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Retrofit of heat exchanger networks without topology modifications and additional heat transfer area

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HIGHLIGHTS

- Cost-effective retrofit based on sensitivity analysis is proposed.
- Energy performance is improved by the use of heat transfer enhancement.
- Network structure is maintained without the need for additional heat transfer area.

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ABSTRACT

Numerous design methods for the retrofit of heat exchanger networks have been proposed over the years, with most depending greatly on topology modification and additional heat transfer area. However, topology modifications and the installation of additional heat transfer area can lead to uneconomic retrofit in many cases, largely as a result of the expense of civil engineering work and pipework modifications. Retrofit of a heat exchanger network can be achieved without the need for topology modifications and additional heat transfer area by the use of heat transfer enhancement. This paper presents a methodology for heat exchanger network retrofit around a fixed network and without the need for additional heat transfer area and topology modifications. Heat transfer enhancement techniques are used to improve the energy performance of an existing heat exchanger network. A dominance ratio is explored to identify the best location to apply enhancement. Sensitivity analysis is used in finding the sequence of the most effective heat exchangers to enhance in order to improve the performance of the network. Sensitivity analysis introduced to study network flexibility is adapted to study heat transfer enhancement. Heat exchanger networks are complex systems with interactions between various components. A change in one component can have an effect on other downstream heat exchangers. Therefore, the proposed methodology presents a way of eliminating the need for additional heat transfer area after enhancement, while ensuring the stream target temperatures are met. This is based on a key optimisation strategy which depends on a trade-off between utility consumption and the need for additional heat transfer area.

1. Introduction

Heat exchanger network (HEN) retrofit is an important way of improving the energy efficiency or accommodating an increase in throughput of an existing plant in the process industries. Generally, the fewer modifications employed in retrofit, the more attractive the retrofit is likely to be. This is because a small number of modifications will tend to lead to a lower capital cost. Conventional methods used in retrofit are, the use of additional heat transfer area and topology modifications (resequencing, repiping and stream splitting). In practice, HEN retrofit through the use of the aforementioned methods may be difficult to implement as a result of layout, safety and downtime constraints. These conventional retrofit methods will also incur an increased capital cost due to the considerable civil engineering and pipework required and potential production losses during modification. Owing to the aforementioned drawbacks in HEN retrofit, there have been increased interests into the use of heat transfer enhancement techniques for the retrofit of HENs. The use of heat transfer enhancement can be a very attractive option in HEN retrofit because the implementation of enhancement devices is a relatively simple task therefore, can be applied during normal maintenance period ensuring production losses are at a minimum. It is also generally cheaper to implement heat transfer enhancement than additional heat transfer area and, the civil engineering

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Nomenclature

P	column vector (–)
D_I	tube inner diameter (m)
L	length (m)
h_t	tube-side heat transfer coefficient (kW m^{-2} C^{-1})
C_P	heat capacity (J kg^{-1} C^{-1})
m	mass flow rate (kg s^{-1})
k	fluid thermal conductivity (W m^{-1} C^{-1})
N_P	number of tube passes (–)
N_T	number of tubes (–)
$d_{TN,inlet}$	inner diameter of the inlet nozzle for the tube-side fluid (m)
$d_{TN,outlet}$	inner diameter of the outlet nozzle for the tube-side fluid (m)
N_S	number of shells (–)
h_s	shell-side heat transfer coefficient (kW m^{-2} C^{-1})
D_o	tube outer diameter (m)
B_C	baffle cut (–)
B	baffle spacing (m)
D_S	shell inside diameter (m)
D_B	outside diameter of the tube bundle (m)
p_T	tube pitch (m)
n_b	number of baffles (–)
B_{in}	inlet baffle spacing (m)
B_{out}	outlet baffle spacing (m)
A	heat transfer area (m^2)
A_E	heat transfer area after enhancement (m^2)
$D_{TN,inlet}$	inner diameter of the inlet nozzle for the shell-side fluid (m)
$D_{TN,outlet}$	inner diameter of the outlet nozzle for the shell-side fluid (m)
L_{eff}	effective tube length (m)
Q	heat duty (kW)
Q_E	heat duty after enhancement (kW)
CP_H	heat capacity flowrate for the hot stream (kW C^{-1})
CP_C	heat capacity flowrate for the cold stream (kW C^{-1})
T_{in}	inlet temperature (°C)
T_{out}	outlet temperature (°C)
T_T	stream target temperature (°C)
$T_{T,E}$	stream target temperature after enhancement (°C)
U	overall heat transfer coefficient (kW m^{-2} °C^{-1})
U_E	enhanced overall heat transfer coefficient (kW m^{-2} °C^{-1})
F_T	correction factor (–)
ΔT_{LM}	log mean temperature difference (°C)
N_S	number of streams (–)
N_E	number of heat exchanger (–)
ΔT_{min}	minimum temperature approach (°C)
CP_{min}	minimum heat capacity flowrate (kW C^{-1})
ΔQ_{max}	maximum heat duty (kW)
TC_B	total cost for base case ($)
TC_E	total cost after enhancement ($)
$TC_{,HU,B}$	total hot utility cost for base case ($)
$TC_{,HU,E}$	total hot utility cost after enhancement ($)
$TC_{,CU,B}$	total cold utility cost for base case ($)
$TC_{,HU,E}$	total hot utility cost after enhancement ($)
$TC_{,R}$	total cost of retrofit ($)
$TC_{,E}$	total cost of enhancement ($)
$TC_{,A}$	total cost of additional area ($)
$TC_{,BP}$	total cost of bypass ($)
$RP_{,i}$	initial retrofit profit ($)
$RP_{,f}$	final retrofit profit ($)

Greek letters

μ	viscosity (Pa s)
ρ	fluid density (kg m^{-3})

and pipework are also reduced when compared with applying topology modifications in retrofit.

The methods widely used in the retrofit of HEN are either based on pinch analysis, mathematical programming methods, or a combination of these two methods. Tjoe and Linnhoff [1] first proposed the pinch retrofit method. The proposed concept is used to set targets for additional heat transfer area and utility consumption. The drawback associated with this method is, the area target obtained does not reflect the area distribution within the HEN. The limitations posed by the pinch retrofit method were overcome by the technique proposed by Shokoya and Kotjabasakis [2]. This technique incorporates the area distribution of the existing HEN into the targeting mechanism. This method provides a more realistic area target and retrofit design than that proposed by Tjoe and Linnhoff [1]. Although the pinch analysis promotes good user interaction and provides physical insights into the HEN retrofit problem, choosing the best retrofit design is left to the user and is based on their experience. In addition, the design process is time consuming due to the heuristic nature of the design.

With mathematical programming, HEN retrofit is converted into an optimisation task, by formulating the retrofit problem as a mathematical model. The two important aspects in mathematical programming methods are: finding an efficient way of representing the problem and providing an efficient optimisation technique for solving the problems. The objective when performing optimisation is to identify the most cost effective design from many possible solutions embedded in a superstructure. Yee and Grossmann [3] were the first to report retrofit of HENs that was based on a mathematical method. They developed a mixed integer linear programming (MILP) assignment–transhipment model for predicting the smallest number of structural modifications in an existing network. This was based on the transhipment model proposed by Papoulias and Grossmann [4]. The objective of the model was to maximise the utilisation of existing heat exchanger units, minimise the number of new heat exchangers required and the reassignment of existing heat exchanger units to different matches. This led to a final network structure that was as close as possible to the existing one. Ciric and Floudas [5] proposed a two-stage procedure for retrofitting HEN. The first stage, a match selection stage, involved the formulation of a MILP model. This model is used in the identification of ideal structural modifications. The pairings of all possible matches and heat exchangers are evaluated and decisions regarding selecting matches, reassigning heat exchangers, adding new heat exchangers and repiping streams are made. In the second stage, the optimisation stage, a superstructure is generated containing all possible network configurations based on the result obtained from the first stage. This is then formulated and solved as a non-linear programming (NLP) problem. They then went on to present a single stage mixed-integer non-linear programming (MINLP) model [6] that simultaneously optimised the HEN retrofit. Yee and Grossmann [7] proposed an improved two-stage model for retrofitting HENs: a pre-screening stage and an optimisation stage. The purpose of the pre-screening stage is to determine the optimal heat recovery level and the economic feasibility of the retrofit design. The optimisation stage takes into consideration only the number of new units required to achieve the optimum investment. It consists of the construction of a retrofit superstructure that includes all the possible retrofit designs embedded within it. To