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Shell side mass transfer in a transverse flow hollow fiber membrane contactor

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Abstract

The free surface model was introduced to describe the shell side fluid flow in a transverse flow hollow fiber membrane contactor, and a new method was developed to calculate the shell side hydraulic diameter, the effective average velocity, and the Reynolds number. An empirical shell side mass transfer correlation was presented for commercial Liqui-Cel® Extra-Flow contactors on the basis of the experimental data reported by Sengupta et al. The data were correlated very well with maximum discrepancies of ±10% between the predicted and observed results.

Keywords: Membrane contactors; Transverse flow; Mass transfer; Hydrodynamics; Free surface model

1. Introduction

A membrane contactor is a device that achieves gas/liquid or liquid/liquid mass transfer without dispersion of one phase within another. This is accomplished by passing the fluids on the opposite sides of a microporous membrane. Through the careful control of the pressure difference between the fluids, one of the fluids is immobilized in the pores of the membrane so that the fluid/fluid interface is located at the mouth of each pore [1]. Usually, two types of modules, called *parallel flow* and *transverse* or *cross flow* are used. It has been reported that the transverse flow module has a number of advantages such as a larger shell side mass transfer coefficient, minimal flow channeling, better scale-up characteristics and more precise performance prediction [2]. The main features of the transverse flow module have been summarized by Gabelman and Hwang [1] and Sengupta et al. [2].

The most well-known transverse flow module, which is schematically shown in Fig. 1, is the Liqui-Cel® Extra-Flow module commercialized by CELGARD LLC (Charlotte, USA). Celgard® microporous polypropylene hollow fiber membranes used in this module have been woven into fabric to allow more uniform fiber spacing, which in turn leads to high mass transfer coefficient. The Extra-Flow module contains a central shell side baffle, a feature that offers two advantages: (1) the baffle can improve the mass transfer efficiency by minimizing shell side by-passing; (2) it provides a component of velocity normal to the membrane surfaces, which results in a higher mass transfer coefficient than that achieved with strictly parallel flow [2].

Generally, mass transfer in a hollow fiber contactor can be described using a resistance-in-series model [1]. The tube side mass transfer can be described with the Lévêque equation and the membrane resistance can be calculated from known membrane parameters such as membrane thickness, tortuosity and porosity. However, mass transfer correlation for shell side fluid flow has not been well established up to now. A conventional approach is to use the empirical correlation of the following form:

$$Sh = \alpha Re^{\beta} Sc^{0.33} \tag{1}$$

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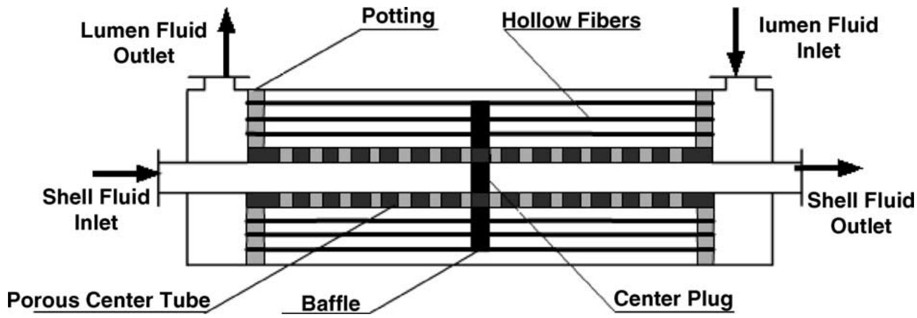

Fig. 1. Sketch of the Liqui-Cel® Extra-Flow membrane contactor (redrawn from Ref. [2]).

where the constants α and β are determined from experimental results. Based on this equation, some empirical correlations have been proposed for transverse flow modules [3–14]. However, there are only three correlations have been found applicable for commercial Liqui-Cel® Extra-Flow membrane contactors, as listed in Table 1. Among them, the correlations reported by Schöner et al. [10] and Baudot et al. [11] were derived directly from liquid–liquid extraction experiments using a 2.5 in. × 8 in. Liqui-Cel® Extra-Flow contactor. The correlation suggested by Kreith and Black [12], which was originally for a closely packed shell-and-tube heat exchanger, was found to give a good prediction of the shell side mass transfer coefficient in the Liqui-Cel® contactors in some studies [13,14]. Sengupta et al. [2] studied the shell side mass transfer in the large-scale application of membrane contactor for gas stripping with Liqui-Cel® modules. These investigations indicated that the shell side mass transfer coefficient is proportional to $Q^{0.38–0.45}$ (Q is the feed flow rate into the module) [2]. However, they did not present a correlation in the form of Eq. (1).

Besides, different methods were used for the calculation of the effective shell side velocity, the hydraulic diameter, and thus the Reynolds number [10–11,13–16]. This is due to the fact that there is no fundamental mathematical description of the shell side flow in a transverse flow contactor. Regarding to Seibert and Fair's work [17], the shell side flow was assumed to be perfectly mixed. However, as commented by Baudot et al. [11], this is not true for fluid flow through the fiber bundles.

In the literature, a method describing viscous flow relative to the arrays of solid rods is Happel's free surface model [18]. This model was developed on the basics that two concentric cylinders can serve as the model for fluid moving through an assemblage of cylinders. The inner cylinder consists of one of the rods in the assemblage and the outer cylinder of a fluid enveloped with a free surface [18]. In previous studies [19–21], the free surface model was adapted to describe the shell side fluid flow in a parallel flow hollow fiber membrane contactor. In fact, the free surface model can also be applied to the case of transverse flow [18]. The only difference is that, for the transverse flow, the boundary condition is that the fluid radial direction velocity (u_r), the fluid angular direction velocity (u_θ) and the free surface velocity (u_c) hold the following relationship at the free surface [18]:

$$u^2 = u_r^2 + u_\theta^2, \quad u_r = u\cos\theta, u_\theta = -u\sin\theta \tag{5}$$

The present work extends the idea of free surface model to the case of a transverse flow module. It is expected to derive expressions for the calculation of the shell side effective velocity and the hydraulic diameter, which can then be used to calculate the Reynolds number. It is also aimed to find an applicable correlation to predict the shell side mass transfer coefficients in the commercial Liqui-Cel® Extra-Flow membrane contactors. This part of the work is based on the experimental results reported by Sengupta et al. [2].

2. Theory

In order to study the shell side fluid flow in a transverse flow module, the fiber bundle was firstly divided into small, equally spaced cells with one fiber in each cell. And a free surface was presented at the imaginary cell boundary. It was assumed these flow cells are regularly arranged in layers between the center feed tube and the wall of the module. This means that the fiber number in the layer gradually increases from the layer near the center feed tube to the layer near the

Table 1
Mass transfer correlations for transverse flow modules

Correlation no.	Correlation	Brief conditions[a]	Reference
(2)	$Sh = 1.76Re^{0.82}Sc^{0.33}$	Feed flow rate 0.2–200 × 10^{-6} m^3/s	[10]
(3)	$Sh = 0.56Re^{0.62}Sc^{0.33}$	Feed flow rate 0.2–200 × 10^{-6} m^3/s	[11]
(4)	$Sh = 0.39Re^{0.59}Sc^{0.33}$[b]	Feed flow rate 10–50 × 10^{-6} m^3/s	[13]
		Feed flow rate 33 × 10^{-6} m^3/s	[14]

[a] Applied for Celgard Liqui-Cel® Extra-Flow 2.5 in. × 8 in. contactor.
[b] Kreith and Black equation, originally for a closely packed shell-and-tube heat exchanger [12].