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Design of distributed wastewater treatment networks of multiple contaminants with maximum inlet concentration constraints

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ABSTRACT

We present a heuristic rule-based method for the design of distributed wastewater treatment networks of multiple contaminants with maximum inlet concentration constraints, based on the insight that one of the important essences of distributed wastewater system integration is to reduce the total treatment flow rate by minimizing unnecessary mixing amount of streams. The design procedure includes the following main steps: (1) selecting treatment processes; (2) determining the precedence order of the selected processes; (3) developing initial network structure(s) and identifying key contaminant(s); (4) obtaining the final design by considering maximum inlet concentration constraints, contaminant mass load balances, and identification of the pinch point simultaneously. To meet maximum inlet concentration constraints or environmental regulations, some treatment process(es) might take recycling structure. The results of three literature examples demonstrate that the designs obtained with the proposed method are comparable to those obtained with mathematical programming approach. It is shown that the proposed method is simple and of clear physical insight.

1. Introduction

One of the major causes for the increasing global water crisis is the discharge of large amounts of industrial effluents and municipal sewages directly into water bodies. Wastewater treatment network (WTN) integration is one of the most effective approaches to alleviate the water crisis. Distributed wastewater treatment systems segregate waste streams for treatment primarily and only mix them where appropriate (Kuo and Smith, 1997; McLaughlin, 1992; Wang and Smith, 1994). Compared to traditional centralized treatment systems, distributed treatment systems can not only reduce treatment costs, but also increase the chances of wastewater reuse and resource recovery. Because most wastewater systems contain a few contaminants, this paper will focus on the synthesis of distributed wastewater treatment systems with multiple contaminants.

Wang and Smith (1994) first introduced pinch analysis method into WTN integration. Kuo and Smith (1997) improved the work of Wang and Smith (1994). They used mixing exergy loss concept to evaluate the degree of wastewater degradation caused by inappropriate mixing of streams. This concept provides valuable insight into the design of distributed treatment systems with multiple contaminants. Kuo and Smith (1998) further discussed the relationship between wastewater treatment and water-using subsystems and proposed the concept of total water network. Sahu et al. (2013) developed an algebraic methodology, as well as graphical representation, to optimize the cost of the single contaminant WTN with fixed outlet concentration type treatment units based on pinch analysis. Soo et al. (2013) studied multiple treatment systems with one- or two-contaminant by wastewater composite curve (WCC). The above methods can be classified into pinch methods. In general, pinch methods can only deal with wastewater treatment systems of single contaminant or simple ones of multiple contaminants.

Mathematical programming methods are the main tools for multiple contaminant WTN integrations. Takama et al. (1980) established a superstructure including water-using and wastewater treatment units, and provided a complex solving strategy. Galan and Grossmann (1998) presented a successive relaxed procedure to solve nonlinear model for design of distributed WTNs. Non-convex nonlinear models of distributed wastewater treatment

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superstructures can be solved by many newly developed strategies, for example, superstructure decomposition and parametric optimization strategies (Hernandez-Suarez et al., 2004), hybrid search procedure (Martín-Sistac and Graells, 2005), particle swarm optimization method (Liu et al., 2006), two-stage strategy (Castro et al., 2007, 2009), sequential approach based on pinch technique (Statyukha et al., 2008), discretization optimal approach (Burgara-Montero et al., 2012) and global optimization solvers BARON and LINDOGlobal (Nidret et al., 2012). In addition, Saif et al. (2008, 2014) and Karuppiah et al. (2012) studied the optimal design of reverse-osmosis WTN. Lim et al. (2008) and Park et al. (2013) considered the trade-offs between environmental impacts and economic costs in synthesis of wastewater treatment systems. Quaglia et al. (2014) integrated wastewater engineering concepts and models, together with optimization methods and solution algorithms, to handle problems with complexity of industrial relevance in design of wastewater treatment and reuse networks. Sueviriyapan et al. (2016) developed retrofit design schemes for complex industrial WTN based on recycling and rerouting strategies. Alnouri et al. (2015) incorporated on-site decentralized and off-site centralized wastewater treatment for the optimal design of interplant water networks within an industrial park. Rubio-Castro et al. (2012) addressed retrofit method of the WTN in industrial parks.

In design of distributed WTNs, one of the most important tasks is to reduce the total treatment flow rate. Liu and his coworkers realized that it is the unnecessary mixing of wastewater streams that causes the increase of total treatment flow rate of a WTN system. Based on this insight, a few new methods were proposed. Shi and Liu (2011) presented a concept, total treatment flow rate potential (TTFP), which can reflect the minimum total treatment flow rate of a process to meet the environmental limit, to determine the precedence order of treatment processes. Liu et al. (2013) put forward a few heuristic rules to determine the process sequence and used pinch identification method to calculate the minimum treatment flow rate of each process. Li et al. (2015) proposed a numerical indicator, total mixing influence potential (TMIP), to reflect the influence of stream mixing caused by performing a process on the total treatment flow rate of a WTN. The process with the smallest TMIP value was performed first in the design procedure. Complex problems can be solved easily with the procedure based on the numerical indicator.

Recently, with the development of wastewater treatment techniques, more and more treatment processes are available. For some widely-used processes, such as membrane separation and biochemistry reaction, the inlet concentrations for some contaminants cannot be higher than certain values. To consider this issue, Wang and Smith (1994), Kuo and Smith (1997), Galan and Grossmann (1998) and Liu et al. (2012) investigated the synthesis of the WTNs with maximum inlet concentration constraints for single contaminant systems. Teles et al. (2012) addressed a verity of water network design problems with a mathematical optimal approach, in which both single and multiple contaminant WTNs with maximum inlet concentration constraints were investigated. They obtained the global optimal solutions for these networks by using multi-parametric disaggregation strategy.

Li and Liu (2016) presented a heuristic approach for design of the single contaminant WTN with maximum inlet concentration constraints. This paper will extend the work of Li and Liu (2016) to the multiple contaminant systems. In the design procedure, initial network(s) can be developed with the heuristic rules proposed in this paper. The final design can be obtained by adjusting the initial network(s) based on maximum inlet concentration constraints, contaminant mass load balances and pinch point identification simultaneously. To meet maximum inlet concentration constraints or environmental regulations, some treatment process(es) might take recycling structure. In the remainder of this paper, relevant basic concepts will be described first. Then, a design procedure based on heuristic rules proposed will be presented. Finally, three literature examples will be investigated to show the usage of the method proposed.

2. Problem statement

The following information is given: (i) a set of wastewater streams containing multiple contaminants with known flow rates and contaminant concentrations; (ii) a set of available treatment processes, each being able to remove one or a few contaminants; (iii) the maximum inlet concentration constraints and removal ratios of each treatment process; (iv) the environmental regulation of each contaminant. The objective is to minimize the total treatment flow rate and the number of treatment processes of a distributed WTN under the premise of meeting the environmental regulation of every contaminant. It is assumed that each process can only be used once and there is no water loss during treatment operations.

3. Basic concepts

In order to discuss the design procedure clearly, let us consider a few basic concepts first.

3.1. Model of stream recycling

Recycling structure shown in Fig. 1 needs to be adopted when one of the following cases is met: (a) the maximum inlet concentration constraint(s) of one or a few contaminants cannot be met in any available processes. For example, in Table 1 of Example 1, when stream S_2, with the concentrations of (110, 140) ppm, is treated, the maximum inlet constraint concentrations in no treatment process are higher than (110, 140) ppm. Thus, recycling structure must be adopted; (b) the environmental regulation(s) of one or a few contaminant(s) cannot be met even if all the available processes are employed. In this case, recycling structure must be adopted to remove the surplus mass load. This is illustrated in Example 2.

It is important to obtain the recycling flow rate of TP_j for the structure shown in Fig. 1. Let us consider the situation when the inlet concentration of contaminant k is constrained. The mass load balance for contaminant k at the inlet of TP_j is shown in Eq. (1):

$$F_j C_{j,k}^{in} + F_j^R C_{j,k}^{out} = F_j C_{j,k}^{in} + F_j^R C_{j,k}^{\max}\left(1 - RR_{j,k}\right) = \left(F_j + F_j^R\right) C_{j,k}^{\max} \quad (1)$$

where F_j is the flow rate of wastewater stream treated by TP_j, F_j^R is the recycling flow rate of TP_j, $C_{j,k}^{in}$ is the concentration of contaminant k in the wastewater stream, $C_{j,k}^{out}$ is the concentration of contaminant k at the outlet of TP_j, and $C_{j,k}^{\max}$ and $RR_{j,k}$ are the maximum inlet constraint concentration and removal ratio (RR) of TP_j for contaminant k.

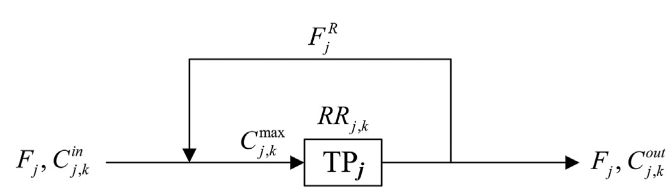

Fig. 1. Model of stream recycling.