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Retrofit of low-temperature heat recovery industrial systems using multiobjective exergoeconomic optimization

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ABSTRACT

Reducing the energy consumption of a plant often conflicts with the investment required for heat recovery. This paper presents a design study of shell and tube heat exchanger and direct-contact heat exchanger in three retrofit configurations. Multiobjective optimizations are employed to find optimal solutions that increase exergy efficiency at justifiable costs. A numerical modelization of heat transfer equipements is developed using heat transfer, pressure drop and cost correlations from the open literature. In order to verify the capability of the proposed approach, a case study for heat recovery in a pulp and paper plant is presented. In which multiple structural modifications of existing heat recovery systems are proposed based on an analysis of the Grand Composite Curve pinch targeting method. Each proposed modification is subject to multiobjective optimization based on the fast non-dominant sorting genetic algorithm (NSGA-II). The case study's results shows significant steam operation cost reduction of up to 89% reducing exergy destruction by 82%. It has also been shown that for some heat recovery modifications the most cost effective solution is close to the minimum exergy destruction solution subject to equipment design constraints.

1. Introduction

In order stay concurrentiel in a growing economy, it becomes increasingly important to understand mechanisms that degrade energy and develop solutions to improve the efficiency of industrial processes. Developing tools for designing more efficient yet cost-effective energy systems is one of the foremost challenges in the energy engineering field. Exergoeconomic analysis is a technique which combines exergy analysis with economic constraints to provide additional information to conventional energy analysis and economic evaluation [1]. In most cases, exergoeconomic analysis consists of defining cost functions owing to thermodynamic inefficiencies in specific components and finding a single optimal design balancing exergy and cost [2–4]. Efforts to automate an iterative optimization exergoeconomic method for real thermal systems has been made [5,6]. However, it might be advantageous for the designer to rapidly identify optimal retrofit designs with higher efficiency and marginally lower short term value. In recent work, Multiobjective optimization have been used to find optimal temperatures and pressure distribution in predefined thermal systems [7]. Similarly, equipment design using evolutionary algorithms is often tested to optimize cost, efficiency and ecological impact of individual components [8,9]. In this paper, multiobjective optimizations are used to optimize the heat exchanger design in a retrofit situation and identify solutions with higher exergy efficiencies while maintaining maximum economic performances. The proposed method capitalizes on the best parts of exergoeconomic analysis and evolutionary algorithm driven heat exchanger design. By means of the multiobjective optimization, both exergy and economic performances are maximized independently instead of combining both parameters into a single cost function. The result being a set of heat exchanger designs that maintains the optimal trade-off between a retrofit system maximal economic value and its efficiency. The motivation is in identifying more efficient alternatives to the optimal economic solution without lowering its value significantly. There are additional advantages of knowing more than the best economic solution and the trade-off between exergy efficiency and cost:

- Knowing multiple Pareto optimal solutions between exergy destruction and investment provides a way to identify more efficient solutions at comparable economic value.

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Nomenclature

A_{Hex}	heat transfer area (m^2)
B	baffle spacing (m)
C_{final}	corrected equipment cost (USD)
$C_{equipment}$	equipment cost (USD)
CE_{actual}	economic index (current)
$CE_{correlation}$	economic index of correlation
Cp	capacity rate (J/(kg K))
d_i	tube inside diameter (m)
d_o	tube outside diameter (m)
D_s	shell diameter (m)
E	exergy (W)
E_D	exergy destruction (W)
f_{mat}	material correction factor
$f_{shipping}$	shipping correction factor
f_{ICF}	installation cost correction factor
f_{DC}	direct cost correction factor
f_{IC}	indirect cost correction factor
f'	slope of saturated air enthalpy-temperature (J/(kg K))
F	friction factor
$Flow_{wet\ air}$	humid air flow-rate (kg/s)
G	mass flux (kg/s m^2)
H	heat transfer coefficient (W/m^2 K)
h	enthalpy (J/kg)
h^{sat}	enthalpy at water conditions (saturated air) (J/kg)
K	conductivity (W/(m K))
L_{tube}	tube length (m)
$\dot{m}$	mass flow rate (kg/s)
$\dot{m}_{DA}$	dry air mass flow rate (kg/s)
$\dot{m}_w^+$	water side capacity rate (kg/s)
n	number of tube passes
Nt	number of tubes per pass
Pr	Prandtl number
Pt	tube arrangement pitch (m)
q_{now}	heat flux (W/m^2)
$R_{fouling}$	conductive fouling resistance (m^2 K/W)
Re	Reynolds number
Re_{eq}	Reynolds number (phase change equivalent)
s	entropy (J/(kg K))
T	temperature (K)
T_{out}^{DB}	air side outlet temperature (dry-bulb) (K)
U	overall heat transfer coefficient (W/m^2 K)
$\dot{W}_{pump}$	pump load (W)

Greek symbols

δ	enthalpy correction factor (J)
ϵ	heat transfer effectiveness
ρ	density (kg/m^3)
μ	viscosity (Pa s)

Subscripts

ave	average conditions
i	control point
in	inlet conditions
l	liquid part
O	ambient conditions
out	outlet conditions
s	shell side
t	tube side
v	vapor part
w	heat transfer interface
win	water side inlet conditions
$wout$	water side outlet conditions

- Since each Pareto optimal designs have fully defined heat exchanger dimensions, it is simpler to further analyze their design than traditional methods acting on heat exchange surface distribution or thermal parameters optimization [11].
- With lower exergy destruction, high quality energy sources such as steam or high temperature effluents are kept for applications requiring high exergy sources. Thus, variations in energy costs would have less of an impact on operating costs.
- Equipment cost correlations are relatively imprecise [10], the added dimension of exergy destruction provides a relevant indicator for long term economic performances.

After describing the equipment design procedure as well as the optimization algorithm (NSGA-II) [12], proper cost functions are selected and the concept of exergy is explained. A case study for a pulp and paper plant retrofit is presented in order to assess the capabilities of the proposed method at comparing systems under optimal conditions. Grand composite curves are first used to propose topology changes to the heat exchanger network (HEN), namely retrofit scenarios by adding heat exchangers [13]. Multiobjective optimizations are then used to generate Pareto optimal solutions, each of which represents a set of heat exchanger dimensions. The results of such a methodology yield an optimal trade-off solution set or Pareto front between the most exergy efficient retrofit solution and the most economical.

2. Retrofit methodology

The retrofit procedure proposed in this paper consists of two stages; targeting and optimization. The targeting stage is used to identify and select topology modifications to be made to an existing HEN by adding new equipment. The resulting topology is then passed to the optimization stage where mathematical models of the added components are optimized and produce a trade-off curve of optimal retrofit design for economic and exergy ratings. The following sections cover both the tools used in the retrofit procedure and the modeling used in the case study.

2.1. Targeting stage – defining the energy targets

The targeting stage consists of evaluating HEN configurations by defining energy targets. Using energy targets for the HEN, rather than going directly into the design, allows many design options for the overall process to be screened quickly and conveniently [14]. This interactive design process allows the designer to influence the design with his perception of the relevant constraints, such as geographical position of streams, or the presence of obstacles between them. The selected pinch technique is the grand composite curve method [13], which displays the energy available for heat integration at different temperature levels given a pinch temperature. Energy targets are used to predefine the HEN structure of retrofit scenarios. Equipment design within each scenario can then be optimized to find the optimal trade-off solutions between cost and exergy destruction.

2.2. Optimization stage – comparing flowsheets under optimal conditions

The optimization stage is based on two objective functions: economic value and exergy destruction. By pre-defining the HEN