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# Retrofit of heat exchanger networks with heat transfer enhancement based on an area ratio approach

Mary O. Akpomiemie *, Robin Smith

*Centre for Process Integration, School of Chemical Engineering and Analytical Science, The University of Manchester, Manchester M13 9PL, UK*

## HIGHLIGHTS

- Cost-effective retrofit based on area ratio approach is proposed.
- Energy performance is improved by the use of heat transfer enhancement.
- Fixed network topology and no need for additional heat transfer area in retrofit.
- Analysis is dependent on heat exchanger geometry.

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## ABSTRACT

The goal for performing heat exchanger network (HEN) retrofit is not only to reduce utility consumption but to ensure that the retrofit is economically viable. The problem of using heat transfer enhancement for retrofit lies with the uncertainty of the best location in which to apply enhancement, the augmentation level and dealing with downstream effects after enhancement is conducted.

To solve these problems, a systematic methodology is proposed. The first step in this methodology is the identification of candidate heat exchangers. In the second step, two methods, sensitivity analysis and an area ratio approach are compared for the identification of the best candidate heat exchangers to enhance. Heat transfer enhancement is then performed on the best candidate heat exchanger and, a non-linear optimisation based model is used to deal with the downstream effects after enhancement, subject to meeting set constraints on the HEN, such as the stream target temperatures and heat transfer area. Following this approach, the problems posed by the use of enhancement for retrofit can be addressed in a simple and computationally inexpensive manner.

Heat transfer enhancement is an attractive option for HEN retrofit as it can provide energy saving without the need for topology modifications and additional heat transfer area with an added benefit of reduced implementation time, as modifications can be carried out during normal shutdown periods.



## 1. Introduction

The desire to improve the energy efficiency in process industries has resulted in a rise of interest into the retrofit of heat exchanger networks (HENs). This is based on the heat integration strategies proposed to recover and utilise more of the heat available in the processes and reduce dependence on external utilities in satisfying process heating and cooling demands. The success or failure of these heat integration strategies depends on the design of HENs. The retrofit of heat exchanger networks (HENs) is commonly centred on the use of pinch analysis, mathematical programming or a combination of both methods (hybrid methods). The pinch analysis method was first proposed by Tjoe and Linnhoff [1]. This work provided retrofit targets (for additional heat transfer area and utility consumption), network analysis tools, and a modification strategy for energy saving retrofits. The drawback associated with this work was that the area targets obtained did not reflect a complete area distribution within the HEN. Polley and Panjeshahi [2] extended this work to take into account pressure drop constraints. Shokoya and Kotjabasakis [3] proposed a new technique that tackled the limitations of the pinch design method. The technique proposed takes into account the area distribution of the existing HEN into the retrofit target. This method provides a more realistic area target than that proposed by Tjoe and Linnoff [1] due to the consideration of area distribution. Carlsson et al. [4] introduced the cost matrix method for HEN retrofit. They considered the cost of heat transfer area, physical piping distance

* Corresponding author.
*E-mail address:* mary.akpomiemie@manchester.ac.uk (M.O. Akpomiemie).

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**Nomenclature**

$Q$ heat duty, kW
$U$ overall heat transfer coefficient, kW m$^{-2}$ °C$^{-1}$
$A$ heat transfer area, m$^2$
$\Delta T_{LM}$ log mean temperature difference, °C
$F_T$ correction factor, –
$A_{existing}$ existing heat transfer area, m$^2$
$Q_{utility}$ heat duty of utility heat exchangers, kW
$h_S$ shell-side heat transfer coefficient, kW m$^{-2}$ °C$^{-1}$
$h_{SF}$ shell-side fouling resistance, kW m$^{-2}$ °C$^{-1}$
$D_o$ tube outer diameter, m
$D_i$ tube inner diameter, m
$k_{tube}$ tube thermal conductivity, kW m$^{-1}$ °C$^{-1}$
$h_{TF}$ tube-side fouling resistance, kW m$^{-2}$ °C$^{-1}$
$h_T$ tube-side heat transfer coefficient, kW m$^{-2}$ °C$^{-1}$
$A_R$ area ratio, –
$y$ twist ratio, –
$H$ twist pitch, m
$u$ fluid velocity, m s$^{-1}$
$p$ axial roughness pitch, m
$e$ wire diameter, m
$C_P$ heat capacity, J kg$^{-1}$ °C$^{-1}$
$k$ fluid thermal conductivity, kW m$^{-1}$ °C$^{-1}$
$m$ mass flowrate, kg s$^{-1}$
$T_{in}$ inlet temperature, °C
$T_{out}$ outlet temperature, °C
$N_P$ number of tube passes, –
$N_T$ number of tubes, –
$N_S$ number of shells, –
$p_T$ tube pitch, m
$L_{eff}$ effective tube length, m
$D_S$ shell inside diameter, m
$B$ baffle spacing, m
$n_b$ number of baffles, –
$B_{in}$ inlet baffle spacing, m
$B_{out}$ outlet baffle spacing, m
$B_C$ baffle cut, %
$D_{TN,inlet}$ 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
TT target temperature, °C
TS supply temperature, °C
THI hot inlet temperature, °C
THO hot outlet temperature, °C
TCI cold inlet temperature, °C
TCO cold outlet temperature, °C
THIS hot inlet temperature of stream, °C
THOS hot outlet temperature of stream, °C
TCIS cold inlet temperature of stream, °C
TCOS cold outlet temperature of stream, °C
RP retrofit profit, $
RC retrofit cost, $
UC utility cost, $
EC enhancement cost, $
AC area cost, $
BC bypass cost, $
CCU cost parameter for cold utility, $/y
CHU cost parameter for hot utility, $/y
OT operating time, y
EF enhancement factor, –

*Greek letters*

$\mu$ viscosity, Pa s
$\rho$ fluid density, kg m$^{-3}$
$\delta$ tape thickness, m
$\varphi$ physical correction factor, –

*Dimensionless groups*

$Nu$ Nusselt number $= \frac{hD_i}{k}$
$Pr$ Prandtl number $= \frac{C_p \mu}{k}$
$Re$ Reynolds number $= \frac{\rho u D_i}{\mu}$
$Sw$ Swirl number $= \frac{Re}{\sqrt{y}} \frac{\pi}{\pi - 4(\delta/D_i)} \left[1 + \left(\frac{\pi}{2y}\right)^2\right]^{\frac{1}{2}}$

*Subscripts*

$B$ base
$E$ enhanced
$T$ tube
$S$ shell
UWT uniform wall temperature
$b$ bulk
$w$ wall
ex exchanger
HS hot stream
CS cold stream
CU cold utility
HU hot utility
$i$ initial
$f$ final
$E, O$ enhanced and optimised

between pair of streams, auxiliary equipment and, pumping cost. The pinch analysis method although promoting good user interaction, can be very time consuming due to its heuristic nature. The heuristic nature of the decision process could make it difficult to apply pinch analysis to larger problems due to the increased number of design alternatives.

Mathematical programming methods can be further subdivided into deterministic and probabilistic (stochastic) optimisation methods. In both cases, the retrofit problem is converted into an optimisation task by formulating the problem as a mathematical model. Ciric and Floudas [5] proposed a systematic two-stage approach for retrofit of HENs. In the first stage, a minimum temperature approach for the HEN is selected and calculations for the minimum utility cost are made. All possible pairings of streams and heat exchangers are then considered, so that all possible structural modifications are included in the mixed integer linear programming (MILP) model. This model is then solved to obtain the minimum modification cost. The second stage consists of producing a superstructure containing all the alternative network structures and then solving this superstructure as a non-linear programming (NLP) problem. The solution of this superstructure is the retrofitted network with the minimum cost of investment. A major limitation of this methodology is the large and complex superstructure in the mathematical formulation. The complexity of the superstructure could make the application of the methodology to large systems prohibitive, as very long computational times (and cost) could be required to obtain a feasible solution. To relieve this problem, they then went on to present a single stage mixed integer non-linear programming (MINLP) model [6] that simultaneously optimised the HEN retrofit. To better account for