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Heat exchanger network retrofit with a fixed network structure

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HIGHLIGHTS

- Heat exchanger network retrofit method with a fixed network structure is proposed.
- Cost-effective retrofit is allowed based on an improved sensitivity analysis.
- Energy performance is improved by the selective use of heat transfer enhancement.
- The method is applicable for streams with linear or non-linear physical properties.

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ABSTRACT

Finding cost effective retrofits for heat exchanger networks remains a challenge. Whilst it is often straightforward to find retrofit changes to an existing network that can improve energy performance, in practice such changes are most often uneconomic. This paper will present an approach to heat exchanger network retrofit around a fixed network structure. Network energy performance is improved through the selective use of heat transfer enhancement. A sensitivity analysis is used to find the most effective heat exchangers to enhance in order to improve the performance of the overall network. The sensitivity analysis used is an extension of a previous sensitivity analysis that was introduced to study network flexibility. The proposed method is applicable for heat exchanger networks involving streams with linear or non-linear physical properties. The enhancement of the most sensitive heat exchangers and avoiding new equipment, together with piping and civil engineering costs, allow much more cost-effective heat exchanger network retrofit.

1. Introduction

The retrofit of existing heat exchanger networks (HENs) is an important research field. Whilst many retrofit methods have been proposed, the network modifications suggested most often lead to uneconomic projects. It might be suspected that the major problem is justification for the purchase of new equipment. However, the modification of heat exchanger networks to allow new equipment to augment existing equipment is extremely expensive from the point of view of piping and civil engineering costs. Cost-effective retrofit most often involves the fewest modifications to the existing network. The HEN retrofit problem can be described as: given a set of hot and cold streams/utilities with their corresponding physical properties, flowrates and inlet/outlet flow conditions and a set of heat exchangers with specified geometries and assignments of duty/streams/position in an existing HEN, the existing HEN is retrofitted by means of the change of matching, resequencing, reassignments, adding new areas/exchangers, heat transfer enhancement, etc. to achieve some retrofit objective, whilst fulfilling the energy requirements of all process streams. Retrofit objectives vary, but might be to reduce the energy consumption to a specified level, minimise the utility requirements under a fixed budget and retrofit complexity, maximise the retrofit profit, minimise the retrofit cost under a certain energy recovery level, minimise the total annual cost after retrofit, satisfy the increased throughput or changed operation conditions, etc. In addition, the HEN retrofit is normally subject to some significantly different constraints from those for new HEN design. For example, pressure drops may be highly constrained due to the operation requirements of upstream and downstream units; the spatial and repiping constraints impede the implementation of retrofit; some on-site constraints and retrofit feasibility and ease of implementation are difficult to quantify. In summary, the HEN retrofit problem features more complex constraints and objectives.

The previous research in HEN retrofit can be grouped into pinch analysis methods, mathematical programming methods and

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Nomenclature

A	heat transfer area (m)
B	central baffle spacing (m)
B_C	baffle cut (–)
B_{in}	inlet baffle spacing (m)
B_{out}	outlet baffle spacing (m)
C	known temperature matrix (°C)
CP	stream heat capacity flowrate (product of mass flowrate and average specific heat capacity) (W K^{-1})
CP_C	heat capacity flowrate for the cold stream (product of mass flowrate and specific heat capacity) (W K^{-1})
CP_H	heat capacity flowrate for the hot stream (product of mass flowrate and specific heat capacity) (W K^{-1})
CP_i	heat capacity flowrate of Stream i (W K^{-1})
c_p	fluid specific heat capacity (J kg^{-1} K^{-1})
D_S	shell inside diameter (m)
d_I	tube inner diameter (m)
d_O	tube outer diameter (m)
$d_{NS,inlet}$	inner diameter of the inlet nozzle for the shell-side fluid (m)
$d_{NS,outlet}$	inner diameter of the outlet nozzle for the shell-side fluid (m)
$d_{TN,inlet}$	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)
F_T	temperature difference correction factor (–)
h_S	shell-side heat transfer coefficient (W m^{-2} K^{-1})
h_T	tube-side heat transfer coefficient (W m^{-2} K^{-1})
k	fluid thermal conductivity (W m^{-1} K^{-1})
k_{tube}	tube conductivity (W m^{-1} K^{-1})
L	tube length (m)
L_{BB}	shell-bundle diametric clearance (m)
L_{eff}	tube effective length (m)

m	mass flowrate (kg s^{-1})
N_B	number of baffles (–)
N_P	number of tube passes (–)
N_{SHELLS}	number of shells connected in series (–)
N_{STREAM}	number of streams involved in a heat exchanger network (–)
N_T	number of tubes (–)
N_{UNIT}	number of heat transfer units in a network (–)
P	thermal effectiveness of heat exchanger (–)
P_{1-2}	thermal effectiveness of each 1–2 shell connected in series (–)
p_T	tube pitch (m)
Q	heat duty (W)
Q_C	heat duty on the cold stream (W)
Q_H	heat duty on the hot stream (W)
R	ratio of stream heat capacity flowrates (–)
T	temperature (°C)
T_{C1}	inlet temperature of the cold stream (°C)
T_{C2}	outlet temperature of the cold stream (°C)
T_{H1}	inlet temperature of the hot stream (°C)
T_{H2}	outlet temperature of the hot stream (°C)
T_i	temperature of Stream i (°C)
T_{MIX}	temperature of the mixing junction (°C)
U	overall heat transfer coefficient(W m^{-2} K^{-1})
Z	parameter matrix (–)

Greek letters

ΔP_S	shell-side pressure drop (Pa)
ΔP_T	tube-side pressure drop (Pa)
ΔT_{LM}	log mean temperature difference (°C)
μ	fluid viscosity (N s m^{-2})
ρ	fluid density (kg m^{-3})

combined methods. The work of Tjoe and Linnhoff [1] is representative of pinch retrofit methods. These workers first applied the pinch concept in retrofitting HENs. However, their method cannot provide information on exactly where the additional areas are added and how many network modifications such as re-piping are required. When applying mathematical programming to HEN retrofit, the HEN retrofit problem is a mixed integer non-linear programming (MINLP) problem. Though theoretically this approach can handle different kinds of constraints simultaneously, obtaining a good solution by solving one single MINLP model in a single step has still not yet to be fully successful due to the non-linearity of the area equations and the complexity of constraints, particularly in large problems. Thus the MINLP problem is normally simplified or decomposed as mixed integer linear programming (MILP) [2], non-linear programming (NLP) or liner programming (LP) by making some assumptions and step-wise manipulation [3,4]. Most work using mathematical programming, required two steps: screening and optimization. Even though the network structure is simplified, solving the MINLP model is still time consuming and solutions are still very often trapped at a local optimum. To overcome this problem, some research has introduced stochastic algorithms, such as simulated annealing algorithms [5], genetic algorithms [6,7], to replace deterministic methods to solve the HEN retrofit MINLP. Asante and Zhu [8] proposed a step-by-step interactive approach for heat exchanger network retrofit by combining the features of pinch and mathematical programming. They introduced the concept of the network pinch that identifies the bottleneck of the existing network and the most effective change. The retrofit MINLP problem was then decomposed into a MILP problem and a NLP problem. Smith et al. [9] further modified Asante and Zhu's method to consider temperature-dependent thermal properties of streams and combined structural modifications and cost optimisation in a single step to avoid missing cost-effective solutions.

Most previous investigations are struggling to solve the complex HEN retrofit MINLP problem for large problems. Though the mathematical solution of the HEN retrofit problem would be an ideal method, its effectiveness and industrial applicability are quite problematic. Complex modifications recommended by optimising the MINLP are unacceptable in the view of most industrial practice. Wang et al. [10] used heuristic rules to retrofit HENs without solving mathematical programming, which can be a promising strategy for complex industrial revamps. However, their work was based on a HEN sensitivity analysis with the assumption of pure countercurrent heat exchangers, which is obviously unrealistic. Their method gave the amount of energy saving, position and extent of required heat transfer enhancement, but did not consider the retrofit ease of implementation and feasibility of the required heat transfer enhancement. The procedure involves a considerable amount of unavoidable trial-and-error. Thus this work attempts to develop a simple and practical method for HEN retrofit without any topological changes. This method applies a different solution strategy from the MINLP method, and does not rely on mathematical optimisation.

2. Methodology

Though topology changes, such as inserting new matches, repiping, resequencing and additional splitting, can be used for