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Simultaneous optimization of heat-integrated water allocation networks

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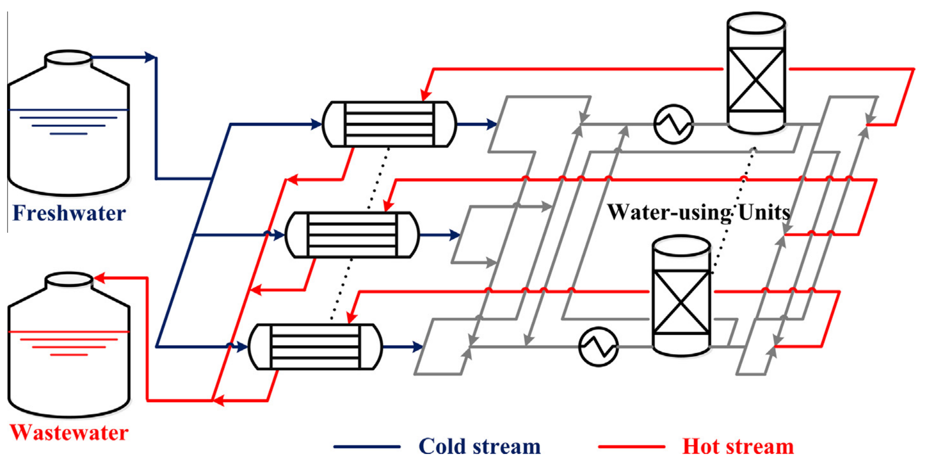
HIGHLIGHTS

- It is a novel mathematical programming model for HIWAN design, which can solve large scale problems.
- The superstructure gives the network structure with a parallel HEN structure.
- The proposed method is applicable for both wastewater uniform treatment and separate treatment cases.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presented a novel mathematical programming model for the simultaneous optimization of heat integrated water allocation networks featuring parallel heat exchanger network (HEN) structure. In the HEN structure, both freshwater and wastewater can be split freely. This model was suitable for both uniform wastewater treatment and separate wastewater treatment cases. The proposed model was formulated as a MINLP (mixed-integer non-linear programming) problem, making it applicable to large scale problems. The main objective was to minimize the total annual cost. Three literature examples, including a large scale example, were illustrated to demonstrate the applicability of the model. It was shown that the proposed method was as accurate as the literature methods for small scale problems, but performed better for large scale problem applications.

1. Introduction

Sustainable development is one of most important challenges facing humanity, especially in chemical process industries which are characterized by the enormous consumption of natural resources [1], such as water and energy are getting scarcer and scarcer. Large amounts of water and energy are consumed in petroleum refineries [2] and paper mills [3] for different purposes (washing, liquid–liquid extraction, absorption, etc.). Moreover, environmental regulations and laws have become stricter and stricter. Industries are exploring strategies for efficient usages of water and energy to meet new environmental standards and keep competitiveness [4]. In process industries, water and energy are inextricably intertwined, especially inside process water networks. If one wants to save more freshwater, more energy consumption might be occurred. Similarly, if one wants to save more energy,

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Nomenclature

Sets

D	expanded demand (include wastewater), $D = (j\|j = 1, 2, \ldots, N_D)$
K	heat exchangers, $K = (k\|k = 1, 2, \ldots, N_K)$
S	expanded source (include freshwater), $S = (i\|i = 1, 2, \ldots, N_S)$

Variables

AH_j	area of heater j, m^2
A_k	area of heat exchanger k, m^2
fi_i	outlet flowrate of each operation, kg/s
fj_j	inlet flowrate of each operation, kg/s
CU	cold utility consumption, kW
FW	freshwater consumption, kg/s
HU	hot utility consumption, kW
$kd_{k,j}$	flowrate from exchanger k to demand j, kg/s
n	the number of operations
qh_j	heat flow of heater j, kW
q_k	heat flow of heat exchanger k, kW
$sd_{i,j}$	flowrate from source i to demand j, kg/s
$sk_{i,k}$	flowrate from source i to exchanger k, kg/s
TAC	total annual cost, $
tco_k	outlet temperature of cold stream of heat exchanger k, K
thi_k	inlet temperature of hot stream of heat exchanger k, K
tho_k	outlet temperature of hot stream of heat exchanger k, K
t_j	mixing temperature of inlet stream of each operation, K

Binary variable

zhu_j	existence of the heater of inlet stream into demand j
z_k	existence of the heat exchanger k

Parameters

B	exponent for area cost
C	area cost coefficient, $/$m^2$
CF	fixed charge for exchangers, $
CFW	cost of freshwater, $/kg
CCU	per unit cost for cold utility, $/(kW yr)
CHU	per unit cost for hot utility, $/(kW yr)
c_p	heat capacity of water, J/(kg K)
$cjin_j$	limited inlet concentration of each operation, ppm
$cjout_j$	limited outlet concentration of each operation, ppm
$cout_i$	limited outlet concentration of each operation, ppm
$d1$	temperature approach for the cold end of heat exchangers
$d2$	temperature approach for the hot end of heat exchangers
H	hours of plant operation per annum, h
HT	highest operating temperature of all operations
LT	lowest operating temperature of all operations
mm_j	mass load of each operation, g/s
tci_k	inlet temperature of cold stream of heat exchanger k, K, equal to t_{fw}
td_j	inlet temperature of each operation (operating temperature), K
t_{fw}	temperature of freshwater, K
$thui$	inlet temperature of hot utility, K
$thuo$	outlet temperature of hot utility, K
ts_i	outlet temperature of each operation, K
t_{ww}	temperature of discharge water, K
U	heat transfer coefficient, kW/(m^2 K)
$\Omega 1$	upper bound for heat-transfer load of heaters
$\Omega 2$	upper bound for heat-transfer load of heat exchangers

Subscript

i	expanded source (include freshwater)
j	expanded demand (include wastewater)
k	heat exchangers

Abbreviations

CUC	cold utility cost
FWC	freshwater cost
GDP	generalized disjunctive programming
HEN	heat exchanger network
HIWAN	heat integrated water allocation network
HUC	hot utility cost
IC	investment cost
IWAHEN	interplant water allocation networks and heat exchanger networks
MILP	mixed-integer linear programming
MINLP	mixed-integer non-linear programming
MIP	mixed-integer programming
MPEC	mathematical program with equilibrium constraints
NLP	non-linear programming
SMEC	superimposed mass and energy curves
TAC	total annual cost
TCOCC	temperature and concentration order composite curves
WAN	water allocation network

it's likely more freshwater consumption is needed. This fascinating topic is frequently related to the heat integrated water allocation networks (abbreviated as HIWAN).

In general situations, water is required to be heated or cooled to meet operation requirements. There is a strong interaction between water and energy. Consequently, the techniques for synthesizing HIWAN have been developed for the efficient utilization of water and energy. Generally, HIWAN can be broken down into two subsystems: water allocation networks (abbreviated as WAN) and heat exchanger networks (abbreviated as HEN). Comprehensive reviews about WAN design can be found in Bagajewicz [5], Foo [6] and Jezowiski [7]. Additionally, comprehensive reviews of HEN can be found in Furman and Sahinidis [8]. Since water serves as a carrier of both contaminants and energy in process industry, the utilization of water and energy should be considered simultaneously. If these subsystems were treated separately, unnecessary water and energy consumption may result. Comprehensive review of HIWAN can be found in Ahmetović [9]. Nevertheless, there are significant amounts of interconnections within HIWAN and therefore plenty of opportunities for heat integration within the network. It is quite a big challenge to obtain good results for HIWAN problems. Therefore, synthesis of HIWAN has been an active research area during the past decade and will continue to be a hot topic in the future.

The design methodology of HIWAN can be classified into two categories: conceptual design and mathematical programming. The first works of conceptual design were done by the research group in Manchester [10–14]. Savulescu et al. studied simultaneous energy and water minimization with no water re-use [12] and maximum water re-use [13]. They introduced a two stage procedure. In the first stage, a new grid representation, called the two-dimensional grid diagram, was introduced to guide the WAN