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Optimal integration of organic Rankine cycles with industrial processes

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ABSTRACT

This paper presents a procedure for simultaneously handling the problem of optimal integration of regenerative organic Rankine cycles (ORCs) with overall processes. ORCs may allow the recovery of an important fraction of the low-temperature process excess heat (i.e., waste heat from industrial processes) in the form of mechanical energy. An integrated stagewise superstructure is proposed for representing the interconnections and interactions between the HEN and ORC for fixed data of process streams. Based on the integrated superstructure, the optimization problem is formulated as a mixed integer nonlinear programming problem to simultaneously account for the capital and operating costs including the revenue from the sale of the shaft power produced by the integrated system. The application of this method is illustrated with three example problems. Results show that the proposed procedure provides significantly better results than an earlier developed method for discovering optimal integrated systems using a sequential approach, due to the fact that it accounts simultaneously for the tradeoffs between the capital and operating costs as well as the sale of the produced energy. Also, the proposed method is an improvement over the previously reported methods for solving the synthesis problem of heat exchanger networks without the option of integration with an ORC (i.e., stand-alone heat exchanger networks).

1. Introduction

Nowadays the energy savings as well as the environmental impact minimization are important concerns in the process industry. In this regard, one of the most important strategies implemented to solve this problem is the implementation of heat exchanger networks (HENs). A large number of methods has been published for the optimal synthesis of HENs over the past three decades [1–4]. Basically, these procedures are based on sequential and simultaneous approaches. Among them, the pinch analysis [5–7] is one of the most successful sequential strategies, while mathematical programming techniques [8–14] are required to implement simultaneous approaches for synthesizing HENs.

The methods based on pinch analysis for synthesizing HENs have been focused on determining targets including the minimum consumption of hot and cold utilities, the minimum number of heat-transfer units and the minimum heat transfer area (to generate the economic trade-offs between capital and operating costs ahead of design). The targets for hot and cold utilities typically can be obtained using the composite curves [15], the table algorithm [16] and direct numerical geometric-based techniques [17]. Also, to determine the minimum utility cost there are some methods that consider constant temperatures [11], not constant temperatures [18] and account for design constraints such as forbidden matches between the process streams [19]. Papoulias and Grossmann [11] formulated a transshipment model and Viswanathan and Evans [18] proposed a method based on the out-of-kilter algorithm to calculate the minimum utility cost for multiple utilities. Recently, Serna-González et al. [19] proposed an algorithm to calculate the area targets for HENs with different heat transfer coefficients and non-uniform exchanger specifications. Then, Serna-Gonzalez and Ponce-Ortega [20] developed a new method for simultaneous targeting of network area and pumping power cost. Castier [21] presented a rigorous sequential multiple utility targeting approach. Moreover, several approaches for HEN retrofitting based on sequential approaches have been reported [22–24].

Respect to the mathematical programming-based approaches, the work by Yee and Grossmann [13] represents a basic framework for the optimal synthesis of HENs. This problem is formulated as a mixed integer non-linear programming (MINLP) problem, which is based on a superstructure that is a stagewise representation where within each stage heat exchange can occur between participating

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Nomenclature

Binary variables

z_j^{cond}	binary variables for the match between the ORC condenser and cold process stream *j*
z^{acu}	binary variables for the match between the ORC condenser and cold utility in the ORC
z_i^{cu}	binary variables for the match between hot process stream *i* and cold utility in the HEN
z_i^{evap}	binary variables for the match between hot process stream *i* and the organic fluid in the ORC evaporator
z_j^{hu}	binary variables for the match between hot utility and cold process stream *j* in the HEN
$z_{i,j,k}$	binary variables for match (i, j) in stage *k* of the superstructure of the HEN

Greek letters

β^{cond}	exponent for area of condensers in cost equation
β^{cu}	exponent for area of coolers in cost equation
β^{hu}	exponent for area of heaters in cost equation
β^{econ}	exponent for area of regenerator in cost equation
β^{evap}	exponent for area of evaporators in cost equation
β^{exch}	exponent for area of exchangers in cost equation
β^{pump}	exponent for power of pump in cost equation
β^{turb}	exponent for power of turbine in cost equation
δ	small number
η^{econ}	efficiency parameter of the regenerator
η^{ORC}	efficiency parameter of the ORC
η^{pump}	efficiency parameter of the pump

Parameters

C^{acu}	unit cost of cold utility for ORC
C^{cu}	unit cost of cold utility
C^{hu}	unit cost of hot utility
C^{power}	unit price of power generated
C^{pump}	unit cost of pumping power
CF^{cond}	unit fixed cost for the condensers
CF^{acu}	fixed charge associated with the ORC coolers
CF^{cu}	fixed charge associated with the HEN coolers
CF^{econ}	fixed charge associated with the regenerator
CF^{evap}	fixed charge associated with the ORC evaporators
CF^{hu}	fixed charge associated with the HEN heaters
CF	fixed charge associate with the HEN exchangers
CF^{pump}	fixed charge associated with the organic fluid pump
CF^{turb}	fixed charge associated with the ORC turbine
Cp_i	specific heat capacity for hot process stream *i*
Cp_j	specific heat capacity for cold process stream *j*
CV^{acu}	variable cost coefficient for the ORC coolers
CV^{cond}	variable cost coefficient for the ORC condensers
CV^{cu}	variable cost coefficient for the HEN coolers
CV^{econ}	variable cost coefficient for the regenerator
CV^{evap}	variable cost coefficient for the ORC evaporators
CV^{hu}	variable cost coefficient for the HEN heaters
CV	variable cost coefficient for heat transfer units in the HEN
CV^{pump}	variable cost coefficient for the ORC pump
CV^{turb}	variable cost coefficient for the ORC turbine
$dt^{acu\text{-}hot}$	temperature difference at hot end of ORC condensers using cold utility
$dt^{acu\text{-}cold}$	temperature difference at cold end of ORC condensers using cold utility
$dt^{econ\text{-}hot}$	temperature difference at hot end of the ORC regenerator
$dt^{econ\text{-}cold}$	temperature difference at cold end of the ORC regenerator
F	flow rate
FCp_i	heat capacity flow rate for hot process stream *i*
FCp_j	heat capacity flow rate for cold process stream *j*
h_i	film heat transfer coefficient for hot process stream *i*
h^{cu}	film heat transfer coefficient for the cold utility used in the HEN
h^{hu}	film heat transfer coefficient for the hot utility used in the HEN
h_j	film heat transfer coefficient for cold process stream *j*
h^{evap}	film heat transfer coefficient for the organic working fluid in the evaporators of the ORC
h^{cond}	film heat transfer coefficient for the organic working fluid in the condensers of the ORC
h^{acu}	film heat transfer coefficient for the cold utility of the ORC
$h^{econ\text{-}hot}$	film heat transfer coefficient for the organic working fluid at hot side of the regenerator of the ORC
$h^{econ\text{-}cold}$	film heat transfer coefficient for the organic working fluid at cold side of the regenerator of the ORC
H_Y	annual operating time
K_F	factor used to annualize capital costs
Q_i^{max}	upper bound for heat load of hot process stream *i*
Q_j^{max}	upper bound for heat load of cold process stream *j*
$Q_{i,j}^{max}$	upper bound for the heat exchanged in the match (*i*,*j*)
T^{turb}	organic fluid outlet temperature of turbine
TIN^{cond}	organic fluid inlet temperature of the ORC condensers
TIN^{acu}	inlet temperature for the cold utility in the ORC
TIN_i	inlet temperature of hot process stream *i*
TIN_j	inlet temperature of cold process stream *j*
TIN^{evap}	organic fluid inlet temperature of the ORC evaporators
$TOUT^{cond}$	organic fluid outlet temperature of the ORC condensers
$TOUT^{acu}$	outlet temperature of the cold utility in the ORC
$TOUT_i$	outlet temperature of hot process stream *i*
$TOUT_j$	outlet temperature of cold process stream *j*
$TOUT^{evap}$	organic fluid outlet temperature of the ORC evaporators
$\Delta T^{cond\text{-}max}$	upper bound for temperature difference for condensers
$\Delta T^{acu\text{-}max}$	upper bound for temperature difference for cold utility of the ORC
$\Delta T_i^{cu\text{-}max}$	upper bound for temperature difference for cold utility
$\Delta T^{evap\text{-}max}$	upper bound for temperature difference for evaporators
$\Delta T_j^{hu\text{-}max}$	upper bound for temperature difference for hot utility
$\Delta T_{i,j}^{max}$	upper bound for temperature difference for exchangers
ΔT^{min}	minimum approach temperature difference

Scripts

cond	condensers
cu	cold utility
econ	regenerator
exch	exchangers
evap	evaporators
hu	hot utility
NOK	total number of stages
ORC	organic Rankine cycle
turb	turbine

Sets

CPS	set for cold process streams *j*
HPS	set for hot process streams *i*
i	index for hot process streams
j	index for cold process streams
k	index for stages (1, ..., *NOK*) and temperature locations (1, ..., *NOK* + 1)
ST	set for stages in the superstructure *k*