Chemical Engineering Science 140 (2016) 76–89

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Simultaneous optimization of heat-integrated water networks by a nonlinear program

Fangyou Yan [a], Hao Wu [a], Wei Li [a], Jinli Zhang [b,*]

[a] Key Laboratory for Green Chemical Technology MOE, School of Chemical Engineering and Technology, Tianjin University, Tianjin 300072, China
[b] Key Laboratory of Systems Bioengineering MOE, School of Chemical Engineering and Technology, Tianjin University, Tianjin 300072, China

HIGHLIGHTS

- A NLP model is developed for simultaneous heat-integrated water networks synthesis.
- The NLP model removes binary variables of MINLP model.
- A method for the existence of process match is developed without discrete variable.
- A method for identifying stream roles is proposed without any discrete variable.

ARTICLE INFO

Article history:
Received 27 April 2015
Received in revised form
19 August 2015
Accepted 23 September 2015
Available online 22 October 2015

Keywords:
NLP
MINLP
HIWNS
Simultaneous heat-integrated water network synthesis

ABSTRACT

Considerable attention has been paid to the heat-integrated water network synthesis (HIWNS) because it has the advantages of reducing water consumption, energy consumption and total cost. In this work, a revised superstructure of Ahmetović and Kravanja (2013a Energy 57, 236–250) for simultaneous HIWNS is developed by changing the position of the heaters and coolers. Based on the superstructure, a nonlinear programming (NLP) model is developed for the HIWNS. We develop a method to denote the existence of a process match, which is generally addressed using discrete variables. In addition, the temperature difference terms are incorporated into the objective function using a reformed approximated equation for the logarithmic mean temperature difference (LMTD); therefore, the temperature approach variables are not necessary in the NLP model. A method to identify the stream roles as hot or cold streams is proposed with no discrete variables. The number and type of variables are reduced by these strategies. Branch-And-Reduce Optimization Navigator (BARON) solver is used to solve the NLP model with the default initial point (the lower bounds) by GAMS. The model was tested on single- and multiple-contaminant problems using seven cases, where one case has an identical total annual cost (*TAC*) to the literature value and the other six cases have smaller *TAC* than the literature reported values.

1. Introduction

Large quantities of water and energy are consumed in many processes in the chemical industry, such as the washing, separation, steam and power regeneration and cooling processes. Recently, the growing chemical industrial water and energy demands are causing enormous stress on the hydrological cycle and atmospheric environment. It is crucial to find a method to reduce the water and energy consumptions in the chemical industry using water network and heat exchanger network designs. Considerable attention has been devoted to the heat-integrated water networks synthesis (HIWNS) because of the advantage of saving water and energy consumptions.

Ahmetović and Kravanja (2013a) presented a brief literature review regarding HIWNS, which had been an active research area over the past years and will be a main direction for future study. Savulescu and Smith (1998) proposed the topic of HIWNS problems for the first time. The conceptual method and mathematical optimization method are two main approaches for HIWNS. Savulescu and Smith (1998) introduced the conceptual method first by sequentially solving the water problem and energy problem. These researchers simultaneously minimized water and energy using the “two dimensional grid diagram” in their later work (Savulescu et al., 2005a, 2005b). Hou et al. (2014) developed a conceptual method for HIWNS, which is known as temperature and concentration order composite curves (TCOCC).

The mathematical optimization methods are divided into two main types: sequential method (Bagajewicz et al., 2002;

* Corresponding author.
E-mail address: zhangjinli@tju.edu.cn (J. Zhang).

http://dx.doi.org/10.1016/j.ces.2015.09.036
0009-2509/

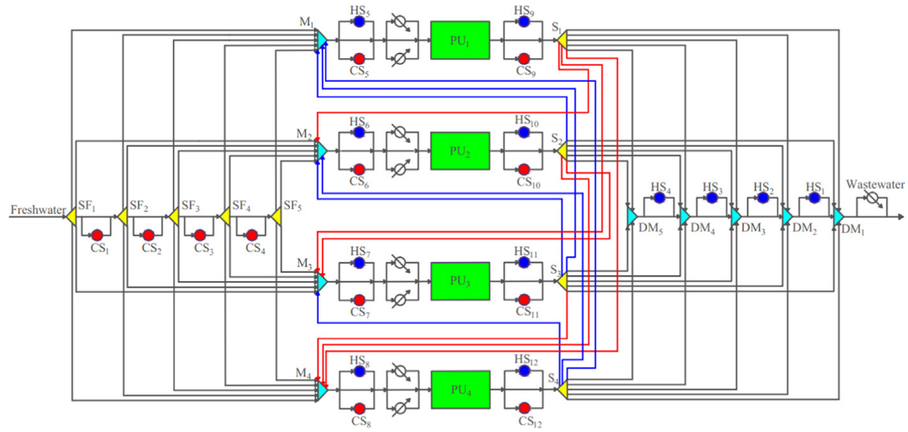

Fig. 1. Simultaneously heat-integrated water network synthesis superstructure.

Leewongtanawit and Kim, 2004; George et al., 2010) and simultaneous method (Kim et al., 2009; Xiao et al., 2009). The sequential method aims at designing heat-integrated water networks using multiple steps. Liao et al. (2011) addressed HIWNS by establishing a mixed integer linear programming (MILP) model. First, hot and cold streams were specified; next the targeting and design steps were performed. Boix et al. (2012) presented a two-step mathematical programming formulation for the HIWNS: in the first step, a mixed integer linear programming (MILP) model is developed for several objectives; in the second step, the best results of the first step are improved with energy integration into the water network.

The primary advantage of the sequential method is that subproblems can be easily treated. However, the trade-offs among mostly concerned indices, such as the freshwater consumption, utility consumption and investment cost, are not simultaneously considered, which may result in suboptimal networks. The simultaneous HIWNS can overcome the limitations of the sequential approach. The synthesis problem is treated as a single-task problem by minimizing the total annual cost and all trade-offs are simultaneously considered in the simultaneous synthesis approach.

Bogataj and Bagajewicz (2008) developed a MINLP model for the simultaneous HIWNS based on the superstructure that they proposed. A systematic design method was developed in the work of Dong et al. (2008) for the simultaneous HIWNS problem. A modified state-space representation was applied to capture the structural characteristics of the HIWNS problem, and a MINLP model was accordingly formulated. Ahmetović and Kravanja (2013a) presented a simultaneous HIWNS superstructure, where the water and heat exchanger networks were combined using interconnecting hot streams and cold streams. In their later work (Ahmetović and Kravanja, 2013b), an extended superstructure was developed, which involved process-to-process streams, and other streams in the overall network. The MINLP model was used in the above two Refs. (Ahmetović and Kravanja, 2013a, 2013b). Zhou et al. (2015) adopted the stream identification method, which was proposed by Liao et al. (2011), and extended the original sequential approach to a simultaneous method. Both the MINLP model and mathematical model with equilibrium constraints (MPEC) were developed for HIWNS by the authors.

In general, the MINLP model is used for HIWNS. Large numbers of discrete variables are used in the MINLP model to denote the existence of a process match and identify the hot and cold streams. In this work, we developed the methods to denote the existence of a process match and identify the stream roles with no discrete variable. The number and type of variables are reduced by the our method. Next, a nonlinear programming (NLP) model for the simultaneous HIWNS is tested on single- and multiple-contaminant problems.

2. Problem statement

The process unit consumes water with a specific quality and temperature. The heat-integrated water network synthesis is aimed to determine the interconnections, flowrates, contaminant concentrations, and temperatures of each stream. The limits on the inlet and outlet contaminant concentrations, mass load of contaminant to be removed in the process unit, temperatures of the discharged wastewater and freshwater and operating temperatures of the process units are specified. The minimum total annual cost (*TAC*) is set as the objective function for the simultaneous HIWNS.

The superstructure of the simultaneous HIWNS in this work is shown in Fig. 1, which is revised from the superstructure developed by Ahmetović and Kravanja (2013a). As shown in Fig. 1, the freshwater stream is a cold stream or bypass stream and can be divided into multiple-streams. The discharged wastewater stream is a hot stream or bypass stream, and can be divided into multiple-streams. The outlet water stream of one process unit can be reused in another process unit. The streams from the water mixers to the process units and the streams from the process units to the wastewater splitters can be hot, cold or bypass streams, which are determined by the temperature variables. The hot streams (including discharged wastewater stream, inlet water stream of a process unit and outlet water stream of a process unit) exchange heat with the cold streams (including freshwater stream, inlet water stream of a process unit and outlet water stream of a process unit). The primary revision of the superstructure in this work is the position of heaters and coolers. A heater may be necessary and is presented before the stream enters a process unit if the stream from the water mixer to a process unit is a cold stream. A cooler may be necessary and is presented before the stream enters a process unit if the stream from the mater mixer to a process unit is a hot stream. A cooler may be necessary and is presented before the wastewater stream is discharged. The numbers of freshwater splitters ($|SF|$) and discharged wastewater mixers ($|DM|$) are revised as adjusted parameters: $|SF| \le |PU| + 1$, $|DM| \le |PU| + 1$.

As shown in Fig. 2, a stage-wise superstructure, which was simplified from the work of Yee and Grossmann (1990), is applied to the heat exchanger network synthesis. All potential matches between hot and cold streams are achieved by splitting the streams. The inlet and outlet temperatures of each stage are treated as variables. Isothermal mixing of the streams is assumed. Unlike the stage-wise superstructure in the work of Yee and Grossmann (1990), no cold or hot utility is presented in the