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A one-dimensional transient model of down-flow through a swelling packed porous bed

Martin A. Shadday Jr.*

Westinghouse Savannah River Company, Savannah River National Laboratory, Aiken, SC 29808, USA

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Abstract

A transient model of down-flow through an ion-exchange column in which the resin swells has been developed. The model is herein described and results are presented. Wall friction can lead to high bed stresses when the resin in columns with high length to diameter ratios swells. These stresses can lead to high and potentially excursive hydraulic pressure drops along a column. A non-dimensional grouping that effectively correlates the final steady-state hydraulic behavior of a column, with the resin compressibility and column geometric and flow parameters, has been determined.
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Keywords: Ion exchange; Packed bed; Modelling; Transient response; Swelling resin; Wall friction

1. Introduction

Many ion-exchange resins exhibit considerable shrinking and swelling as they change ionic form, with the potential consequence of significant bed stresses in ion-exchange columns. High bed stress reduces bed porosity and increases the hydraulic pressure drop along the column, and it is a consequence of friction between the resin and the column wall that restricts axial expansion of the resin bed. Though this phenomenon has been long recognized, Zenz and Othmer (1960) described a glass ion-exchange column that burst due to resin swelling and Kunin (1976) discusses the dangers of swelling-induced high stresses in high length to diameter ratio (L/D) laboratory columns, there has not been, to the author's knowledge, a quantitative study of the impact of swelling on ion-exchange hydraulics. This paper describes a numerical model of down-flow through an ion-exchange column in which the resin swells due to ion-exchange reactions. The model predicts the transient changes in bed height, pressure drop, and the axial distributions of bed stress and porosity, as the concentration front moves axially down the column.

The hydraulic performance of ion-exchange columns with compressible resins is an area of active research; the goal is generally to develop models for scaling the results of small diameter laboratory tests to large diameter production columns. Fluid drag and wall friction are generally opposing forces on a resin bed. Fluid drag, as a body force, is proportional to the square of the column diameter and the wall friction force is linearly proportional to the diameter. Fluid drag can therefore collapse the bed in a large diameter column with a sufficiently compressible resin, resulting in an excursive pressure drop, whereas wall friction can support the bed in a small diameter column. This phenomenon is important in scaling from the laboratory to commercial application. Whereas large diameter commercial columns frequently have L/D ratios on the order of unity, small diameter laboratory columns, in which bed length and contact time are preserved, can have very large L/D ratios. There have been a number of studies of the impact of wall friction on steady flow through ion-exchange columns with a compressible resin (Chase and Willis, 1992; Colby et al., 1996; Davis and Bellhouse, 1989; Eisfeld and Schnitzlein, 2001; Freitag et al., 1994; Hamed, 2002; Jiang et al., 2000; Keener et al., 2002; Mohammad et al., 1992; Niven, 2002; Park et al.,

* Tel.: +1 803 725 5060; fax: +1 803 725 8829.
E-mail address: martin.shadday@srs.gov.

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2002; Parker et al., 1987; Östergren and Trägårdh, 1997, 1999; Östergren et al., 1998; Shalliker et al., 2002; Sodré and Parise, 1998; Stickel and Fotopoulos, 2001; Tiller and Lu, 1972; Tiller et al., 1972; Verhoff and Furjanic, 1983). Verhoff and Furjanic (1983) developed a simple one-dimensional model that clearly demonstrated the effects of column diameter and resin compressibility on pressure drop. The purpose of this model was to facilitate scaling from small diameter laboratory columns to large diameter production columns, and it correctly predicted the excursive pressure drops observed by Mohammad et al. (1992). Östergren and Trägårdh (1997, 1999) and Östergren et al. (1998) developed a two-dimensional model of steady flow through a compressible bed. Both models dealt solely with elastic compression of the resin, the resin particles could deform under stress but were precluded from moving relative each other. Similar models for the transient hydraulic performance of packed columns with swelling resins are not described in the literature. Marra and Cooney (1973, 1974) modelled the shrinking and swelling of resin in ion-exchange columns, and the impact on concentration profiles. They did not include a force balance in their model, and the predicted swelling was therefore unconstrained. This model was benchmarked only with the results of column tests in which the resin was shrinking.

There have been a number of studies of the consolidation of packed beds in columns (Cherrak et al., 2001; Denny, 2002; Guiochon et al., 1999; Koh et al., 1998; Lee and Wang, 2000; Spencer et al., 1950; Yew et al., 2003a,b). Consolidation is the irreversible compaction of a bed under an applied stress, caused by the relative movement of particles. Under the applied stress, the bed particles are rearranged into a more efficient configuration. The process of consolidation is not included in the model, but it must be considered in column tests, and it can impact the radial heterogeneity of the bed (Denny, 2002; Koh et al., 1998; Tiller et al., 1972; Yew et al., 2003b). The resin beds in column hydraulic tests must be fully consolidated to ensure that the compression is purely elastic.

Pilot scale tests of an ion-exchange process to remove ^{137}Cs from high-level radioactive alkaline waste with SuperLig® 644, an elutable organic ground resin, provided the impetus for this investigation. There are plans to remove the ^{137}Cs from radioactive waste (a legacy of the production of nuclear weapons materials at the US Department of Energy's Hanford Site) for concentration and vitrification in high-level waste glass. During the regeneration step of the process in which the resin is converted from hydrogen to sodium form with 0.25 M sodium hydroxide solution, the resin swells by approximately 30%. The pressure drops during the regeneration steps in small diameter prototypic height column tests increased significantly and were occasionally excursive. While a survey of the literature indicated that wall friction was restraining the swelling resin, nothing was found that addressed the swelling and dynamic compression of the resin quantitatively. The model herein described was developed to provide insight into the important phenomena involved in the regeneration process and the impacts on the hydraulic behavior of the column.

2. Model description

The model scenario is down-flow through a packed bed with a constant inlet volume flowrate. The resin is initially in its shrunken form, and an ion solution flows through the column, simultaneously exchanging ions with and swelling the resin. The model tracks the axial motion of the concentration wave fronts of solvent and solid concentrations of the adsorbed ion species, and the resultant local resin swelling and movement of the bed. The transient axial bed stress and porosity distributions and the resultant hydraulic pressure drops are also calculated.

2.1. Model equations

The equation set consists of conservation equations for ion concentrations in the solvent and resin, the solvent continuity equation, an axial force balance on the resin, and constitutive relations for porosity and resin swelling. Hydrodynamic pressure is not a fundamental variable in the model. The pressure drop across the bed is functionally dependent on the axial porosity and flowrate distributions, and can be easily determined at any desired point in the transient. The boundary conditions are zero stress at the top of the bed and constant inlet volume flowrate. The resin is initially in the shrunken state. A zero-flow axial porosity distribution is specified. The initial bed stress and porosity distributions are calculated for steady flow of water through the column. The porosity is defined as the fraction of bed volume occupied by interstitial void. At time zero, the inlet flow is switched from water to a solution with a specified ionic concentration that will swell the resin. The transient concludes when the resin concentration is at capacity and the column effluent has the same concentration as the inlet flow.

A simple first-order kinetic sorption model is assumed to govern ion exchange between the solvent and resin. With the assumptions that the surface concentration varies linearly with the resin concentration and adsorption ceases when the resin concentration reaches the capacity, the molar adsorption rate is a function of the solvent and resin concentrations. This is a simple rate expression that relates the free stream solvent and resin concentrations with the mass transfer coefficient k:

$$\frac{\mathrm{d}N_a}{\mathrm{d}t} = kA_{\mathrm{srf}}(C_{\mathrm{slv}} - C_{\mathrm{srf}}) = kA_{\mathrm{srf}}C_{\mathrm{slv}}\left(1 - \frac{C_{\mathrm{sld}}}{C_{\mathrm{cap}}}\right). \tag{1}$$

Marra and Cooney (1973) used a similar relation in their model of a shrinking and swelling resin, and they demonstrated the adequacy of the relation with data. The rate equation for the resin concentration results from dividing by the resin mass:

$$\frac{\partial C_{\mathrm{sld}}}{\partial t} = \frac{kA_{\mathrm{srf}}}{m_{\mathrm{res}}} C_{\mathrm{slv}}\left(1 - \frac{C_{\mathrm{sld}}}{C_{\mathrm{cap}}}\right). \tag{2}$$

The solvent concentration transport equation accounts for both axial convection and adsorption by the resin. Axial dispersion is neglected in this model. This includes both axial diffusion and eddy dispersion, which is due to the meandering flow paths through the packed bed and the resultant local velocity changes (Helfferich, 1995). At the solvent superficial velocities characteristic of pressure-driven flow through a bed, advection will