Journal of Cleaner Production 71 (2014) 128–138

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Heat integrated resource conservation networks without mixing prior to heat exchanger networks

Yin Ling Tan [a,*], Denny K.S. Ng [b], Dominic C.Y. Foo [b], Mahmoud M. El-Halwagi [c,d], Yudi Samyudia [a]

[a] Chemical Engineering Department, Curtin University, Sarawak Campus, CDT 250, 98009 Miri, Sarawak, Malaysia
[b] Department of Chemical and Environmental Engineering/Centre Excellence for Green Technologies, The University of Nottingham, Malaysia Campus, Broga Road, 43500 Semenyih, Selangor, Malaysia
[c] Chemical Engineering Department, Texas A&M University, College Station, TX 77843, United States
[d] King Abdul-Aziz University, Jeddah, Saudi Arabia

ARTICLE INFO

Article history:
Received 7 August 2013
Received in revised form
7 January 2014
Accepted 7 January 2014
Available online 18 January 2014

Keywords:
Process integration
Targeting
Property integration
Heat integration
Resource conservation
Optimisation

ABSTRACT

This paper presents a generic approach for the synthesis of heat integrated resource conservation networks (HIRCNs) of the fixed flow rate problem, where process sources linked directly to process sinks without any prior mixing. The mixed integer non-linear program (MINLP) formulation complemented by *floating pinch* concept was developed to determine the optimum fresh material resources as well as hot and cold energy utilities. The proposed approach is applicable for both concentration- and property-based direct reuse/recycle system with variable operating parameters (i.e. flow rates, temperatures and properties). Three literature case studies are solved to illustrate the proposed approach.

1. Introduction

Huge amount of energy and fresh resources (i.e. water, chemicals, solvents) are consumed by process industries to achieve the desired product throughput and quality. The current drive toward sustainability and business competitiveness has driven the process industries to effectively use these resources. Thus, resource conservation activities have become the centre of attention as compared to conventional end-of-pipe waste treatment system.

With enormous developments in the past three decades, Process Integration techniques have been widely accepted as effective tools for resource conservation and waste reduction for the process industry. El-Halwagi (2006) defines *Process Integration* as a holistic approach to process design, retrofitting and operation which emphasises the unity of the process. Available tools of Process Integration techniques for resource conservation and waste reduction can be generally categorised as Heat, Mass and Property Integration. Several important reviews can be found in literature, e.g. Furman and Sahinidis (2002) for *Heat Exchange Network* (HEN), Dunn and El-Halwagi (2003) for *Mass Exchange Network*, and Foo (2009) for Material *Resource Conservation Networks* (RCNs).

In the past decades, active developments were seen for RCNs, which includes Water, Hydrogen and Property Integration. In all cases, the main objective is to reduce both fresh resource consumption and waste generation. Review on RCNs synthesis can be found in textbooks, including both in-plant and inter plant material recovery systems (El-Halwagi, 2006; Foo, 2012).

It should be noted that most of the RCNs works do not consider temperature effect in the process streams. There are many cases where both mass and heat recovery are equally important. For instance, when dry air is used to remove volatile organic compounds from wastewater stream in a stripper, the air stream needs to possess specific temperature and properties before entering the stripper. Therefore, simultaneous consideration of mass, property and heat recovery should be addressed.

* Corresponding author. Tel.: +60 85 443833; fax: +60 85 443837.
E-mail addresses: tanyinling@gmail.com (Y.L. Tan), Denny.Ng@nottingham.edu.my (D.K.S. Ng), Dominic.Foo@nottingham.edu.my (D.C.Y. Foo), el-halwagi@tamu.edu (M.M. El-Halwagi), yudi.samyudia@curtin.edu.my (Y. Samyudia).

0959-6526/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jclepro.2014.01.014

In the past decades, extensive work was reported for simultaneous energy and water minimisation. These techniques can also be classified as insight-based and mathematical optimisation approaches. The former are developed based on sequential approach; while the latter considered both sequential and simultaneous approaches. As reported in the literature, various insight-based techniques were developed but they are limited to single property RCN problems. These techniques include two dimensional grid diagram and separate systems with (Savulescu et al., 2005b) and without water reuse (Savulescu et al., 2005a), water energy balance diagram (Leewongtanawit and Kim, 2009), source-demand energy composite curves (Savulescu et al., 2002), heat surplus diagram (Manan et al., 2009), superimposed mass and energy curves (Wan Alwi et al., 2011), stream merging principles (Feng et al., 2008), graphical thermodynamic rules (Sorin and Savulescu, 2004), thermodynamic principles for threshold problem (Polley et al., 2010), energy recovery algorithm (Sahu and Bandyopadhyay, 2010), modified problem table algorithm (Bandyopadhyay and Saha, 2010) and temperature versus concentration diagram (Martínez-Patiño et al., 2011).

On the other hand, mathematical optimisation techniques have been established to overcome limitation associated with insight-based techniques. Sequential linear programming models have been developed to first determine the minimum fresh water consumption followed by minimum energy requirement. Detailed Heat Integrated Water Network (HIWN) is then identified via MINLP models. Bagajewicz et al. (2002) initiated the sequential approach for the synthesis of Heat Integrated Water Networks (HIWNs). The fresh water and energy targets are firstly achieved using an LP formulation based on the necessary conditions of optimality. In the second stage, an MINLP heat transhipment model is generated. These models incorporate non-isothermal mixing as well as forbidden and compulsory flow connections and heat transfer matches (Bagajewicz et al., 2002).

Feng et al. (2009) analysed the interconnections between the design of a water allocation network and the design of a heat exchanger network. The authors discovered that reducing the number of temperature local fluctuations along the sub-streams in water networks improves the energy performance of the system. As a result, mathematical model with this consideration was proposed to synthesise a HIWN.

However, the above-mentioned works are primarily applicable to *fixed load problems*. To overcome this limitation, George et al. (2011) established a sequential approach for the *fixed flowrate problems* which is applicable for both single and multiple contaminants problems with the incorporation of isothermal and non-isothermal mixing of streams. In this approach, a linear programming model is formulated to identify the fresh water target. As for HEN model, a linear transshipment model is formulated for isothermal mixing problem while a nonlinear programming model with a discountinuous derivative (DNLP) is formulated for non-isothermal mixing cases.

On the other hand, Liao et al. (2011) presented an approach for HIWNs that allow splitting of hot and cold streams. Based on Liao et al. (2011), an MILP model that treats the direct and indirect heat transfer separately is developed to identify the promising matches between hot and cold streams. Next, an MINLP model with consideration of the splitting and non-isothermal mixing features inside the HEN is initiated to achieve the desired HIWN.

Recently, Sahu and Bandyopadhyay (2012) extended the concept of modified problem table algorithm (Sahu and Bandyopadhyay, 2010) to formulate HIWNs as linear programming model. The authors formulated three LP models for targeting the fresh water and energy consumptions for isothermal and non-isothermal mixing situations. The proposed formulation avoids the sub-optimality issues of MINLP and DNLP formulations for the case of non-isothermal mixing as found in the previous work (George et al., 2011). However, iteration of different pinch points is needed to identify the minimum energy requirement (Sahu and Bandyopadhyay, 2012).

On the other hand, the total cost of HIWNs can be minimised via simultaneous techniques. Leewongtanawit and Kim (2008) initiated mathematical models for synthesis of HIWNs with multiple contaminants. The authors formulate the overall problem as an MINLP optimisation problem. Decomposition approach is introduced to decompose the overall MINLP problem into MILP and NLP sub-problems which are solved in sequence using an iterative process. The method has also considered an economic trade-off between water network and HEN, non-isothermal and generation of separate systems. Furthermore, Bogataj and Bagajewicz (2008) developed another MINLP model for HIWNs synthesis. The established MINLP model includes the NLP formulation of water network superstructure and the MINLP formulation of heat exchange network superstructure for non-isothermal stream mixing.

Note that the models presented by Leewongtanawit and Kim (2008) and Bogataj and Bagajewicz (2008) utilised heuristics to reduce the number of hot and cold streams in the HEN, which had reduced the size of the model. However, the limitation of these approaches is that, the potential promising HIWNs may be excluded based on the heuristics. As a result, Dong et al. (2008) modify the state-space superstructure to formulate an MINLP model which covers a broader network structures. However, the model is very large in size and it is computational extensive when the problem scale increases. Thus, Dong et al. (2008) established an integrated optimisation strategy to improve the solution quality and efficiency. The potential global optimum may be identified by applying an interaction method proposed.

Ataei and Yoo (2010) proposed a sequential approach for multiple contaminant systems with the consideration of flowrate changes and heat loss in the HIWNs. Firstly, an NLP model is established to identify the feasible non-isothermal mixing points that provide the overall network with minimum fresh water and energy consumptions. Next, HEN is simplified through a new generation of separate system in HEN (Ataei and Yoo, 2010).

Ahmetović and Kravanja (2013) presented a HIWN superstructure with direct heat exchange by the mixing of streams and indirect heat exchange in heat exchangers. The model is formulated as non-convex MINLP and the objective is to minimise the total annual costs. Furthermore, the authors developed a set of new constraints to identify the interconnecting hot and cold streams between water network and HEN. Later, this model was extended to include process-to-process streams and other streams within the overall network for heat integration (Ahmetović and Kravanja, 2014). Two strategies were proposed for heat integration of process-to-process streams. This extended model was also a non-convex MINLP while the objective is to minimise the total annual cost of the network.

Recently, some work on simultaneous Property and Energy Integration has been observed. The first work on simultaneous Property and Energy Integration was presented by Kheireddine et al. (2011). The authors took into consideration of the thermal constraints in mass and property-based RCN. A nonlinear programming (NLP) model was presented to minimise the total cost of RCN, while satisfying a set of process and environmental constraints. In addition, the model also accounts for heat of mixing and the interdependency of properties. Nevertheless, the proposed model does not allow temperature adjustment through heaters and coolers.

Thus, Rojas-Torres et al. (2013) established a systematic approach for the synthesis of property-based RCN with property interceptors where heaters and coolers are modelled as thermal