Journal of Cleaner Production 189 (2018) 878–886

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

New superstructure-based optimization of property-based industrial water system

Chun Deng [a, *], Wei Jiang [a, 1], Wenjin Zhou [a, 1], Xiao Feng [b]

[a] State Key Laboratory of Heavy Oil Processing, China University of Petroleum-Beijing, 18 Fuxue Road, Changping, Beijing, 102249, China
[b] School of Chemical Engineering & Technology, Xi'an Jiaotong University, No.28, Xianning West Road, Xi'an, Shaanxi, 710049, China

ARTICLE INFO

Article history:
Received 26 December 2017
Received in revised form
29 March 2018
Accepted 31 March 2018
Available online 5 April 2018

Keywords:
Mathematical programming
Water network
Property integration
Wastewater minimization
Superstructure

ABSTRACT

Traditional industrial water network only consists of water-using processes and water treatment processes. The practical water-using processes may use freshwater, desalted water, condensation water, steam, circulating cooling water etc. and those are typically water utilities. It is not considered in the up-to-date model of industrial water network. To overcome the limitation, this paper proposed a novel superstructure of property-based industrial water system and it consists of water utility, water-using and water treatment sub-systems. The developed mathematical model includes the relevant equations among different water utilities, flowrate and mass balance constraints and property constraints. The water system of a certain coal-based chemical complex in China is optimized to illustrate the proposed model. The results show that the total annualized cost of the water system is reduced from 1.825×10^8 CNY/y (preliminary design) to 1.494×10^8 CNY/y (optimum design) and the flowrate of water resource is decreased from 1369.855 t/h to 1030.498 t/h.

1. Introduction

The population growth and rapid development of urbanization and industrialization results in the increase of freshwater intake. It is projected that the global water demand will increase by 55% globally between 2000 and 2050, as reported by Organization for Economic Co-operation and Development (OECD, 2012). The major increment of water demand will be caused by manufacturing, electricity and domestic. The optimum water management and reutilization is very helpful for water minimization of manufacture industries. Enormous pinch techniques and mathematical programming optimization approaches are proposed for the optimum design of water network.

On the basis of the concept of synthesis of mass exchange network (El-Halwagi and Manousiouthakis, 1989), Wang and Smith (1994) firstly proposed the limiting composite curve and water supply line to locate the flowrate targets (i.e. minimum flowrate of freshwater, regenerated water) and it is considered as pioneering work of water pinch technique. The mass problem table as an alternative technique for flowrate targeting is proposed by Castro et al. (1999). Considerable contributions, i.e. improved problem table as well as limiting composite curve and water supply line for regeneration recycling (Feng et al., 2007) and regeneration re-use (Bai et al., 2007), zero liquid discharge (Deng et al., 2008), have been addressed. Numerous graphical and tabular water pinch techniques are proposed, i.e. Water Surplus Diagram (Hallale, 2002), Material Recovery Pinch Diagram developed separately by El-Halwagi et al. (2003) and Prakash and Shenoy (2005), Water Cascade Analysis (Manan et al., 2004), Source Composite Curve (Bandyopadhyay et al., 2006), Material Surplus Composite Curve (Saw et al., 2011), Composite Table Algorithm and improved limiting composite curve (Agrawal and Shenoy, 2006) and its extension improved problem table for flowrate targeting water network with multiple water resources (Deng and Feng, 2011) and multiple partitioning interception units (Deng et al., 2016). The progress of the pinch technique for water system optimization is addressed by Foo (2009). However, there are difficulties for pinch techniques to handle the optimum design of water network with multiple impurities or contaminants, and the annualized operating and investment costs as the objectives.

Takama et al. (1980) initially proposed a superstructure of refinery water system which includes water-using units and water-regeneration/treatment units. Huang et al. (1999) improved the previous superstructure proposed by Takama et al. (1980) and it

---

* Corresponding author.
E-mail address: chundeng@cup.edu.cn (C. Deng).
[1] Wei Jiang and Wenjin Zhou contributed equally to this work.

https://doi.org/10.1016/j.jclepro.2018.03.314

Notation

Sets and indices

N*k*	set of process water sources
N*s*	set of process water sources
SN*s*	sub-set of N*s*
N*t*	set of water treatment system
N*p*	set of water properties
s	index for water sources
k	index for water sinks
t	index for water treatment system
e	index for environment
p	index for water properties

Parameters

α_{FWS}	freshwater production ratio of FWS
α_{PS}	boiler blowdown ratio of PS
α_{DWS}	desalted water production ratio of DWS
α_t	production ratio of regenerated water of wastewater treatment *t*
CN	cycle concentration of cooling tower
K	temperature coefficient
$c_{k,p}^{UB}$	upper limit value of water property p of water sink *k*
E_{fresh}	unit cost of water resource
E_{FWS}	unit treatment cost of FWS
E_{DWS}	unit treatment cost of DWS
E_{PS}	unit treatment cost of PS
E_{CWS}	unit treatment cost of CWS
E_t	unit treatment cost of WTS *t*
E_{MOE}	unit treatment cost of effluent sent to MOE
AWH	annual working hours
Af	annual factor

Variables

f_{FWS}^{out}	outlet flowrate of pretreated freshwater, t/h
f_{FWS}^{in}	inlet water flowrate of FWS, t/h
$f_{FWS,k}^{FW}$	freshwater flowrate allocated from FWS to water sink *k*, t/h
$f_{s,k}^{DW}$	desalted water flowrate allocated from DWS to water sink *k*, t/h
$f_{t,k}^{prod}$	flowrate of regenerated water from water treatment unit *t* to water sink *k*, t/h
f_k^{in}	inlet water flowrate of water sink *k*, t/h
$c_{k,p}^{in}$	inlet property *p* of water sink *k*, t/h
c_p^{FW}	property *p* of fresh water, t/h
c_p^{DW}	property *p* of desalted water, t/h
$c_{t,p}^{prod}$	property *p* of regenerated water, t/h
$c_{s,p}^{out}$	outlet property *p* of water source *s*, t/h
f_s^{out}	outlet flowrate of water source *s*, t/h
$f_{s,k}$	flowrate from water source *s* to water sink *k*, t/h
$f_{s,t}$	flowrate from water source *s* to wastewater treatment unit *t*, t/h
fe	flowrate of evaporation, t/h
fw	flowrate of splash loss, t/h
fr	flowrate of circulating cooling water, t/h
Δt	temperature difference between the inlet and outlet circulating cooling water, °C
f_t^{in}	inlet flowrate of wastewater treatment unit *t*, t/h
f_t^{prod}	regenerated water flowrate of wastewater treatment unit *t*, t/h
f_t^{resd}	residual water flowrate of wastewater treatment unit *t*, t/h
f_t^{loss}	water loss flowrate of wastewater treatment unit *t*, t/h
$c_{t,p}^{in}$	inlet property *p* of wastewater treatment unit *t*, t/h
$f_{t,k}^{prod}$	regenerated water flowrate allocated from wastewater treatment unit *t* to water sink *k*, t/h
$f_{t,t'}^{prod}$	regenerated water flowrate allocated from wastewater treatment unit *t* to wastewater treatment unit *t*', t/h
f_e	water flowrate discharged to MOE, t/h
$f_{t,e}^{prod}$	regenerated water flowrate from wastewater treatment unit *t* to MOE, t/h
$f_{t,e}^{resd}$	residual water flowrate from wastewater treatment unit *t* to MOE, t/h
$c_{e,p}$	property *p* of water stream discharged to MOE, t/h
$c_{t,p}^{resd}$	property *p* of the residual water for wastewater treatment unit *t*, t/h

Superscripts/Subscript

out	outlet
in	inlet
FW	fresh water
DW	desalted water
CDW	condensation water
loss	water loss
steam	steam
prod	regenerated water
UB	upper bound
resd	residual water

Abbreviations

FWS	fresh water station
DWS	desalted water station
CWS	cooling water system
PS	power and steam system
WTS	wastewater treatment system
MOE	municipal wastewater treatment system or the environment

included multiple fresh water sources and water generation and loss. Bagajewicz and Savelski (2001) proposed the linear mathematical models for the design of water system on the basis of the proposed the necessary conditions (Savelski and Bagajewicz, 2000). Gunaratnam et al. (2005) proposed the superstructure of total water network and the water-using system and treatment system could be optimized simultaneously. Karuppiah and Grossmann (2006) proposed the superstructure of integrated water network and the global optimization strategy was developed. Ng et al. (2009a, b) presented the automated targeting model for the optimization of single-contaminant water network with direct reuse/recycling (Ng et al., 2009a) and single-pass or partitioning