Journal of Membrane Science 366 (2011) 295–303

Contents lists available at ScienceDirect

Journal of Membrane Science

journal homepage: www.elsevier.com/locate/memsci

A generalized model for clarification of fruit juice during ultrafiltration under total recycle and batch mode

Sourav Mondal[a], Alfredo Cassano[b], Franco Tasselli[b], Sirshendu De[c,*]

[a] Department of Chemical Engineering, Jadavpur University, Kolkata 700032, India
[b] Institute on Membrane Technology, ITM-CNR, c/o University of Calabria, via P. Bucci, Cubo 17/C, I-87030 Rende, Cosenza, Italy
[c] Department of Chemical Engineering, Indian Institute of Technology Kharagpur, Kharagpur 721302, India

ARTICLE INFO

Article history:
Received 6 May 2010
Received in revised form 5 October 2010
Accepted 7 October 2010
Available online 14 October 2010

Keywords:
Kiwi fruit juice
Gel layer
Sherwood number
Ultrafiltration
Concentration boundary layer

ABSTRACT

A generalized gel layer controlled filtration model is presented in this work. The model was developed using an integral method for analysing the concentration boundary layer and it was successfully applied to experimental ultrafiltration data obtained in the clarification of kiwi fruit juice by ultrafiltration (UF). Both total recycle and batch concentration modes were included in the model. Most model parameters, such as, gel layer concentration, viscosity, parameter in Sherwood number, etc., were obtained by minimizing the error involved between calculated values and experimental data. This generalized model can be utilized for ultrafiltration of any fruit juice.

1. Introduction

A typical fruit juice processing unit comprises of various unit operations, namely, depectinization, centrifugation, application of finning agents, filtration agents, filtration by diatomaceous earth, polished filtration, etc. [1]. The processing time may vary between 24 and 36 h [1]. Membrane based separation process can be an alternative in this regard. Not only it reduces the time of processing, it also precludes use of some unit operations of conventional process, like, finning treatment, polish filtration, etc. Ultrafiltration (UF) is widely used for removal of pectin and microorganisms from the juice [2]. The clarified juice, being devoid of pectin, does not form haze and it has reasonably high shelf life [3]. There are plenty of studies available for membrane based processes involved in the clarification of fruit juices. For example, UF has been successfully used for processing of kiwi fruit [4], mosambi [5], apple [6,7], orange [8], passion fruit [9], pineapple [10], acerola [11], cactus pear [12], and carrot juice [13].

For scaling up, modelling of UF process is essential. Most models involved in the clarification of fruit juice, are gel layer controlling type [14,15]. This is due to the fact that pectin is a well-known gel forming agent [16]. Apart from pectin, in a real juice, there are other high molecular weight compounds like cellulose, hemicellulose, cell debris, etc. that contribute to the formation of gel over the membrane surface.

In the present work, a model is proposed for ultrafiltration during the clarification of kiwi fruit juice under the framework of gel controlling filtration. Both operational modes, namely, steady state total recycle and batch concentration have been included in the model. The model is successfully applied to the experimental data obtained in the ultrafiltration of kiwi fruit juice [17].

The model presented here is a generalized one. In most of the fruit juice processing, a full proof compact theoretical analysis is often lacking. The need for growing fruit juice industries demands a very predictive and practically applicable model to estimate the steady state flux accounting most of the physical factors at a time. A close look to the modelling approaches of flux decline during clarification of fruit juice using ultrafiltration and/or microfiltration reveals that the resistance in series and pore blocking models are the most popular ones [4,5,7,9,10,18]. Resistance in series model are used by Cassano et al. [4] for UF of kiwi fruit juice, Vladisavljević et al. [7] for UF of depectinized apple juice, Jiraratananon and Chanachai for UF of passion fruit juice [9], Rai et al. [18] for UF of mosambi juice. It may be noted here that the resistance in series model lacks flexibility and generality as far as the prediction capability of flux decline for various kinds of raw materials (juices of different sources). These models are entirely empirical in nature.

Pore blocking models are another class of models to quantify the decline of permeate flux under steady state or transient mode of

* Corresponding author. Tel.: +91 3222 283926; fax: +91 3222 255303.
E-mail addresses: sde@che.iitkgp.ernet.in, sirshendu_kgp@yahoo.com (S. De).

0376-7388/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.memsci.2010.10.015

filtration. These models are used by Rai et al. [5] for UF of mosambi juice, De Barros et al. [10] for UF of pineapple juice, Chayya et al. [19] for MF of water melon juice. Again, these models are semi-empirical in nature and lacks much theoretical understanding. The gel/cake controlling model is a variant of pore blocking models. Moreover, often it is observed that various mechanisms, namely, complete, intermediate, standard pore blocking, cake filtration can individually fit same set of experimental flux decline data closely [5]. The suitability of the models is determined by analysing the correlation coefficient values of the fit.

Therefore, a model having more fundamental basis is warranted to quantify the flux decline during UF of fruit juice. The present model is based on gel/cake layer controlling filtration under the framework of boundary layer analysis. The model includes the developing mass transfer boundary layer over the gel layer, which is the most realistic situation. Thus, this model overcomes the shortcoming of conventional film theory [20] that considers a constant thickness of mass transfer boundary layer. Secondly, solution viscosity is a strong function of solute concentration and it varies significantly within the mass transfer boundary layer, as the solute concentration increases from bulk to gel layer concentration. Gel layer concentration is quite often 4–5 times of bulk concentration. This variation of viscosity as a function of concentration is included in the present model. Thirdly, variation of feed temperature affects solution viscosity and solute diffusivity significantly. This phenomenon has been incorporated in the present analysis using the Stokes–Einstein equation. The model parameters involved are gel layer concentration, solute diffusivity and viscosity variation parameter.

A fruit juice being a complex mixture of various components, it is difficult to estimate these parameters independently. Thus, these parameters can be easily evaluated from the steady state permeate flux data at various operating conditions. The present model is also extended to quantify the flux decline as well as the volume reduction factor (VRF) during batch mode of operation from the first principles by writing down the overall material balance, overall solute balance and solute balance within the mass transfer boundary layer. A numerical solution of these balance equations leads to the flux decline and VRF profile. Specific gel layer resistance is the only parameter that has to be optimized using experimental data. The parameters obtained from the steady state model are used in the batch mode filtration model. Therefore, the present model is a comprehensive one including various fundamental transport aspects. The extensive analytical treatment makes the model easy to estimate the steady state flux values in either of the operation modes by simple computational techniques.

The designers may find it extremely useful in studying the model results while selecting the processing equipment, the mode of operation, optimum operational time, etc. The model parameters are evaluated for this particular juice and may be used for the purpose of scaling up.

2. Theoretical development

2.1. Total recycle mode

In this mode of operation, both the permeate and retentate streams are recycled back to the feed tank so that a steady state is attained with fixed concentration of the feed. This is a popular mode of operation in any membrane based process in order to evaluate the effects of operating parameters (feed concentration, cross flow velocity, transmembrane pressure drop) on steady state permeate flux and permeate quality [5]. In order to quantify the permeate flux, mass transfer coefficient has to be estimated. In this regard, an analysis in a tubular module is presented in this section.

During ultrafiltration of juice, high molecular weight solutes are transported towards the membrane wall, forming a gel/cake type of layer over the membrane surface. It may be pointed out here that in membrane literature, generally cake refers to an assembly of deformable particles, like polymers, polysaccharides, etc. On the other hand, gel indicates a collection of non-deformable materials, like, protein, silica, etc. However, in the present study, it is assumed that the cake and gel are equivalent in nature without the loss of generality of the physics involved in this system. The gel concentration is assumed to be constant within this layer. Therefore, there exists a concentration boundary layer next to the gel layer with a variation in concentration from bulk to gel concentration. The convective–diffusive flux equation for gel forming solute within concentration boundary layer is given for a tubular module as

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial r} = \frac{\partial}{\partial r}\left(D\frac{\partial C}{\partial r}\right) \tag{1}$$

Since, the thickness of the concentration boundary layer is much less than the radius of the tube, the curvature effect is entirely lost and Eq. (1) is reduced to a planar coordinate by defining, $y = R - r$, where y is the distance from the membrane surface (tube wall). Under this coordinate system the above equation becomes

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D\frac{\partial^2 C}{\partial y^2} \tag{2}$$

It may be noted that the cross flow velocity in a membrane module is generally 5 to 6 order of magnitude higher compared to the permeation velocity. Thus, it can be assumed that the parabolic velocity profile (under laminar flow regime) inside the tubular module remain undisturbed due to permeation in the wall. The velocity in the tube is given as [21]:

$$u = 2u_0\left[1 - \left(\frac{r}{R}\right)^2\right] \tag{3}$$

Fixing the co-ordinate system on the wall of the tube, $y = R - r$, within the thin mass transfer boundary layer the velocity profile becomes linear [22]. Since, $(y/R) \ll 1$, the x-component velocity profile simplifies to

$$u = 4u_0\frac{y}{R} \tag{4}$$

Since, the concentration boundary layer thickness is extremely small, it can be assumed that the y-component velocity is equal to the permeation velocity at the wall [23]. Therefore, the y-component velocity becomes

$$v = -v_w \tag{5}$$

Inserting the velocity profiles into Eq. (2) the following equation is obtained:

$$4u_0\frac{y}{R}\frac{\partial C}{\partial x} - v_w\frac{\partial C}{\partial y} = D\frac{\partial^2 C}{\partial y^2} \tag{6}$$

Using $x^* = x/L$; $y^* = y/R$; $C^* = C/C_0$, the above equation is non-dimensionalized as

$$\frac{u_0 d^2}{DL}y^*\frac{\partial C^*}{\partial x^*} - \frac{v_w d}{2D}\frac{\partial C^*}{\partial y^*} = \frac{\partial^2 C^*}{\partial y^{*2}} \tag{7}$$

where $d_i = 2R$. It is to be noted here that $u_0 d_i^2/DL = Re\,Sc(d/L)$ (denoted as A, henceforth) and $v_w d_i/D$ is the non-dimensional flux (denoted as P_{ew}).

So, Eq. (7) can be rearranged as

$$Ay^*\frac{\partial C^*}{\partial x^*} - \frac{P_{ew}}{2}\frac{\partial C^*}{\partial y^*} = \frac{\partial^2 C^*}{\partial y^{*2}} \tag{8}$$