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Retrofit of heat exchanger networks with pressure recovery of process streams at sub-ambient conditions

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ABSTRACT

This paper presents a new mathematical programming model for the retrofit of heat exchanger networks (HENs), wherein the pressure recovery of process streams is conducted to enhance heat integration. Particularly applied to cryogenic processes, HENs retrofit with combined heat and work integration is mainly aimed at reducing the use of expensive cold services. The proposed multi-stage superstructure allows the increment of the existing heat transfer area, as well as the use of new equipment for both heat exchange and pressure manipulation. The pressure recovery of streams is carried out simultaneously with the HEN design, such that the process conditions (streams pressure and temperature) are variables of optimization. The mathematical model is formulated using generalized disjunctive programming (GDP) and is optimized via mixed-integer nonlinear programming (MINLP), through the minimization of the retrofit total annualized cost, considering the turbine and compressor coupling with a helper motor. Three case studies are performed to assess the accuracy of the developed approach, including a real industrial example related to liquefied natural gas (LNG) production. The results show that the pressure recovery of streams is efficient for energy savings and, consequently, for decreasing the HEN retrofit total cost especially in sub-ambient processes.

1. Introduction

Reducing energy consumption through the implementation of more efficient and innovative strategies is one of the major concerns in processing plants. In this way, heat exchanger networks (HENs) are responsible for the integration of thermal streams, playing a crucial role in the energy efficiency enhancement of industrial processes [1–3]. Despite the considerable effort over the past few decades to solve the problem of HENs synthesis [4,5], a much smaller portion of the research was directed to the retrofit of existing networks [6,7]. Nowadays, the HENs retrofit are getting more attention in both academic and industrial fields [8,9], due to increased interest in energy conservation and its efficient use for economic reasons, as well as the rising demands to reduce environmental impacts related to high energy consumption [10,11].

It is worth to remember that energy savings by the minimization of energy-related costs in the design of industrial process is also a fundamental strategy to improve the performance of industries in the market, increasing their competitiveness [12]. Thus, the retrofit emerge as an effective way to enhance heat recovery and to achieve the desired energy savings from an established HEN [13,14]. The HENs retrofit is aimed at reducing the consumption of thermal utilities, by minimizing changes needed for the heat transfer enhancement in terms of restructuring the possibilities of thermal exchange between streams (i.e., re-piping), and modifying or replacing existing heat exchangers, often translated as a process costs function [15–17]. Conventional approaches for HENs retrofit include increasing the heat exchange area and/or installation of new equipment, the use of technologies for heat transfer enhancing, in addition to the reconfiguration of the heat exchange structure [8,18–20]. Among the above approaches, the structural changes related to the rearrangement of existing networks usually require a higher capital cost of investment to implement the retrofit design of HENs. Jiang et al. [21] point out that the most cost-effective HEN retrofit frequently involves the application of the lowest number of possible modifications into the existing network.

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Nomenclature

Roman letters

A	heat transfer area
A^{add}	additional heat transfer area
A^{ex}	existing heat transfer area
C	cost
C^{add}	additional cost
CC	cost parameter for the cooling
CE	cost parameter for the electricity
CH	cost parameter for the heating
Cp	heat capacity
CPO	cost of a unitary equipment
CV	cost parameter for the electric power revenue
f	factor of annualization for capital cost of investment
FBM	correction factor for cost
h	individual coefficient of heat transfer
M	big-M formulation parameter
ny	number of years
p	pressure
Q	heat duty
Q^{add}	additional heat duty
Q^{ex}	existing heat duty
r	fractional interest rate per year
T	temperature
T_{in}	streams inlet temperature
T_{out}	streams outlet temperature
T_U^c	cold utility temperature
T_U^h	hot utility temperature
ΔT_{min}	temperature minimal approximation
W	work
Wc^a	work of compression of the compressor allocated on the shaft
Wc^s	work of compression of the stand-alone compressor
We^a	work of expansion of the turbine allocated on the shaft
We^s	work of the stand-alone turbine
Wh	helper motor work
y	binary variable defining the energy integration between heating and cooling streams
y^a	binary variable defining the use of compressors and turbines coupling
y^{bigger}	binary variable defining the use of heat exchangers larger than existing equipment
y^s	binary variable defining the use of stand-alone turbines and compressors
$y^{smaller}$	binary variable defining the use of heat exchangers smaller than existing equipment

Acronyms

BB	branch-and-bound
CEPCI	chemical engineering plant cost index
GAMS	general algebraic modeling system
GDP	generalized disjunctive programming
HEN	heat exchanger network
LCO_2	liquid carbon dioxide
LIN	liquid inert nitrogen
LNG	liquefied natural gas
MINLP	mixed-integer nonlinear programming
NG	natural gas
WEN	work exchange network

Greek letters

η	isentropic efficiency
κ	polytrophic exponent

Subscripts

compressor	compressors
H_{ex}	heat exchangers
i	hot streams
j	cold streams
k	superstructure stages
m	heating utility
n	cold utility
turbine	turbines

In general, three groups of optimization methods are used for HENs retrofit. The first includes approaches based on heuristics and thermodynamic concepts, including pinch analysis; the second is related to methods based on mathematical programming and the third, the hybrid methods combining both techniques [6,18]. The pioneering work with a proposal to solve HENs retrofit by pinch analysis was introduced by Tjoe and Linnhoff [22]. The referred authors proposed a two-step approach—targeting and design—for the systematic solution of the problem. In mathematical programming, HENs retrofit is considered as an optimization problem, comprising the field with the highest advances due to its ability to obtain better solutions. Yee and Grossmann [23] presented a mathematical approach to achieve some main goals in HENs retrofit, including the maximum use of existing heat exchangers, allocation of available units to obtain new streams combinations at minimum piping cost, and minimal utilization of new heat transfer equipment. Later, Yee and Grossmann [24] extended their simultaneous model for HENs synthesis—presented in Yee and Grossmann [25]—for the HENs retrofit. Asante and Zhu [26] proposed a method for HENs retrofit combining mathematical programming and pinch analysis. The authors developed an iterative procedure to gradually remove the network pinches, in which the potentially most convenient configuration obtained after the diagnosis is optimized by means of deterministic optimization techniques. Note that, although being very useful for the design of intensive and complex energy processes, pinch analysis-based approaches do not guarantee the global optimal solution, since they cannot be used simultaneously with material balances [27].

According to Onishi et al. [28], despite a significant number of efforts to optimize the recovery of heat by synthesizing new HENs, few studies in the literature have tried to solve the optimization problem of integration between heat and work. It should be emphasized that none of these researches considers the possibility to retrofit existing networks. In fact, the streams pressure manipulation consumes considerable energy amounts, playing an especially important role in sub-ambient processes such as the liquefied natural gas (LNG) production [29–32]. In the offshore section of the LNG production chain shown in Fig. 1, the high pressure natural gas (NG) undergoes pre-heating by liquid carbon dioxide (LCO_2) across a heat exchanger. Then, it is expanded to achieve a lower pressure for thermal exchange with the liquid inert nitrogen (LIN). In the next stage, the NG is expanded by a turbine to attain the desired pressure for storage. The LIN at high pressure is cooled by way of two heat exchangers [33–36]. It is highlighted that the elevated consumption of cold utilities—extremely expensive in this type of process—is accountable for the high operating