Chemical Engineering Journal 228 (2013) 381–391

Contents lists available at SciVerse ScienceDirect

Chemical Engineering Journal

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

Design of distributed wastewater treatment systems with multiple contaminants

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HIGHLIGHTS

- Design of distributed wastewater treatment is investigated in this paper.
- New method to reduce unreasoning stream-mixing in design is proposed.
- Processes divided into three-unit groups based on minimum-mixing rule proposed.
- Precedence of the units in the group selected is determined by heuristic rules.
- It is shown that the design method proposed is simple and effective.

ARTICLE INFO

Article history:
Received 16 January 2013
Received in revised form 26 April 2013
Accepted 30 April 2013
Available online 16 May 2013

Keywords:
Design
Environment
Water
Systems engineering
Pinch method
Process synthesis

ABSTRACT

In design of a distributed wastewater treatment system, wastewater degradation caused by unreasoning stream-mixing will increase the total treatment flowrate, and this will often increase treatment cost. Therefore, it is necessary to reduce unreasoning stream-mixing as much as possible in the design procedure. This paper proposes a new method to reduce unreasoning stream-mixing in the design of distributed wastewater treatment networks. The design procedure includes following steps: (1) the main function of each treatment unit is identified; (2) the minimum treatment amount of each unit for its main contaminant, without considering other contaminants, is obtained with pinch method; (3) for the systems with many treatment units, a three-unit-group is selected and the precedence order of the units in the group is determined with the heuristic rules proposed in this paper. The above procedure will continue till the number of the units left is equal to or less than three. Some literature examples are investigated, and the results obtained in this work are compared to that obtained in the literature. It is shown that the design method proposed is simple and effective.

1. Introduction

Water is an important resource for process industry and agriculture. Water network synthesis is an important research aspect in process synthesis. Researchers have presented considerable work for design of water-using networks based on the water pinch analysis and/or the mathematical optimization. The development of water-using network design can be found in recent reviews [1,2].

The design for effluent treatment system is another important aspect of water network integration. Eckenfelder et al. [3] and Lankford et al. [4] addressed that distributed treatment systems had obvious advantages over centralized systems, because streams are treated separately or mixed when appropriate in the former system. This can reduce the treatment amount and cost of the system.

For distributed treatment system design, the methods proposed can be classified into pinch analysis methods, mathematical optimization methods and other methods.

The first work based on pinch analysis was proposed by Wang and Smith [5]. In their work, before design, the minimum flowrate target was determined by pinch analysis method. Kuo and Smith [6] proposed a concept of mixing exergy loss to measure the wastewater degradation when the streams are mixed. After 1990, a few insight-based approaches were proposed for the wastewater treatment network integration [7,8].

The mathematical optimization methods have become increasingly popular to design complex systems with many processes. Galan and Grossmann [9] applied a non-convex nonlinear procedure to find the global optimum. Hernandez-Suarez et al. [10] presented an optimization approach to break a complex superstructure down into a number of basic network superstructures. Karuppiah and

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http://dx.doi.org/10.1016/j.cej.2013.04.112

Nomenclature

S_i	stream S_i
f_i	flowrate of stream S_i
RR_A	removal ratio of contaminant A
$c_{i,A}$	concentration of contaminant A in S_i
$m_{i,A}$	mass load of contaminant A in S_i
$m_{in,A}$	mass load of contaminant A at TP_j inlet
$m_{out,A}$	mass load of contaminant A at TP_j outlet
C_A^{dis}	concentration of contaminant A in discharging stream
TP_j	treatment unit j
$M_{TPj,A}^{rem}$	removed mass of contaminant A by TP_j
$M_{TPj,A}$	mass load of contaminant A at TP_j inlet
S_{TPj}	collection of streams treated by TP_j
S_{Uj}	outlet stream of TP_j
$S_{Uj\text{-}P}$	bypassed flow rate of pinch stream for TP_j
$F_{TPj,in}$	treatment amount of TP_j for its main contaminant
$c_{Env,A}^{\lim}$	environment limit concentration of contaminant A
$M_{Env,A}^{\lim}$	environment mass load limit of contaminant A

Grossmann [11,12] proposed a superstructure model that included all feasible alternatives for wastewater treatment, reuse and recycle. Castro et al. [13] adopted an algorithm, which is composed of two parts, to find global optimal solutions. Statyukha et al. [14] designed wastewater treatment network with a hybrid approach, which is a sequential method integrating insight-based techniques and mathematical programming. Bandyopadhyay [15] proposed an algebraic methodology based on process integration to determine the minimum treatment flowrate.

Shi and Liu [16] proposed a new concept, the total treatment flowrate potential (TTFP), to reduce the unreasoning mixing of streams in the design procedure. Liu et al. [17] designed the wastewater treatment networks with single contaminant by optimizing the treatment amount function. Soo et al. [18] extended the graphical targeting technique to determine the minimum treatment flowrate for the single and two contaminant system with multiple processes.

In design of a distributed wastewater treatment system, wastewater degradation caused by unreasoning stream-mixing will increase the total treatment flowrate, this will often increase treatment cost. Therefore, it is necessary to reduce unreasoning stream-mixing as much as possible in the design procedure [5,6,16,17]. In this paper, the reducing of stream-mixings is considered as a major factor to decrease the total treatment amount of the system. A new heuristic (minimum-mixing) rule is proposed to determine the precedence order of the treatment units. Pinch method is used to calculate the minimum treatment amount of each unit for its main contaminant, without considering other contaminants. The main contaminant of unit is identified by its removal ability to each contaminant. Some literature examples are investigated, and the results obtained in this work are compared to that obtained in the literature. It is shown that the design method proposed is simple and effective.

2. Problem statement

Given is a group of wastewater streams, which contain certain contaminants with known concentrations. Given is also a group of treatment units and each unit can remove one or a few contaminants. It is assumed that there is no flowrate loss in the treatment process. The task is to design a distributed treatment system for removing certain contaminant(s) to meet the environmental limiting with minimum total treatment amount, because the treatment amount is often proportional to the treatment cost [5,6].

3. Design procedures for the systems with multiple treatment units and contaminants

The design flow chart is shown in Fig. 1. The detailed discussion of each step shown in Fig. 1 will be given in the following sections.

3.1. The main function of treatment unit

In a multiple contaminant system, each unit can often remove one or a few contaminants. For the system in which each unit can remove only one contaminant, the design procedure is simple. For the system in which some units can remove more than one contaminant, we need to identify the main contaminant of the units. For a treatment unit TP_j with contaminant removal ratios of RR_A, RR_B..., the contaminant which corresponds to the largest removal ratio (say RR_A) will be the main contaminant of TP_j. In this situation, the main function of TP_j is to remove contaminant A. If we only consider its main contaminant without considering the influence of other contaminants, the treatment amount of TP_j can be obtained by pinch method.

3.2. Obtaining the streams treated by each unit for its main contaminant and determining the elements of S_{TPj}

Pinch point is one of the key issues for design of the effluent treatment networks. According to Wang and Smith [5], the streams above the pinch of system are entirely treated, the pinch stream is partially treated, and those below the pinch are fully bypassed.

Let us consider the situation when the main function of TP_j is to remove contaminant A and this contaminant in all the streams is removed by TP_j, without considering the influence of the other treatment units and contaminants. As shown in Table 1, all the streams are rearranged as decreasing concentration order of contaminant A, from S_1 to S_{nk}, where f_i is the flowrate of S_i, and $c_{i,A}$ and $m_{i,A}$ are the concentration and mass load of contaminant A in S_i, respectively The removal ratio RR_A is defined as $RR_A = (m_{in,A} - m_{out,A})/m_{in,A}$, where $m_{in,A}$ and $m_{out,A}$ are the mass loads of contaminant A at inlet and outlet of TP_j, respectively. $c_{Env,A}^{\lim}$ is the environment limit concentration of contaminant A.

For the system shown in Fig. 2, if stream S_p is the pinch stream, the minimum mass load of contaminant A removed by TP_j should be:

$$M_{TPj,A}^{rem} = \sum_{i=1}^{nk} m_{i,A} - M_{Env,A}^{\lim} \tag{1}$$

where $\sum_{i=1}^{nk} m_{i,A}$ is the total mass load of contaminant A in all streams, and $M_{Env,A}^{\lim} = c_{Env,A}^{\lim} \times \sum_{i=1}^{nk} f_i$ is the limiting mass load of contaminant A in the discharging stream.

The mass load of contaminant A at the inlet of TP^j will be:

$$M_{TPj,A} = \left(\sum_{i=1}^{nk} m_{i,A} - M_{Env,A}^{\lim}\right) \Big/ RR_A \tag{2}$$

Then, the treated amount of pinch stream S_p will be: