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Selecting the column configuration with lowest media replacement cost for small adsorption systems

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ABSTRACT

A framework was developed for preliminary evaluation of the relative media replacement costs of three alternative column configurations used for adsorption systems with two vessels, such as those serving small systems. The media replacement cost is the cost of fresh media and the replacement service cost (including transportation, labor, and other non-material costs). Cost normalization methods were developed in part based on the data from US EPA Arsenic Treatment Technology Demonstration Program. Adsorption equilibrium and kinetics were modeled using the PSDM model and breakthrough curves were normalized using the target effluent to influent concentration ratio (C/C_o) and the mass transfer zone fraction (%MTZ_{BT}). Two factors were found to be important for the relative replacement cost of each configuration – the frequency which at least one column needed replacement of media, and the cycle replacement cost (CRCost) which is a combination of the fresh media cost and the replacement service cost. The lead-lag configuration has the lowest annual replacement cost at low target C/C_o, high %MTZ_{BT}, and high CRCost ratios. The parallel configuration performs better at high target C/C_o, high %MTZ_{BT}, and high CRCost ratios. Although the single configuration (two columns operated in tandem and replaced simultaneously) has higher media consumption compared to lead-lag and parallel, it can result in the lowest replacement cost at short %MTZ_{BT} and very low CRCost ratios due to savings in the replacement service cost.

1. Introduction

Adsorption systems based on various types of media (activated alumina, granulated activated carbon, ion exchange media, iron-based media and iron-modified resins, etc.) are commonly used by water treatment facilities due to simple operation, reliability, and reasonable operating costs (Crittenden et al., 2012). For many systems, the cost of spent media replacement accounts for the major part of the operating and maintenance (O&M) cost. Previous studies have evaluated several methods of reducing the sorbent usage rates (SUR) and, consequently, the cost of treated water (Narbaitz and Benedek, 1983; Dvorak et al., 2008; Denning and Dvorak, 2009; Stewart et al., 2013).

From 2003 to 2011, the United States Environmental Protection Agency (US EPA) conducted an Arsenic Treatment Technology Demonstration Program (ADP) to evaluate various arsenic removal technologies, adsorption column configurations, and associated treatment costs; they found that media replacement costs for adsorptive media (AM) systems averaged at almost 80% of total O&M costs (Sorg et al., 2015). Following the US EPA approach, water treatment systems serving less than 10,000 customers with daily flowrates up to 770 gpm are considered "small." Such "small" water treatment systems in many cases might not have the economy of scale similar to the larger systems.

It is possible to arrange multiple columns in different ways in order to reduce the SUR or to provide additional reliability. Narbaitz and Benedek (1983) found that selecting the best adsorption column configuration may reduce the annual costs by 6–8% compared to the second lowest cost configuration. Dvorak et al. (2008), Denning and Dvorak (2009), and Stewart et al. (2013) observed that using some column configurations, such as parallel or in-series, may reduce SUR by up to 20% depending on site-specific characteristics.

Parallel and lead-lag arrangements often overcome the main limitation of many adsorption systems – a low fractional utilization rate of the adsorption media by utilizing staggered column

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replacement that increases media saturation in each individual column and reduces the adsorbent usage rate. In this study, three basic column configurations of two identical columns were evaluated: single, parallel, and lead-lag. Typically, small systems in the United States utilize at least two columns to provide a "safety factor" even if the systems are operated on an "as needed" basis for a few hours each day.

The single configuration was modeled as two identical adsorptive beds placed in two treatment trains. Contaminated influent is divided equally between the trains and moves down the column, until effluent reaches the target concentration level. Both columns are replaced simultaneously.

The parallel configuration also consists of two identical columns with the same layout as single. However, column replacement is sequenced so only one column with saturated media is replaced at a time. The other, partially saturated bed stays in operation, which results in effluent blending from the fresh column and the saturated column. This approach allows for one to increase the individual operating time for each column and, therefore, to get lower SUR values, but it also requires more frequent media changeout because only one vessel is replaced at a time.

The lead-lag configuration consists of the very same two vessels as single and parallel, which are placed in-series one after another. Contaminated influent is fed to the lead column, passes through the adsorptive media, and then flows into the lag column, which provides a "polishing" effect for the effluent from the lead column. Once effluent from the lag column reaches the target concentration, media from the lead column is removed and replaced. The partially saturated lag column is connected as a new "lead" supplying water to the newly replaced column connected in a "lag" position. Lead-lag configuration also increases the operating time for each individual column by allowing columns to operate above the target concentration level. In addition, lead-lag is sometimes viewed as being easier to operate to meet an effluent concentration requirement when operating conditions are uncertain, given the ability to monitor the first of the two columns. Ultimately both parallel and lead-lag operation may result in more efficient use of the adsorptive media, but due to individual replacement of columns, each will require more frequent site visits to replace the spent media.

The objective of this study is to create a configuration selection framework using figures and not requiring use of computational models that includes adsorption fundamentals and media replacement cost in order to identify the configuration for a two-column system with the lowest media replacement cost. This framework can be applied to the new projects at the initial design stages, as well as to the currently operating systems where actual cost and operating data have been gathered.

2. Methodology

2.1. Chromatographic breakthrough front modeling

Chromatographic breakthrough front analysis was used to evaluate a range of adsorbent-adsorbate combinations and adsorption system configurations. Effluent concentration profile analysis is vitally important for configuration selection, since it describes relative performance of the systems operated in various configurations. Since some column configurations are more suitable for certain types of mass transfer zone (MTZ) shapes than the other, the preliminary decisions on the configuration selection can be made based on the breakthrough curve.

An example effluent profile is illustrated in Fig. 1 with a normalized concentration (effluent to influent concentration ratio, C/C_o) plotted on the y-axis and a cumulative number of bed volumes (BV) treated by the system plotted on the x-axis. Following

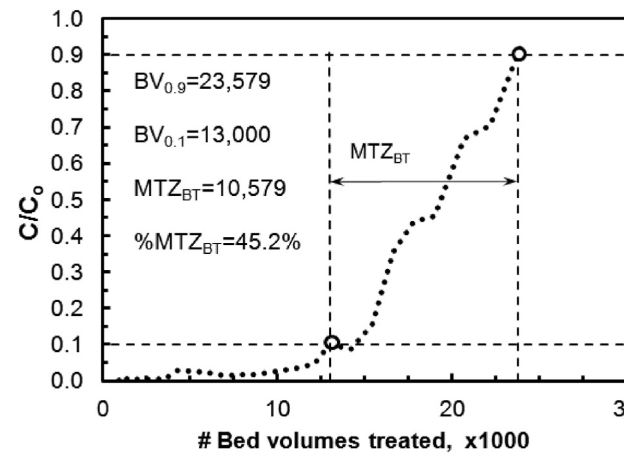

Fig. 1. Mass transfer zone length estimation from an actual breakthrough curve at Klamath Falls, Oregon (From US EPA, 2008a).

Crittenden et al. (1987), part of the breakthrough curve from C/C_o of 0.1–0.9 represents the MTZ where the media is only partially saturated. At C/C_o below 0.1, media is considered as "fresh" and at C/C_o above 0.9, media is considered as "fully saturated" or spent. Following Worch (2012), practitioners can calculate the MTZ_{BT} ratio for any modeled or actual breakthrough curve that has a standard S-shape profile and either reaches a target concentration ratio of 0.9 or can be extrapolated to that extent. The $BV_{0.9}$ and $BV_{0.1}$ represent the breakthrough volumes treated to C/C_o of 0.9 and 0.1, respectively, for an individual column:

$$\%MTZ_{BT} = \frac{BV_{0.9} - BV_{0.1}}{BV_{0.9}} \times 100\% \tag{1}$$

The MTZ_{BT} ratio represents a relative length of the mass transfer zone compared to the total operating time before media saturation. The sample MTZ profile illustrated in Fig. 1 has an estimated $\%MTZ_{BT}$ of about 45%. The systems with low $\%MTZ_{BT}$ and very sharp mass transfer zones will have a relatively short time gap between the initial breakthrough and full media saturation. The systems with high $\%MTZ_{BT}$ will have a long time period between the initial start of the curve and full media saturation. The C/C_o ratio, in turn, represents a part of the mass transfer zone that is relevant for a particular system, which is operated until reaching the target concentration and never reaches a full saturation of the adsorption bed.

2.2. Sorption modeling

To model adsorption scenarios for a range of $\%MTZ_{BT}$ and C/C_o values, the Pore and Surface Diffusion Model (PSDM) introduced by Crittenden et al. (1980, 1986) was used to simulate the breakthrough front. This model utilizes a set of partial differential equations (PDEs) for each compound of interest. It assumes that a local equilibrium exists at the surface of the adsorbent particle. It has been found to accurately predict the concentration breakthrough and to fit breakthrough curves for various adsorbent-adsorbate combinations (e.g., Fritz et al., 1980; Zimmer et al., 1988; Hand et al., 1989; Hristovski et al., 2008; Corwin and Summers, 2011). The PSDM has been incorporated into the user interface of the proprietary AdDesignS™ software (Hokanson et al., 1999a) which was used for this study.

Two adsorbent–contaminant combinations were modeled in this study which have been listed in Table 1. The first scenario was modeled based on the data from Stewart et al. (2013) and Hokanson