Chemical Engineering Science 134 (2015) 44–56

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Analysis of water-using networks with multiple contaminants involving regeneration recycling

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HIGHLIGHTS

- Influence of regenerated concentrations on regenerated stream usage is analyzed.
- Multi-contaminant water networks are classified into simple ones and complex ones.
- Regenerated stream consumption can be predicted easily for simple networks.
- Contaminant which influences regeneration mostly is identified for complex networks.

ARTICLE INFO

Article history:
Received 20 June 2014
Received in revised form
14 March 2015
Accepted 23 April 2015
Available online 5 May 2015

Keywords:
Water-using network
Regeneration recycling
Wastewater minimization
Regenerated stream target
Water resource management

ABSTRACT

The introduction of regeneration recycling unit can significantly reduce freshwater consumption and consequently reduce wastewater discharge of water-using systems. In this paper, the influences of the regenerated concentrations of contaminants on regenerated stream consumption are investigated for the fixed mass-load water networks with multiple contaminants. The multi-contaminant water networks involving regeneration recycling are classified into simple ones and complex ones in this paper. Simple networks are similar to single-contaminant ones, in which only the key contaminant limits the usage of regenerated water. The regenerated stream consumption of simple networks can be predicted easily when the regenerated concentration of the key contaminant changes. The concentrations of other contaminants, if having influence on the regenerated stream consumption as well, should be reduced to their maximum allowable values. There is great difference between the features of complex networks of multiple contaminants and that of networks of single contaminant. The influence of the regenerated concentrations on regenerated stream consumption of complex networks is analyzed based on mass balances of the contaminants. The contaminant which has the most influence on regenerated stream consumption is identified. The methods proposed can contribute to evaluation of the appropriate regenerated concentrations for design or retrofit of the water networks with multiple contaminants.

1. Introduction

The research of the water-using networks involving regeneration recycling has attracted significant attention due to its great potential in reducing freshwater consumption and wastewater discharge (Bandyopadhyay and Cormos, 2008; Klemeš, 2012; Koppol et al., 2004). This is very important in water resource conservation and management. In the following discussion, we will mainly consider the research on the water networks with multiple contaminants involving regeneration reuse/recycling. Wang and Smith (1994) first studied the problem of wastewater regeneration of multi-contaminant water networks with a graphical approach. Kuo and Smith (1998) proposed an improved graphical method, which involved pinch identification, operation grouping and operation migrations, to design water networks involving regeneration reuse. Liu et al. (2004) presented a method which combined heuristic rules with material balances in design of regeneration reuse water networks. Cao et al. (2004) developed a design methodology for multi-contaminant water networks with internal mains involving regeneration recycling on the basis of mass balance and inlet contaminant

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http://dx.doi.org/10.1016/j.ces.2015.04.044
0009-2509/

concentration conditions. Guelli Ulson de Souza et al. (2011) extended the water source diagram (WSD) method, which was originally used for the synthesis of single-contaminant networks (Gomes et al., 2007), to investigate the networks with differentiated regeneration recycling of multiple contaminants. The above work employed graphical approaches or mass balance.

Mathematical programming methods are the most common techniques in synthesizing multi-contaminant water networks. Alva-Argaez et al. (1998) combined pinch analysis with mathematical programming tools to investigate wastewater minimization of industrial systems involving reuse, regeneration reuse/recycling. Faria et al. (2009) developed a nonlinear programming (NLP) model for networks with and without regeneration processes, and obtained the solution by a two-step procedure to minimize freshwater consumption and costs. Handani et al. (2010) established a generic mixed-integer linear programming (MILP) model for the systems involving reuse, recycle, and regeneration to minimize freshwater consumption and wastewater generation amount. Poplewski et al. (2011) presented a single-step approach for designing water networks with regeneration processes, by employing adaptive random search (ARS) algorithm to solve an MINLP/NLP superstructure model. Tudor and Lavric (2011) optimized minimum freshwater consumption, total costs of integrated water/wastewater and treatment networks by solving the NLP model with a genetic algorithm (GA). Hu et al. (2011) proposed three sequential MINLP models via process decomposition strategies to optimize freshwater consumption, regenerated water consumption and contaminant regeneration load. Khor et al. (2012) presented a superstructure consisting of sources for reuse/recycle, membrane separation-based regenerators and sinks for acceptance of water, and attained a globally optimal network topology. Khor et al. (2014) addressed the problem of fixed-flow-rate total water network synthesis under uncertainty with risk management. Recently increasing attentions have been paid to the optimization of multi-objective parameters including freshwater consumption, regenerated water consumption, total costs and network interconnection number. Various algorithms have been developed to solve nonlinear models in order to design robust multi-contaminant water networks involving regeneration recycling (Boix et al., 2011; Feng et al., 2008; Gunaratnam et al., 2005; Iancu et al., 2009; Kim, 2012). In addition to the above studies in grassroots design of networks involving regeneration recycling, many strategies have been developed for retrofit of the existing ones (Faria and Bagajewicz, 2009; Sotelo-Pichardo et al., 2011; Tan and Manan, 2006; Tan et al., 2007). The retrofit schemes usually involve modification for the existing regeneration units and installation of new ones.

Liu et al. (2009a) proposed a new insight that by adding the regenerated stream in the source streams of a network involving reuse only, the network involving regeneration reuse/recycling can be formed. Then the design of the network involving regeneration reuse/recycling can be carried out by using the procedure proposed for the network involving reuse only. The introduction of concentration potential concepts simplified the design procedure for multi-contaminant water networks (Liu et al., 2009b). Based on the above insight and concentration potential concepts, Pan et al. (2012) developed an iterative procedure for design of the multi-contaminant water networks involving regeneration recycling, and Zhao et al. (2013) developed an iterative method for design of the regeneration recycling water networks with internal water mains.

In general, it is more difficult to obtain target and design for a multi-contaminant water network involving regeneration reuse/recycling, compared to designing of a network with reuse only. Meanwhile, when the regenerated concentrations are reduced, consumption of regenerated stream (even freshwater) can be reduced (Feng et al., 2007, 2008; Pan et al., 2012), but regeneration costs are likely to increase. Therefore, it is important to investigate the influences of the regenerated concentrations of contaminants on regenerated stream consumption. For single-contaminant water networks, Feng et al. (2007) investigated the minimum freshwater consumption, the optimal regenerated concentration and the minimum regenerated water consumption by using a graphical method. Xu et al. (2013) developed a few relationships between the regenerated concentration and the regeneration pinch to predict the regenerated stream targets for the water networks of single contaminant. However, for the water networks with multiple contaminants, the influences of the regenerated concentrations of different contaminants may not be the same. Therefore, it is necessary to identify regeneration recycling key contaminant (KC) which has the most influence on regenerated stream consumption. Regeneration of non-key contaminants (NKCs), which have less or no influence on regenerated stream consumption, should be investigated as well.

In this paper, the multi-contaminant water networks involving regeneration recycling are classified into simple ones and complex ones. For a simple network, the regenerated stream consumption can be predicted when the regenerated concentration of the key contaminant changes. The influence of non-key contaminant(s) on the regenerated stream consumption will be investigated as well. For a complex network, the influence of the regenerated concentrations on the regenerated stream consumption is analyzed based on the mass balances of contaminants, and the procedure to identify the key contaminant will be proposed.

2. Characteristics of simple and complex networks

For single-contaminant water networks, Savelski and Bagajewicz (2000) proved that the contaminant should reach the maximum concentration at the outlet of a freshwater user process. For multi-contaminant water networks, Savelski and Bagajewicz (2003) addressed that at least one contaminant should meet the above optimality condition. Similarly, for water networks involving regeneration recycling, the theorems given by Savelski and Bagajewicz (2000, 2003) should also be applicable to the processes that use regenerated water.

As mentioned above, a simple network of multi-contaminants is similar to single-contaminant one, in which only the key contaminant reaches the limiting concentrations at the outlet of the processes that use regenerated water. For a complex network, the contaminants, which reach the limiting concentrations of the processes that use regenerated water, might not be the same; even for a single process, the contaminant reaching the limiting inlet concentration (contaminant *I*) and the one reaching the limiting outlet concentration (contaminant *O*) are not always the same. Thus, the statement of "the cumulative contaminant mass load of the demands below the regeneration pinch is equal to that of the sources which satisfy the demands (Xu et al., 2013)" for single-contaminant networks does not hold. We will discuss simple and complex networks separately.

3. Assumptions

The networks investigated in this paper are the fixed mass-load ones. There is no water loss in regeneration process. The contaminant concentrations of freshwater are assumed to be 0 ppm and the regenerated concentrations of every contaminant are assumed to be not higher than the lowest limiting inlet values except zero (freshwater), as adopted by Feng et al. (2007).

4. Simple multi-contaminant water networks involving regeneration recycling

4.1. Analysis of simple networks

The methods proposed by Xu et al. (2013) for single-contaminant networks can be appropriately modified to predict the regenerated