

Explicit equation for the determination of the overall mass transfer coefficient in a hollow fiber membrane contactor



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HIGHLIGHTS

- An explicit equation for the overall mass transfer coefficient was obtained.
- The method of characteristics was used in the solution of fiber mass balance.
- The explicit equation gives reasonable estimations of the mass transfer coefficient.
- The procedure was validated using experimental data from the literature.

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ABSTRACT

An explicit equation for the determination of the overall mass transfer coefficient in a hollow fiber membrane contactor is developed. This equation results from the solution of the model equations when the solute concentration in the organic extractant phase can be assumed zero throughout the operation of the system. The method of characteristics is used in the solution of the fibers mass balance partial differential equation. The numerical solution of the system using collocation in finite elements is used to identify and validate the region of applicability of the derived explicit equation, showing that it can be applied with small estimation errors even when the operating conditions are far from those imposed in the derivation. Based on an experimental run, a procedure is suggested to estimate the overall mass transfer coefficient using the explicit equation presented in this work. Finally, the proposed estimation procedure is validated using experimental data from the literature.

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1. Introduction

Membrane-based separation processes, namely based on hollow fiber membrane contactors, offer several advantages such as a high interfacial area and a dispersion-free operation. In these systems, the porous membrane acts as a barrier and supports the aqueous-organic interface. The hollow fiber membrane contactors allow versatility and ease of operation, as well as a straightforward extrapolation from the laboratory to the industrial conditions and flowrates, just by increasing the number of modules employed, since the same fibers and fluid velocities can be used in both environments. This hollow fiber based non-dispersive solvent extraction technique is gaining popularity (Gabelman and Hwang, 1999; Pabby and Sastre, 2013; Singh et al., 2013) and has been

studied for several applications, such as in the organic acids separation from fermentation broths (Moraes et al., 2015), in the recovery of aroma compounds from natural sources (Haghshenas et al., 2016), and in the metals recovery, e.g., in the recovery of rare earth elements (REEs) (Ambare et al., 2013).

Trébouet et al. (2006) proposed some guidelines that enable the application of a pseudo-steady state approximation developed by Cussler and coworkers (D'Elia et al., 1986; Qi and Cussler, 1985) to the estimation of the overall mass transfer coefficient in these hollow fiber membrane contactors. On the other hand, Özdural and Alkan (2003), developed an explicit equation for the determination of overall mass transfer coefficients in continuous flat-plate dialyzers, that does not rely on the pseudo-steady state assumption.

The objective of this paper is the development of an explicit equation for the determination of the overall mass transfer coefficient in hollow fiber membrane modules, taking into account the

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Nomenclature

C_s	solute concentration in the organic phase (mol m^{-3})	V_w	volume of aqueous phase inside the aqueous reservoir (m^3)
C_w	solute concentration in the aqueous phase (mol m^{-3})	x	normalized axial coordinate ($=z/L$) (dimensionless)
d_i	internal diameter of the fibers (m)	z	axial coordinate along the module (m)
f_s	normalized solute concentration in the organic phase ($=\frac{C_s}{HC_w^0}$) (dimensionless)		
f_w	normalized solute concentration in the aqueous phase ($=\frac{C_w}{C_w^0}$) (dimensionless)		
H	distribution coefficient (ratio of the equilibrium solute concentrations in the organic and aqueous phases) (dimensionless)		
K_w	overall mass transfer coefficient based on the aqueous side transfer area (m s^{-1})		
L	useful length of the module (fibers and shell) (m)		
N_d	number of overall mass transfer units ($=\frac{4K_w V_m}{d_i Q_w}$) (dimensionless)		
Q_s	flowrate of the organic phase ($\text{m}^3 \text{s}^{-1}$)		
Q_w	flowrate of the aqueous phase ($\text{m}^3 \text{s}^{-1}$)		
t	time (s)		
V_c	volume of organic phase inside the module (m^3)		
V_m	internal volume of the fibers (volume of aqueous phase inside the module) (m^3)		
V_s	volume of organic phase inside the organic reservoir (m^3)		

Greek symbols

λ	coefficient of the linear combination in Eq. (17)
θ	time normalized by the space time for the aqueous phase inside the module ($=t/\tau_w$) (dimensionless)
τ_d	time constant for diffusion ($=\frac{d_i^2}{4K_w}$) (s)
τ_w	space time for the aqueous reservoir ($=V_w/Q_w$) (s)
τ_{sc}	space time for the organic phase inside the module ($=V_c/Q_s$) (s)
τ_{wm}	space time for the aqueous phase inside the module ($=V_m/Q_w$) (s)
ζ_M	module capacity factor ($=\frac{HV_c}{V_m}$) (dimensionless)

Subscripts

0	at $z = 0$
L	at $z = L$

Superscripts

0	at time $t = 0$
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unsteady state conditions within the membrane contactor, measuring only the transient profiles of the inlet concentration in the aqueous phase, using an approach similar to the one presented by Özdural and Alkan (2003). The model and numerical solution procedure of Trébouet et al. (2006) is used to confirm the safe applicability of the developed equation in the referred determination. Incidentally, it is also shown that the pseudo-steady state approximation developed by Cussler and coworkers (Qi and Cussler, 1985; Trébouet et al., 2006) reflects a specific case of the development presented in this study that conduces, in the limit, to an explicit equation with the same limitations of the approximation itself as presented in Trébouet et al. (2006). Finally, experimental results from the literature are also used to validate the equation developed, confirming its applicability to real systems.

2. Theoretical development

Let us consider a hollow fiber membrane contactor in which the aqueous phase, initially rich in the solute to be extracted, circulates inside the fibers, continuously leaving and returning to its reservoir. The extractant organic phase circulates in the shell side of the modules. The organic phase concentration divided by the distribution coefficient (i.e., the aqueous phase concentration equivalent to the organic phase concentration) can be taken as essentially zero throughout if one or several of the following occurs: the organic phase does not return to its original reservoir or the reservoir is sufficiently large and whether the mass transfer coefficient is sufficiently small or the organic circulation velocity is high enough. The same approximation can also, in principle, be applied to the extraction module of a simultaneous extraction-stripping system, since the concentration in the organic extractant phase is in general small during the operating time (Albaraka et al., 2011; González-Muñoz et al., 2004; Kertész et al., 2005) of these systems. Fig. 1 shows a scheme of the simplified module without recirculation, operating in counter current mode, where the organic phase reservoir was suppressed. For the simplified system,

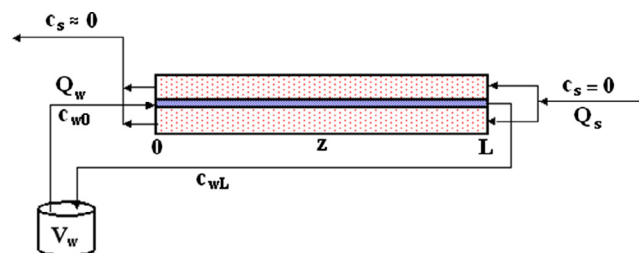


Fig. 1. Scheme of the hollow-fiber module operating in the counter-current mode.

a mathematical model can be deduced from the previously developed one (Trébouet et al., 2006) just by the elimination of the mass balance equations for the solute in the organic phase, with concentration supposed invariant (zero) with time. The system model is then:

Mass balance to the solute in the aqueous phase inside the fibers:

$$Q_w \frac{\partial C_w}{\partial z} + \frac{4V_m}{d_i L} K_w C_w + \frac{V_m}{L} \frac{\partial C_w}{\partial t} = 0 \quad (1)$$

Mass balance to the solute in the aqueous phase reservoir:

$$Q_w C_{wL} = Q_w C_{w0} + V_w \frac{dC_{w0}}{dt} \quad (2)$$

In these equations, C_w is the solute concentration and Q_w is the flowrate of the aqueous phase; V_m is the total internal volume of the fibers of internal diameter d_i and length L ; K_w is the overall mass transfer coefficient between the phases, based on the aqueous side transfer area; z is the axial coordinate along the fibers (module); t is time; C_{w0} and C_{wL} are the concentrations at the inlet ($z = 0$) and outlet ($z = L$) of the module fibers and V_w is the volume of the aqueous phase inside the aqueous reservoir.

Eq. (1) is subjected to the following initial and boundary conditions:

$$t = 0 \quad 0 < z < L \quad C_w = C_w^0 \quad (3)$$

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