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Simultaneous integration of water and energy on conceptual methodology for both single- and multi-contaminant problems

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HIGHLIGHTS

- It is a new conceptual methodology that is employed to solve multi-contaminant problems.
- A new tool named temperature and concentration order composite curves guides the design of water networks.
- Through this new conceptual methodology, the optimized targets of freshwater and utility are obtained in one step.

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ABSTRACT

This paper proposes a new conceptual methodology for simultaneous integration of water and energy. It is applicable to both single- and multi-contaminant problems with fixed contaminant mass load. The method includes a new graphical approach called as temperature and concentration order composite curves (TCOCC) which is employed to guide the design of appropriate water networks for heat recovery. Based on the obtained water allocation network, the heat is integrated in the system. The optimized targets of freshwater and utility are also obtained in one step. Compared to mathematical programming models in which complex calculations are adopted, our method is relatively simple and is visualized to the design procedure since it is a graphical approach. Furthermore, the temperature parameter is taken into account at the stage designing the initial water networks, which is more beneficial to heat integration. Three literature examples are presented to show the effectivity and advantages of this new method.

1. Introduction

Water and energy are major resources for process industries such as petroleum refining and chemical industries. Recently, due to the ever-increasing price of energy, the shortage of freshwater and the strict environmental regulations, process industries are driven by the economic and environmental issues to minimize the consumption of water and energy (Chen and Wang, 2012). In a chemical process, water is usually not only the carrier of contaminants but also the media of energies. Most of the mass exchanger operations are impacted by heating and cooling operations. In order to reduce the consumption of water and energy simultaneously, it is critical to understand the interaction between water networks and energy requirements, and it is necessary to study water allocation and heat exchange networks (WAHEN).

Since Srinivas and El-Halwagi (1994) proposed the simultaneous minimization of heat and water at the first time, many design techniques have been developed to achieve such goals. Among them, mathematical programming techniques and conceptual approaches are the two major methodologies.

The mathematical programming could handle problems involving more complexities of design and more rigorous multi-objectives effectively. Bagajewicz et al. (1998) proposed a conceptual framework of state space approach (SSA) to do the process synthesis. Then, a mixed integer linear mathematical programming (MILP) based on the concept of SSA was established to optimize WAHEN (Bagajewicz et al., 2002). This methodology, which accounts for the non-isothermal mixing, is a sequential model with two steps. Recently, Dong et al. (2008), Liao et al. (2011) and Chen et al. (2014) expanded SSA to a mixed integer non-linear mathematical programming (MINLP) to design WAHEN with the minimum total annualized cost, respectively. All of the three achieve targets in one step. In addition, Ahmetovic and Kravanja (2013) presented a novel superstructure which combines the water network and heat exchanger network by SSA. In their

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paper, the opportunity of direct and indirect heat transfer, and the opportunity of freshwater and wastewater splitting and mixing, have been systematically incorporated into the mathematical model. However, heat integration opportunities have not yet been fully taken into account in their work. Thus, Ahmetovic and Kravanja (2014) presented two strategies for the heat integration of process-to-process streams to improve their superstructure further. Besides of the heat integrated water networks, Tan et al. (2009) introduced SSA to the synthesis of water networks in order to achieve better targets. Leewongtanawit and Kim (2008) presented an approach based on the mathematical optimization of combined superstructures to design both water network and heat exchanger networks simultaneously, and to deal with large-size multiple contaminant problems. As to the complexity of MINLP, George (2011) and Sahu and Bandyoadhyay (2012) developed two different kinds of linear programming formulations for heat integration in a fixed-flow-rate water allocation network (WAN). These two methods are suitable for both single- and multi-contaminant problems. Although the mathematical modeling to deal with the complex WAHEN involving single- and multi-contaminant is attractive, it is like a black box which generates the results automatically after data are input. It is useless to provide engineers the controllability over the solution space as well as the insights on the network design. By contrast, conceptual techniques are typically easier to be understood, and are more important as visualization tools for simultaneous integration of water and energy.

Liu et al. (2009a) introduced the concept of concentration potential of the demand (CPD) and concentration potential of the source (CPS) for the first time, and developed a corresponding methodology for the design of water-using networks with multiple contaminants. Then, the new concept was extended to treat problems of regeneration reuse (Liu et al., 2009b), regeneration recycling (Pan et al., 2012), regeneration recycling water networks with internal water mains (Zhao et al., 2013). Compared to other approaches, this methodology is simpler to the design of water allocation network, but the results are almost the same. However, this method has only been employed to handle WAN up to now. Few works have been done to introduce the concentration potential concept into the simultaneous minimization of water and energy.

By analyzing the petroleum refinery, Huang and Edgar (1995) addressed the concept of combined-exchange network (CEN) to realize the simultaneous minimization of wastewater and energy consumption. Savulescu et al. (2005a, 2005b) presented a systematic design methodology for simultaneous management problems of energy and water. They treated two kinds of problems in their papers: systems with no water reuse and those with maximum water reuse. Manan et al. (2009) introduced a technique combing numerical and graphical methods for simultaneous water and energy reduction in a paper mill plant. A heat surplus diagram was employed to guide the networks design. Wan Alwi et al. (2011) presented a graphical approach named superimposed mass and energy curves (SMEC) for simultaneous mass and energy reduction. This approach is applicable to both mass transfer-based and non-mass transfer-based systems. However, most of conceptual techniques are only applicable to single contaminant problems. This is hardly helpful to solve practical industry problems which are usually multi-contaminant systems. In addition, the optimization strategies mentioned above all belong to the sequential strategy in which the freshwater target is specified first, and then the hot and cold utilities are calculated under the specified freshwater target. In other words, the integration of water and energy is not accomplished in one step, but two. Furthermore, the concentration and temperature parameters are considered separately in the optimization strategy. The temperature parameter is not taken into account in the initial design of water allocation networks. Thus, the order of the performing process is not the best, and is less reasonable for the simultaneous integration of water and energy.

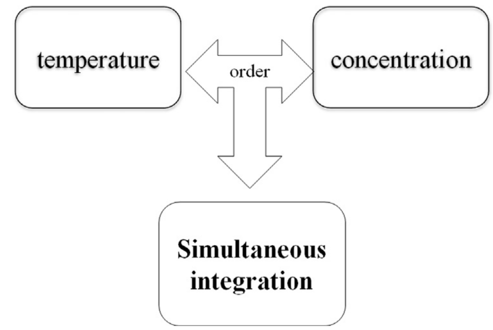

Fig. 1. The procedure for the simultaneous integration of water and energy.

Actually, WAHEN is a network in which heat and water are transferred simultaneously with targets and constraints of temperature and concentration. Temperature (determining utility consumption) and concentration (determining freshwater consumption) are the crucial parameters specifying the order of performing process and impacting the final results. Different orders mean different connection structures and different energy performances. The separated synthesis of water and heat is not the best strategy to the reduction of water and energy. In order to obtain the final optimal results, an appropriate performing order to design the networks must be established. Therefore, the key part of a WAHEN design is the procedure that chooses the reasonable performing order of processes based on temperature and concentration, which is shown in Fig. 1.

This paper proposes a new heuristic procedure for the simultaneous synthesis of water and energy networks. This procedure presents a reasonable and efficient strategy for the choice of the performing order based on temperature and concentration. Currently, mathematical programming is often adopted to solve multi-contaminant problems as we mentioned in the previous paragraphs. By contrast, few literatures present conceptual methods to solve such problems, in spite of wide applications in real industrial processes. This paper presents a novel conceptual methodology which is applicable for both single- and multi-contaminant problems with isothermal mixing. Besides, the minimization of both the freshwater and utility consumption can be achieved in one step. Section 2 presents the assumptions and basic theoretical principles which are helpful to understand the simultaneous integration of water and energy. Then, the new design procedure for the simultaneous integration of water and energy is introduced in Section 3. Three literature examples are investigated in Section 4 to demonstrate the effectivity of our new conceptual approach.

2. Assumptions and basic theoretical foundations

2.1. Assumptions

In order to simplify the analysis of the water and energy system and neglect some unimportant factors, the following assumptions are made:

(1) It is a fixed contaminant mass load problem with water reuse network. Stream data (including the maximum inlet and outlet concentration of contaminants, operating temperature and the contaminant mass load) for each water-using process