds of correlations as the mass transfer coefficient in the liquid. Because these correlations predict a mass transfer coefficient which is directly proportional to some positive power of the diffusion coefficient, we expect that coefficients in the gas are much larger than mass transfer coefficients in the liquid. After all, diffusion coefficients in gas are typically 10,000 times larger than diffusion coefficients in liquid. However, we have to be careful in reaching this conclusion, because the mass transfer coefficient in the gas often will include some type of partition coefficient between liquid and gas. These partition coefficients, often called Henry's Law coefficients, can be dramatically different than one and hence significantly alter the relative importance of the resistances in the liquid and in the gas.

We can also estimate the mass transfer coefficient through the membrane

$$k_{\text{membrane}} = D \frac{(\text{membrane void fraction})}{(\text{effective membrane thickness})}$$

The effective thickness must include any tortuosity, correcting for the twisting and turning of the membranes pores. Again, a Henry's Law coefficient may also appear in this resistance. In particular, if the concentration difference in Equation 1 is in the liquid and the membrane is not wet, then k_{membrane} should again include some sort of partition coefficient. Reference (2) addresses this issue more exactly.

Other issues affecting membrane resistance include membrane type and non-porous coatings. If the membrane were hydrophilic such that liquid filled the pores, membrane resistance would go up markedly because of the lower gas diffusivity in liquids versus gas described above. If a non-porous coating is applied to a hydrophobic microporous membrane, such that the surface micropores are "bridged" or blocked, overall membrane resistance will increase. In both instances above, the impact on observed oxygen transfer rates will be determined by the relative magnitudes of the resistances present. For example, Evren and Piskin (4) found little difference in oxygen transfer rates between non-coated and thin silicone coated membranes of the type examined in this paper. Thicker coatings, however, displayed reduced rates as expected.

Finally, we should comment on the effect of chemical reaction on the mass transfer coefficients. Basically, chemical reaction

accelerates mass transfer. For example, in the case of aeration of blood, the mass transfer coefficient in the liquid phase is accelerated by the reaction of oxygen and hemoglobin. This acceleration may mean that the mass transfer coefficient is no longer as completely dominated by the value in the liquid.

The exact nature of the acceleration of the mass transfer depends on the detail of the chemical reaction. Obviously, if the reaction is very slow, there is almost no effect on the mass transfer coefficient. If the reaction is fast, the effect can be considerable. The effect of fast reaction is most commonly discussed in terms of two limits called the fast reaction limit and the instantaneous reaction limit. The fast reaction limit means what it says, that the reaction is relatively rapid, but that the reagents can coexist in the solution. In the instantaneous reaction limit, the reactants cannot coexist in significant quantities. By these standards, the reaction of oxygen and hemoglobin is fast. The reaction of ammonia and sulfuric acid is instantaneous. For each limit, correlations of mass transfer are known.

Conclusion

Through the exercise above, we hope to illustrate the importance of mass transfer concepts in designing oxygenators. Although the above work related to the simple system of oxygen transfer to water, the working model of a series of resistances (both diffusional and reaction) is relevant to the more complex case of oxygen transfer to the blood. Also, the model is appropriate for all types of membranes, including flat film and hollow fiber. A key to improved designs will revolve around identification of the major resistance and minimizing it. Other factors may also be important. For example, designs which result in high blood velocity may display higher efficiency (Equation 1, 4 and 5) but result in unacceptable blood damage. A balance of all such issues, including mass transfer, will be required.

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