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A blocking model of membrane filtration

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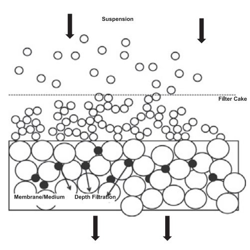
HIGHLIGHTS

- A model for membrane filtration analysis is presented.
- Model is based on particle retention within membranes simultaneously with cake filtration is supposed to occur.
- The model is fairly simple and can be applied easily.
- Tentative correlations of model parameters are proposed.

GRAPHICAL ABSTRACT



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ABSTRACT

A model of membrane filtration based on particle retention within membrane media is proposed. The model provides a realistic description of filtration behavior and is based on current theories of deep bed filtration. Tentative correlations of model parameters are proposed and suggestions to establish more complete correlations are offered.

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1. Introduction

The rapid development and advancement of membrane technology for industrial applications has generated considerable interest in membrane research in recent years. In particular, the use of membranes for fluid/particle separation, or membrane filtration, has attracted increasing attention of numerous investigators. The ultimate aim of membrane filtration studies is the formulation of rational models which can be used in design calculations and process control. However, in spite of the considerable efforts expended, the results obtained so far, have not yet met these expectations (Tien and Ramarao, 2013).

Filtration is an engineering practice of long standing and is used for separating suspended particles from suspending fluid of fluid/particle mixtures. The process is carried out by passing a fluid/particle mixture through a medium with separation taking place as a result of particle retention by the medium. Broadly speaking, there are two types of particle retention; namely, retention at media surface (surface or cake filtration) and retention throughout the entire medium (depth or deep bed filtration), the occurrence of either depends mainly on the relative size of the particles to that of the pores in the medium. A schematic description of these two types of filtration is given in Fig. 1.

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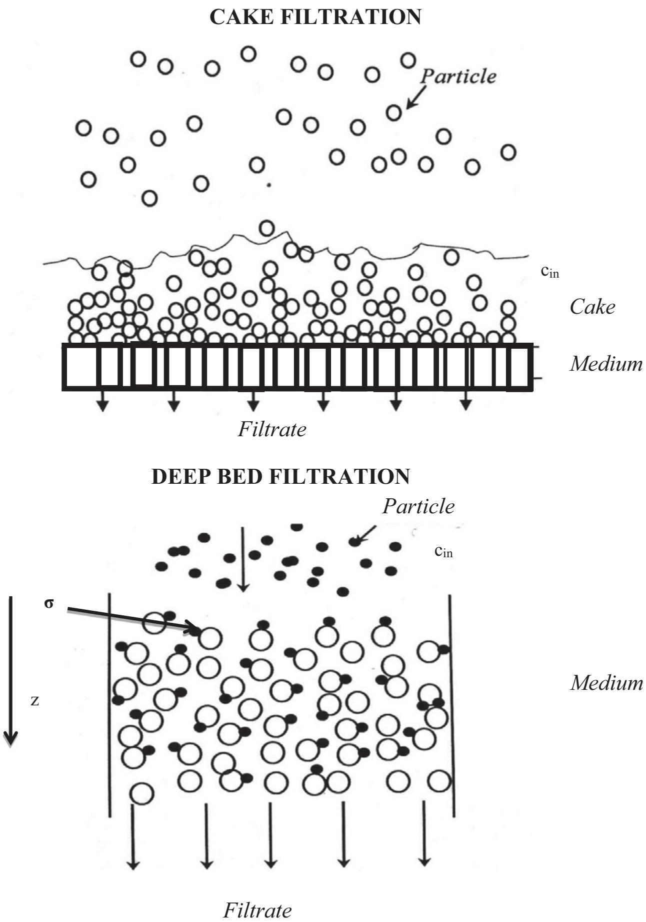

Fig. 1. Schematic representation of the two types of filtration.

Membrane filtration may be viewed as a special case of filtration in which modules fabricated or cast with different types of materials (polymer, inorganic and metal) are utilized as filter media. Considering the relatively smaller pore size in membranes compared to granular packed beds or fibrous media, formation/growth of filter cakes at the surface of the medium can often be expected in membrane filtration. It is, therefore, not surprising that most membrane filtration analyses, especially those of earlier years were made assuming cake filtration as being the dominant mechanism of particle retention [see Davis and coworkers (Davis and Leighton, 1987; Romero and Davis, 1988; Romero and Davis, 1990) and subsequent variations of the Davis model (Bacchin et al., 2002; Kromkamp et al., 2008)].

This cake formation is often observed when membrane modules are used in treating fluid/particle mixtures but this does not mean that membrane filtration and cake filtration are synonymous. Certain membrane materials, because of their internal structure, have been shown to be highly effective in clarifying dilute suspensions of small-sized particles. This fact is reflected by the rapid inroads made by membrane filtration in replacing sand filtration for drinking water treatment in recent years (Ives, 2002; McEwen, 2006).

A number of studies analyzing particle retention within membrane media have appeared in the literature (for example, see (Bolton et al., 2005; Hwang and Lin, 2002; Mondal and De, 2010)). However, most of these studies were aimed at identifying particle retention mechanisms in the context of the so-called laws of filtration (Hermans and Bredee, 1935; Hermia, 1982). As pointed out by the present authors (Tien and Ramarao, 2011), the basis of the laws of filtration is at best, questionable and some of the rate expressions attributed to particular retention mechanisms in the laws are in fact, erroneous. Furthermore, no systematic attempts have been made to determine the condition under which these empirical expressions may be applied.

The purpose of the present work is to present a simple rational model applicable to membrane filtration with particle retention taking place within the membrane media. This condition is met if the relative particle to membrane pore size is small (by at least one order of magnitude as in water treatment). By a rational model, we refer to one whose formulation is consistent with the physical realities of the process/phenomenon to which the model is intended, and is in accord with available experimental observations and relevant theories. The utility of the model is not restricted only to its description of experimental observations but also its predictive capability. It should be possible to determine the model parameters through independent measurements or to estimate them from correlations. Therefore, for a rational model, its use in conjunction with experimental data should enable the determination of model parameters which in turn, can be used for establishing their correlations, or at the least, give indications that developing parameter correlations is likely.

2. Deep bed filtration performance

Consider the one dimensional, case of deep bed filtration in which a suspension of particle concentration of c_{in} passes through a homogeneous medium with an initial porosity, ε_o, the macroscopic behavior of the process may be described by the following equations [15,16]:

$$\text{Continuity equation} \quad u_s \frac{\partial c}{\partial z} + \frac{\partial \sigma}{\partial \theta} = 0 \tag{1}$$

$$\text{Filtration rate expression} \quad \frac{\partial \sigma}{\partial \theta} = u_s \lambda c \tag{2}$$

$$\text{Flow rate} - \text{Pressure gradient relationship} \quad u_s = -\frac{k}{\mu}\frac{\partial p}{\partial z} \tag{3}$$

where the dependent variables c, σ and p denote the suspension particle concentration (vol/vol), the volume of particle deposited per unit medium volume, or the specific deposit, and the fluid pressure, respectively. z is the axial distance or the direction of the main flow, θ, the corrected time defined as

$$\theta = t - \int_o^z \frac{dz}{u_s/\varepsilon} \tag{4}$$

where u_s the superficial velocity or the filtration rate and ε, the local medium porosity. The filtration rate expression given by Eq. (2) was first proposed by Iwasaki (Iwasaki, 1937) with λ known as the filter coefficient. Eq. (3) is the one-dimensional Darcy's law and k is the medium permeability. In deep bed filtration, λ, ε and k are local, time-dependent quantities.

As filtration proceeds and with particle deposition taking place within the medium and affecting the medium structure, λ, ε and k may change accordingly. One may therefore express the local values of these quantities as functions of the extent of deposition, or

$$\varepsilon = \varepsilon_o - \frac{\sigma}{\varepsilon_d} \tag{5}$$

$$\lambda/\lambda_o = \alpha(\sigma) \tag{6}$$

$$k/k_o = \beta(\sigma) \tag{7}$$

where the subscript o refers to the initial or clean medium state. ε_d is the porosity of the deposit. α and β are arbitrary functions and

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