Applied Thermal Engineering 96 (2016) 88–91

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

A shortcut model for energy efficient water network synthesis

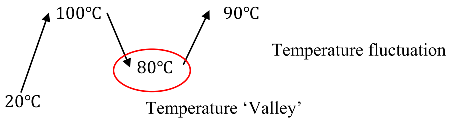
Yingzong Liang, Chi-Wai Hui *

Department of Chemical and Biomolecular Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong

HIGHLIGHTS

- Shortcut model is formulated for energy efficient water network synthesis.
- Energy consumption is minimized by minimizing temperature fluctuations.
- The model is formulated as MILP to achieve global optimum.
- Example shows the model generates water network with minimum energy consumption.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 30 March 2015
Accepted 9 November 2015
Available online 25 November 2015

Keywords:
Water allocation network
Heat integration
Mixed-integer linear programming

ABSTRACT

This paper presents a shortcut model for energy efficient water network synthesis with single contaminant. The proposed model is based on the idea of reducing repeated heating and cooling proposed by Feng et al. [9]. To avoid sub-optimum that can be generated from Feng's model, the proposed model only minimizes the number of temperature 'valleys' instead of the total number of 'peaks and valleys' of the water network. With the new formulation, the proposed model not only guarantees global optimum but also becomes much easier to be solved.

1. Introduction

The process industry is water- and energy-consuming. For example, oil refinery requires sheer bulk of water for washing, striping, and extraction. In certain cases, large amount of water needs to be heated up or cooled down to meet the temperature requirement of the operations. As a result, considerable amount of utility is necessary for water heating and cooling.

In order to reduce water and energy consumption, researchers developed different methods to address the water and energy usage problem based on conceptual design or mathematical programming. El-Halwagi and Manousiouthakis proposed a procedure for mass exchange network [1]. Wang and Smith introduced an approach for wastewater minimization with the underlying concept of pinch analysis [2]. The approach is able to determine minimum water using target without mathematical programming. Bagajewicz and Savelski presented a linear programming model for water allocation network design [3], and discussed the necessary conditions of optimal water networks [4]. Savulescu and Smith introduced a study on simultaneous energy and water minimization [5]. Savulescu et al. provided a systematic method for heat exchanger network and water network design [6,7]. Bagajewicz et al. proposed a mathematical programming method to generate water and heat exchanger network achieving minimum water and energy target [8]. Feng et al. introduced a mixed integer non-linear programming (MINLP) model to construct energy efficient network by minimizing the number of temperature 'peaks' and 'valleys' of the water network [9]. The method is based on the observation that fewer temperature fluctuations in a water network result in smaller energy consumption. Since unnecessary repeated heating and cooling of water leads to utility increase of the network, by minimizing temperature fluctuation, the resulting water network may feature minimum energy consumption if there is no repeated heating or cooling.

However, since the required water using temperature is often higher than fresh water temperature and wastewater discharged

---

* Corresponding author. Tel.: +852 2358 7137; fax: +852 2358 0054.
E-mail address: kehui@ust.hk (C.-W. Hui).

http://dx.doi.org/10.1016/j.applthermaleng.2015.11.020

temperature, temperature ‘peaks’ do not necessarily indicate repeated heating or cooling; minimizing the total number of temperature ‘peaks’ and ‘valleys’ may lead to a sub-optimal solution. In this paper, a shortcut model that only minimizes the number of temperature “valleys’ is proposed. The paper outline is as follows: the problem definition is stated in Section 2, a mixed-integer linear programming (MILP) model is developed in Section 3, and an illustrative example, results, and discussion are presented in Section 4.

2. Problem definition

In process operation, fresh water or reused water is applied to remove contaminant from the processes. And due to the temperature difference between processes and fresh water, heat exchange is necessary to heat up or cool down the water streams to target temperature. The water network problem can be defined as follows.

1. Single contaminant is assumed in the water network.
2. Water using processes have specific requirement of maximum inlet and outlet contaminant concentrations of the water.
3. The processes’ contaminant loads are fixed. Since the contaminant levels in the water streams are very low, the contaminant loads will not be added up to the water flow rate.
4. Water streams need to be heated up or cooled down to the specific temperature before entering the processes, and it is assumed that the water has no heat gain or loss in the processes.
5. It is assumed that the water streams can only exchange heat with other water streams or utilities.
6. Fresh water temperature and wastewater discharged temperature are given.

The purpose of the following formulation is to synthesize a water network with good energy performance. The synthesis of heat exchanger network is not included in this work.

3. Model formulation

In this section, an MILP model is formulated according to the problem definition. The model adopts some constraints from Bagajewicz et al. [8] and Feng et al. [9].

3.1. Mass balance constraints

Mass balance is necessary to generate a feasible water network. Eq. (1)–(4) can be found in Bagajewicz et al.’s work [8].

$$F_j^w + \sum_{i\in U_j} F_{i,j} = \sum_{k\in W_j} F_{j,k} + F_j^D \quad \forall j \in P \tag{1}$$

$$F_j^w C_j^{out} + \sum_{i\in U_j} F_{i,j}\left(C_j^{out} - C_i^{out}\right) = L_j \quad \forall j \in P \tag{2}$$

$$\sum_{i\in U_j} F_{i,j}\left(C_i^{out} - C_j^{in}\right) \le F_j^w C_j^{in} \quad \forall j \in P \tag{3}$$

$$\sum_{j\in P} F_j^w = M \tag{4}$$

Eq. (1) is the water balance of the process. Eq. (2) is contaminant balance of the process, and it is assumed the contaminant in the water reaches maximum concentration at each process outlet. Eq. (3) guarantees that inlet contaminant concentration is lower than required maximum value. Eq. (4) ensures minimum water usage of water network, and M is minimum water flow rate of water network obtained by wastewater minimization approach [2].

3.2. Logic constraints

The concepts of temperature ‘peak’ and ‘valley’ proposed by Feng et al. [9] is adopted. However, in this work, only temperature ‘valleys’ are considered. The constraints used for identifying ‘valleys’ are linearized in the proposed model to make it easier to be solved.

3.2.1. Existence of water reuse

Eq. (5) determines the existence of water reuse between units. If there is water reusing from process *i* to process *j*, the water flow F_{ij} must be larger than zero. The binary variable, Y_{ij}, in Eq. (5) must be equal to 1 to hold the constraint.

$$F_{ij} \le M Y_{ij} \quad \forall j \in P, i \in U_j \tag{5}$$

3.2.2. Existence of temperature ‘valley’

In Eq. (6), if $Y_{ij} = Y_{jk} = 1$, that water reuse from process i to j and from process j to k exists, and $T_i > T_j$, $T_k > T_j$, then X_{ijk}, which denotes the existence of temperature valley at process j, equals to 1. Since the objective is to minimize the total number of ‘valleys’, if Y_{ij} or Y_{jk} is not equal to 1, X_{ijk} is forced to be 0. Eq. (7) defines the set of possible temperature ‘valleys’.

$$X_{ijk} \ge Y_{ij} + Y_{jk} - 1 \quad \forall i,j,k \in V \tag{6}$$

$$V = \{(i,j,k) \mid \forall j \in P, i \in U_j, k \in W_j, T_i > T_j, T_k > T_j\} \tag{7}$$

3.3. Objective function

The objective of the proposed model is to minimize the number of ‘valleys’. With constraints Eq. (1)–(7), the proposed MILP model generates a feasible energy efficient water network.

$$Min \sum_{\forall i,j,k \in V} X_{ijk} \quad \text{(obj)} \tag{Obj}$$

4. Example

In this section, the proposed shortcut model is applied to a water allocation network synthesis example taken from Bagajewicz et al.’s [8] and Feng et al.’s [9] work. The example involves 8 water using processes. Fresh water temperature is 20 °C, wastewater discharged temperature is 30 °C, and minimum heat recovery approach temperature is 10 °C, and the heat capacity of water is 4.2 kJ/kg°C. Water using data are listed in Table 1.

In this example, the proposed model is implemented on GAMS 23.7.0 and solved by CPLEX 12.3 on an Intel(R) Core(TM) i5 3.10 GHz CPU and 8 GB of RAM Computer. Only one core is used for the model solving. 0% optimality tolerance is set. Feng’s model [9] is also implemented and solved by GAMS for comparison. The models’ performances are listed in Table 2.

Regarding solution efficiency, the proposed model is solved in 0.148 s with 18 iterations, faster than Feng’s 6.32 s with 34,614

Table 1
Water using data of example.

Process	L_j (g/s)	C_j^{in} (ppm)	C_j^{out} (ppm)	T_j (°C)
1	2	25	80	40
2	2.88	25	90	100
3	4	25	200	80
4	3	50	100	60
5	30	50	800	50
6	5	400	800	90
7	2	400	600	70
8	1	0	100	50