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A simultaneous methodology for the optimal design of integrated water and energy networks considering pressure drops in process industries

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ABSTRACT

This paper presents a simultaneous methodology for the optimal design of integrated water and energy networks. Heat transfer coefficients are not constant but are related to the velocity of the streams. Pressure drops in heat exchangers and related power costs are considered. The model is a non-convex MINLP (mixed-integer non-linear program) model, in which the objective is to minimize the total annual costs. To accomplish this task, a new superstructure is proposed that follows the energy and mass streams from sources to sinks, enabling us to consider heat exchange between streams in two separate stages of the HENS before and after mixers. Furthermore, heat recovery from wastewater is considered. The model is solved for two examples, and results are presented with and without pressure drop effects. The optimum velocity and heat transfer coefficients for the streams in the heat exchangers are determined, and results are in good agreement with the literature. In this way, the model reflects the real situation in industrial networks where thermal and electrical energy and water requirements interact very closely.

1. Introduction

To reach sustainability in process industries, depletion of significant resources such as energy and water must be minimized, which has extreme effects on cost and operation. On the other hand, efficient utilization of resources to meet demand, environmental restrictions, increasing costs of water and energy and increasing demand for energy and materials, necessitate the optimally integrated design of water and energy networks that has recently become an important issue.

Water and energy networks interact with each other in different process operations such as steam generation, heating and cooling, washing and chemical reactions. Development of process integration techniques for the design of these networks has many advantages, such as process improvement, pollution prevention, energy management and conservation, increased productivity and reduction in the capital and operating costs of chemical plants (Dunn and El-Halwagi, 2003). Process integration techniques may be classified as pinch analysis (Linnhoff and Hindmarsh, 1983; El-Halwagi and Manousiouthakis, 1989) and mathematical programming techniques (Gundersen and Naess, 1988; Gundersen and Grossmann, 1990; Grossmann et al., 2000). Historically, these techniques have been developed for the optimal design of energy networks or water networks (Klemeš et al., 2010).

The state of the art in pinch-based techniques for water network synthesis has been reviewed by Foo (2009). Pinch technology relies on a sequence of targeting followed by a design strategy that considers the location of the pinch point in the network. It requires expertise to reach the optimal design, while mathematical programming considers sequential and simultaneous optimization of utility consumption and network configurations (Bagajewicz et al., 2013). Bagajewicz (2000)

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Nomenclature

Indices

i	process stream
j	process sinks (including waste mixer)
k	inex for stage 1…ST and temperature location 1…$ST+1$ in the first HEN
kk	inex for stage 1…ST_2 and temperature location 1…ST_2+1 in the second HEN
n	process sinks
s	process sinks
r	fresh source
S	shell side of heat exchanger
ST	total number of stages in the first HEN
ST_2	total number of stages in the second HEN
T	tube side of heat exchanger
w	waste mixer
total	total

Series

Hot	hot process streams (*ij*)
cold	cold process streams (*I′j′*)
coldfresh	freshwater streams (*rn*)

Parameters

A_{exp}	area exponent
C_{HE}	fixed cost for heat exchangers ($/a)
C_{FW}	fresh water cost ($/a)
C_{cu}	per unit cost for cold utility, $/(W a)
C_{Area}	area cost of heat exchangers
C_{hu}	per unit cost for hot utility, $/(W a)
C_P	heat capacity (kJ/kg K)
C_{Power}	power cost ($/w) = 0.12
d_i	Inside diameter of tubes (m)
d_o	outside diameter of tubes (m)
EMAT	Exchanger Minimum Approach Temperature
F_{hn}	correction factor to allow for the effect of the number of tube rows crossed
F_{hw}	the window correction factor
F_{hb}	the bypass correction factor
F_{hl}	the leakage correction factor
F_i	tube-side volumetric flowrate
F_o	shell-side volumetric flowrate
F_{pb}	bypass correction factor for pressure drop to allow for flow between the tube bundle and the shell wall
F_{pL}	the leakage correction factor for pressure drop to allow for leakage through the tube-to baffle clearance and the baffle-to shell clearance
H	operating hours per year
K_{pt}	constant value (Eq. (A.2))
K_{ht}	constant value (Eq. (A.4))
K_{hs}	constant value (Eq. (A.6))
K_t	fluid thermal conductivity (W/m K)
L	tube length (m)
P_C	layout configuration factor (here used square tube layout, so $P_C=1$)
P_T	tube pitch (i.e. center-to-center distance between adjacent tubes)
PR	tube pitch over outside diameter
Pr	Prandtl number
S_i	total flowrate for process stream of source *i* (kg/s)
S_n	total flowrate for process stream of sink *j* (kg/s)
Tin_{HU}	Inlet temperature of hot utility
ΔT_{min}	minimum temperature approach (K)
Γ	upper limit for temperature difference (K)
P	density (kg/m^3)
μ	viscosity (Pa s)

Variables

A	area of heat transfer between streams (m^2)
D_s	shell side diameter of heat exchanger
$f_{i,w}$	segregated flowrate for process stream to the waste (kg/s)
f_w	total flowrate for waste (kg/s)
$f_{i,j}$	segregated flow rate for hot stream *ij* from source *i* to sink *j* (kg/s)
$f_{i,n}$	segregated flow rate for hot stream *ij* from source *i* to sink *n* (kg/s)
$f_{i',j'}$	segregated flow rate for cold stream from source *i* to sink *j* (kg/s)
$fr_{r,n}$	segregated flow rate for fresh source to the sinks (kg/s)
fr_{total}	total fresh water (kg/s)
h_T	film heat-transfer coefficient of tube-side stream (W/m^2 K)
h_S	film heat-transfer coefficient of shell-side stream (w/m^{2}k)
LMTD	Log Mean Temperature Difference
$q_{i,j,i',j',ST}$	heat transferred between hot and cold streams in each stage (W)
$q_{i,j,r,n,ST}$	heat transferred between hot and fresh streams in each stage (W)
$q_{n,s,kk}$	heat transferred between sink *n* and sink *s* in stage *kk* in secon HEN (W)
$q_{s,n,kk}$	heat transferred between sink *s* and sink *n* in stage *kk* in secon HEN (W)
q_w	heat transferred between waste discharge and total inlet freshwater (W)
q_{cu}	cold utility (W)
q_{hu}	hot utility (W)
S	total flowrate of each source or sink (kg/s)
T	temperature (K)
$T2_{n,kk}$	temperature of stream in secon heat exchanger (K)
TAC	total annual cost ($/a)
$T_{fresh,in}$	inlet freshwater temperature
$T_{mix,n}$	mixture temperature before sink *n* (K)
$Tc_{i',j',k}$	temperature of cold stream in stage *k* (K)
$Th_{i,j,k}$	temperature of hot stream in stage *k* (K)
$Th_{i,w,k}$	temperature of hot stream (process unit *i* to waste mixer) in stage *k* (K)
Tout	outlet temperature of waste stream mixer (K)
$Tout_2$	outlet temperature of waste stream after waste heat recovery (K)
$Tr_{r,n,k}$	temperature of fresh stream in stage *k* (K)
$T_{outfresh}$	total freshwater temperature after waste heat recovery (K)
$T_{source,i}$	temperature of process unit i (K)
$T_{sink,n}$	temperature of process sink *n* (K)

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