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A stepwise optimal design of water network☆

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ABSTRACT

In order to take full advantage of regeneration process to reduce fresh water consumption and avoid the accumulation of trace contaminants, regeneration reuse and regeneration recycle should be distinctive. A stepwise optimal design for water network is developed to simplify solution procedures for the formulated MINLP problem. In this paper, a feasible water reuse network framework is generated. Some heuristic rules from water reuse network are used to guide the placement of regeneration process. Then the outlet stream of regeneration process is considered as new water source. Regeneration reuse network structure is obtained through an iterative optimal procedure by taking the insights from reuse water network structure. Furthermore, regeneration recycle is only utilized to eliminate fresh water usage for processes in which regeneration reuse is impossible. Compared with the results obtained by relevant researches for the same example, the present method not only provides an appropriate regeneration reuse water network with minimum fresh water and regenerated water flow rate but also suggests a water network involving regeneration recycle with minimum recycle water flow rate. The design can utilize reuse, regeneration reuse and regeneration recycle step by step with minor water network structure change to achieve better flexibility. It can satisfy different demands for new plants and modernization of existing plants.

1. Introduction

Water has been used in abundant quantities by chemical, petrochemical, petroleum refining and other process industries. However, increasing cost of wastewater treatment to meet environmental standards and scarcity of good quality industrial water create a serious economic driving force to minimize the amount of water consumption and wastewater discharge. Without fundamental changes to reduce the operations requiring water, three general approaches are usually for wastewater minimization: water reuse, regenerated water reuse, and regenerated water recycle [1]. Their definitions are as follows [2].

Reuse: the outlet water from one process, which is sufficiently clean, is directly re-used to satisfy the water demand of another process.

Regeneration reuse: the outlet water from a process is treated to be suitable for use in some water-consuming processes. The treatment is called regeneration.

Regeneration recycle: the regenerated water is re-used in the same process.

The total water network for wastewater minimization is separated into two subsystems for reuse: water utilization network [3–8] and wastewater treatment network [9–13]. When the optimal flow scheme only involves the interaction of two subsystems, many opportunities of wastewater minimization such as regeneration reuse are ignored [14]. Many efforts have been made to optimal design of water network due to the inherent complexity of two subsystems involving regeneration reuse [15]. The pinch technology [16–21] shows limitations to address the complexity of the problem, and the research field moves to mathematical programming methods [22–27].

In order to improve design methods and optimization frameworks for water networks in practice, Alva-Argáez *et al.* [28] have addressed an integrated approach, which brought the engineering insight with water pinch analysis and powerful mathematical programming tools. Efforts have been made to obtain global optimality for solutions generated from mathematical programming techniques [29,30]. Faria and Bagajewicz [31] have discussed the network structure of water system. Teles *et al.* [32] have proposed new mixed-integer linear programming models for the optimal design of water-using and wastewater treatment networks. However, most of available design methods and approaches have focused on minimizing water consumption and its operating costs. Gunaratnam *et al.* [33] have developed an automated method for the design of total water systems. Hu *et al.* [34] have adopted appropriate process decomposition strategies to further reduce freshwater usage and avoid recycling. Iancu *et al.* [35] have extended the mathematical model of wastewater network for partial/total stream regeneration.

In order to attain zero discharge, regeneration recycle is used in water network design [36]. Relvas *et al.* [37] developed software AquoMin to design and target the networks involving regeneration

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reuse/recycling. Poplewski *et al.* [38] established a superstructure for water-using network involving reuse/recycling and solved the superstructure with adaptive random search optimization technique. Kim [39] discussed system analysis tools including a graphical method and an optimization method. Khor *et al.* [40] proposed a superstructure with fixed topology for a water network consisting of three layers: sources for reuse/recycle, regenerators for contaminant removal, and sinks for acceptance of water for reuse/recycle. Liu's group [41–44] developed a heuristic design procedure for design of water network including regeneration recycle.

Undoubtedly, the introduction of regeneration process can further reduce the consumption of fresh water. Compared with regeneration recycle, regeneration reuse can avoid the risk of potential build-up of trace contaminants in the process. However, the difference between regeneration reuse and regeneration recycle results in a MINLP problem for water network design. For regeneration reuse, the regeneration process cut the water network into two sub-networks before and after the process. Although the research effort in this area has increasingly focused on mathematical programming methods, the solution will be assisted by exploiting insights from conceptual approaches in order to simplify solution procedures. In this paper, a stepwise design approach is developed, in which reuse, regeneration reuse and regeneration recycle are considered step by step and the insights from the design are used to guide the next design. The MINLP problems for regeneration reuse are changed to NLP or LP problems and the recycling water flow rate is minimized.

2. Model Development

2.1. Problem statement

For a set of water-using processes requiring water of a certain quality and a set of regeneration processes with a certain capacity of treating wastewater, it is desired to determine a network of water streams among the processes so that the overall fresh water consumption is minimized while the processes receive water of adequate quality.

For design of water network, the superstructure is so large that it is difficult to solve or find the optimal solutions for corresponding MINLP problem. To simplify the framework of superstructure and find the optimal design of water network, the options for process k to minimize fresh water consumption by a stepwise adoption of reuse, regeneration reuse and regeneration recycle are shown in Fig. 1. The head process [4] utilizes only fresh water. Direct reuse process and other processes using fresh water reduce fresh water consumption with the addition of regeneration reuse, which will be considered in Section 2.2. The replacement of regeneration reuse water to fresh water and placement before or after the regeneration process are discussed in Section 2.3. The processes that utilize fresh water except head processes adopt regeneration recycle (Fig. 1d).

2.2. Design of water network with direct reuse

For single contaminant systems, processes can be arranged directly in the order of their maximum outlet concentration. However, for multiple contaminant systems, the monotonicity condition of key contaminant must be satisfied. For the process using fresh water only, the contaminant consuming the largest fresh water flow rate is the key contaminant and its outlet concentration attains the maximum for this process.

Usually, the objective function of water network may be the minimization of fresh water consumption.

$$\min \sum_{k} f_k \tag{1}$$

with the total mass balance:

$$f_k - W_k + \sum_{i \neq k} X_{k,i} - \sum_{k \neq i} X_{i,k} = 0 \tag{2}$$

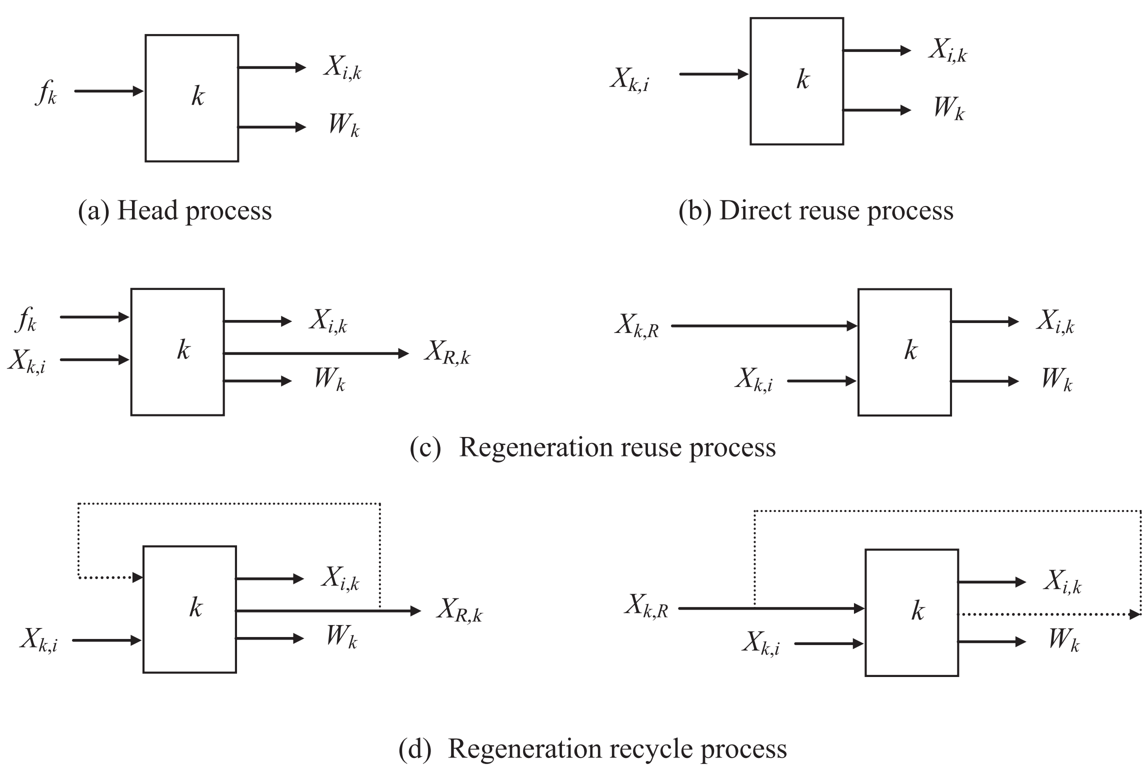

Fig. 1. Options for process k to minimize fresh water consumption.