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Mathematical modeling of transport phenomena and quality changes of fish sauce undergoing electrodialysis desalination

Kuson Bawornruttanaboonya [a], Sakamon Devahastin [a,*], Tipaporn Yoovidhya [a], Nathamol Chindapan [b]

[a] Department of Food Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, 126 Pracha u-tid Road, Tungkru, Bangkok 10140, Thailand
[b] Department of Food Technology, Faculty of Science, Siam University, 38 Phetkasem Road, Phasicharoen, Bangkok 10160, Thailand

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ABSTRACT

Despite many existing attempts on modeling electrodialysis (ED) desalination, no work has so far modeled the effect of water transport due to osmosis across the membranes on the quality changes of such a highly concentrated product as fish sauce during the desalination. In this study, a model taking into account the effect of water transport due to the osmotic pressure and electric potential is proposed. Coupled mass and momentum transport equations, along with appropriate initial and boundary conditions, were numerically solved using the finite element method through COMSOL Multiphysics™ version 4.3. The predictability of the model was compared with that of the model neglecting water transport. The model was capable of predicting the evolutions of the salt concentration and volume as well as the quality changes, in terms of the total nitrogen concentration, total amino nitrogen concentration, total aroma concentration and total change of color, of fish sauce undergoing ED desalination at both laboratory and pilot scales. The model was validated against the experimental results and noted to satisfactorily predict the evolutions of the salt concentration as well as volume of the diluate (fish sauce) and concentrate solutions at both scales; quality changes were also well predicted. The effect of neglecting the water transport during ED on the various predicted values was also illustrated. When water transport was not considered, the evolutions of the salt concentration of both the diluate and concentrate solutions as well as the changes of all quality attributes were not adequately predicted.

1. Introduction

Fish sauce is a popular condiment and is used to prepare a wide variety of dishes in both Thai and other Asian cuisines. Despite its desirable flavor and aroma characteristics, fish sauce contains a high level of salt (sodium chloride), typically in the range of 20–25% (w/w). A high intake of sodium is well recognized to result in higher risks of hypertension and cardiovascular diseases (Ajani et al., 2005). In order to reduce the sodium content of fish sauce, electrodialysis (ED) desalination is an alternative that has recently been investigated (Chindapan et al., 2009). Some important characteristics of fish sauce are nevertheless unavoidably affected by the ED. These include such important quality attributes as the total nitrogen and total amino nitrogen concentrations as well as aroma and color (Chindapan et al., 2009, 2011).

A capability to model and hence optimize the ED desalination process to obtain fish sauce with acceptable salt content and quality is desired. Only a few related studies are so far available, however. Chindapan et al. (2013) employed artificial neural network (ANN) to predict selected quality changes of fish sauce during ED desalination; the process was then optimized via the use of multi-objective optimization using genetic algorithm (MOGA). Although satisfactory predictions were noted, the model relies rather heavily on the training data and is therefore limited. Only the effects of the applied voltage and residual salt concentration are also included in the model. A desirable model should indeed take into account the effects of other important parameters, including the stack construction, flow rates of diluate and concentrate streams and number of ED cell pairs (Lee et al., 2002; Ortiz et al., 2005; Tsiakis and Papageorgiou, 2005; Nikbakht et al., 2007; Fidaleo et al., 2012).

Despite many attempts on modeling ED desalination, none exists to explain the effect of water transport due to osmosis across the membranes on the quality changes of fish sauce (or similar products) during the desalination. It is noted that the effect of water transport would become significant when desalinating such a highly concentrated solution as fish sauce. Although some models do include the osmosis term and hence are capable of predicting the water transport across the membranes during ED

* Corresponding author. Tel.: +66 2 470 9244; fax: +66 2 470 9240.
E-mail address: sakamon.dev@kmutt.ac.th (S. Devahastin).

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desalination, no attempts have been made to employ such a term to explain the quality changes of the diluate (Bailly et al., 2001; Fidaleo and Moresi, 2010, 2011; Rohman et al., 2010; Fidaleo et al., 2013).

In this work, a model based on the conservation equations of mass and momentum along with Nernst–Planck equation, taking into account the effect of water transport due to the osmotic pressure and electric potential is proposed to predict the changes in the salt concentration and volume of fish sauce undergoing ED desalination in a batch recirculation mode. Kinetic model is used in conjunction with the transport model to predict the changes in the fish sauce quality. The model was validated against the laboratory-scale and pilot-scale experimental results. The considered parameters include the initial ion concentrations, flow rates of the diluate and concentrate streams, applied voltage and membrane characteristics. The effect of neglecting the water transport during ED on the predicted values was also illustrated.

2. Materials and methods

Fish sauce obtained from a local distributor was desalinated using both the laboratory-scale and pilot-scale ED systems. The fish sauce contained 38.8% (w/w) total soluble solids, of which about 65% and 32% were sodium chloride and total proteins, respectively (Chindapan et al., 2009). The details of the ED system set-ups and experimental procedures are those of Chindapan et al. (2009) and Jundee et al. (2012). A summary of the basic system and operating information is given in Table 1. The fractions of the total current carried by the sodium ion and chloride ion are known as the transport number. The values of the transport numbers are from the specifications of the anion- and cation-exchange membranes. The applied voltages at the laboratory scale were 6, 7 and 8 V; the pilot-scale system was operated only at 6 V. The upper voltage limit was the highest voltage that provided the current density of not higher than 16 A, which is the recommended maximum current by the membrane manufacturer.

3. Mathematical model development

The model is developed based on two-dimensional transport phenomena. The effects of the initial ion concentrations, flow rates of the diluate and concentrate streams, applied voltage and membrane characteristics are included in the model.

Table 1
A summary of basic system and operating information.

Parameter	Lab-scale	Pilot-scale
Initial volume of diluate (L)	1	100
Initial salt concentration of diluate (% w/w)	25	25
Initial salt concentration of concentrate (% w/w)	1	1
Volumetric flow rates of diluate and concentrate per compartment pair (Q, m^3/s)	1.11×10^{-6}	6×10^{-6}
Volumetric flow rate of electrolyte (m^3/s)	4.44×10^{-6}	6.67×10^{-5}
Thickness of anion and cation-exchange membranes (l_a and l_c, mm)	0.5	0.5
Width of diluate and concentrate compartments (l_{dil} and l_{conc}, mm)	0.5	0.5
Membrane size (mm^2)	110×110	300×500
Compartment length (L, mm)	80	400
Number of compartment pairs (N, dimensionless)	5	50
Total effective membrane surface area (A_{eff}, m^2)	0.064	10
Transport number of anion and cation-exchange membranes (t_a and t_c, dimensionless)	0.93	0.93
Cross-sectional area of diluate and concentrate compartments (A, m^2)	4×10^{-5}	1.25×10^{-4}
Transport number of water (t_w, dimensionless)	7.5	7.5
Constant for membrane transport by osmosis (L_w, mol m^{-2} s^{-1} Pa^{-1})	6×10^{-10}	8×10^{-9}

3.1. Model description and assumptions

The assumed geometry of an ED cell pair consists of a diluate compartment, a concentrate compartment, a cation-exchange membrane, an anion-exchange membrane as well as inlets and outlets for the diluate and concentrate streams. The ED geometry was drawn using COMSOL Multiphysics™ version 4.3 (Comsol AB, Stockholm, Sweden) and is shown in Fig. 1.

The following assumptions are made:

- Electroneutrality during the ED desalination process.
- Diffusivities and mobilities of cation and anion are functions of the ion concentrations.
- Resistance of the membranes is a function of both the salt concentration and time.
- Current densities of the ions are assumed to be equal to the current density of the solutions at the interface of the membranes.
- Density and viscosity of the fish sauce are functions of the salt concentration and were estimated from the data of Chindapan et al. (2009).
- Transport number of anion is equal to the transport number of cation.
- Incompressible laminar flow.
- No chemical reactions.

3.2. Mass transfer phenomenon

The conservation equation that can be used to describe the mass transfer in either a diluate or concentrate compartment consists of the transient term, convection term and flux term. The equation, in terms of the molar concentration of sodium ion (cation), which is equal to the salt concentration, is shown in

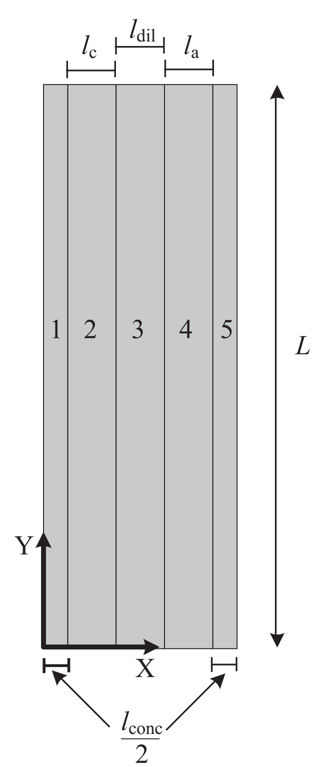

Fig. 1. A schematic diagram of ED compartment pair: 1, 5 = half concentrate compartments ($l_{conc}/2$ = 0.25 mm), 2 = cation exchange membrane (l_c = 0.5 mm), 3 = diluate compartment (l_{dil} = 0.5 mm), 4 = anion exchange membrane (l_a = 0.5 mm). Compartment lengths (L) of laboratory-scale and pilot-scale systems were 80 mm and 400 mm, respectively.