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# Improving heat recovery in retrofitting heat exchanger networks with heat transfer intensification, pressure drop constraint and fouling mitigation

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## HIGHLIGHTS

- New intensification techniques are implemented for HEN retrofitting.
- Fouling effects and pressure drop constraints are considered.
- A new modeling and optimization method is developed for the retrofit problems.
- The proposed methods can perform much better than the existing methods.
- The proposed methods are efficient for practical application.

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ABSTRACT

Implementing heat transfer intensified techniques are now recognised as an efficient retrofit way of improving energy saving in heat exchanger networks (HENs). This not only increases heat recovery, but also prolongs exchanger operating time due to its effect on fouling mitigation. Compared with most of the existing work of HENs based on very simple assumptions for fouling effect, this paper addresses more accurate and complex fouling models reported recently (Yang et al., 2012). Due to the dynamic features of fouling, integration of dynamic equation of fouling rate is used to estimate fouling resistance at different operational times. The novelty of this paper is to present new insights to implementation of heat transfer intensified technologies for HEN retrofitting. It is the first study to implement hiTRAN® (one commercial tube-insert technology) into heat exchangers to increase HEN heat recovery with the consideration of detailed exchanger performances including heat transfer intensifications, pressure drop constraints, and fouling mitigation. The overall retrofit profit is maximized based on the best trade-off among energy savings, intensification implementation costs, exchanger cleaning costs, and pump power costs. To solve such complex optimization problems, a new mixed-integer linear programming (MILP) model has been developed to consider fouling effects in retrofitting HENs with heat transfer intensification. An efficient iterative optimization approach is then developed to solve the MILP problem. In case studies, the new proposed approach is compared with the existing methods on an industrial scale problem, demonstrating that the new proposed approach is able to obtain more realistic solutions for practical industrial problems.



## 1. Introduction

In major process industries such as oil refining, petrochemical processes, food, cement, steel, pulp and paper, there are two common ways to decrease energy consumption and the release of greenhouse gases. One is to increase heat recovery in heat exchange networks (HENs) through heat integration technologies. Another is to avoid the reduction of heat recovery over the period of plant operation before cleaning heat exchangers. These two issues have been widely studied because of increasing the concerns about how energy is utilized and recovered in the existing plants.

For heat integration, a number of approaches for HEN synthesis and retrofit have been demonstrated to achieve significant energy saving in the process industries. General design and retrofit strategies include increasing exchanger areas, adding new exchangers,

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**Nomenclature**

*Indices*
- *cs* cold stream
- *ex* exchanger
- *hs* hot stream
- *k* exchanger cleaning action

*Sets*
- *CS* set of all cold streams
- *EX* set of all exchangers
- *HS* set of all hot streams
- *K* set of all exchanger cleaning actions

*Parameters*
- $ST'^{ave}_{ex}$ initial shell-side average temperature in exchanger *ex* (K)
- $TT'^{ave}_{ex}$ initial tube-side average temperature in exchanger *ex* (K)
- $\Delta T_{\min}$ minimum temperature difference approach (°C)
- $AD_{ex}$ designed area of exchanger *ex* ($m^2$)
- $A_{ex}$ constants of calculating $k_{ex,1}$ (1/h)
- $AR_{ex}$ required area of exchanger *ex* ($m^2$)
- *CCP* cost coefficient (unit cost of power) ($/yr kW)
- *CCU* constant yearly cost for per cold-utility-duty unit ($/yr kW)
- $CFCP_{ex}$ heat-flow capacities (the multiplication between heat capacity and flow-rate) of cold stream in exchanger *ex* (kW/°C)
- $CMF_{ex}$ flow fraction of cold stream in exchanger *ex*
- $COSTA_{ex}$ constant cost of per exchanger-area unit for intensification heat transfer in exchanger *ex* ($\$/m^2$)
- $COSTU_{ex}$ constant cost associated with the ratio of heat transfer coefficients after and before enhancement in tube side of exchanger *ex* ($)
- $CSTI_{cs}$ network inlet temperatures of cold stream *cs* (°C)
- $CSTO_{cs}$ network outlet temperatures of cold stream *cs* (°C)
- $CTI'_{ex}$ initial inlet temperatures of cold streams in exchanger *ex* (°C)
- $CTO'_{ex}$ initial outlet temperatures of cold streams in exchanger *ex* (°C)
- *CU* daily cost parameter per energy-duty unit ($/day·kW)
- $DSUD_{ex}$ reciprocal value of shell-side designed heat transfer coefficient for exchanger *ex* ($(kW/m^2\,°C)^{-1}$)
- $DTU'_{ex}$ initial reciprocal value of tube-side required heat transfer coefficient for exchanger *ex* ($(kW/m^2\,°C)^{-1}$)
- $DU'_{ex}$ initial reciprocal value of overall required heat transfer coefficient of exchanger *ex* ($(kW/m^2\,°C)^{-1}$)
- *E* activation energy or apparent activation energy of tube-side fluid (kJ/mole)
- $ECT_{ex}$ cleaning time of exchanger *ex* if it is taken offline for cleaning (day)
- $FCOSTIHT_{ex}$ fixed charge cost of intensification heat transfer in exchanger *ex* ($)
- $FRR'_{ex}$ initial overall tube side fouling rate in exchanger *ex* ($m^2\,°C/kW\,h$)
- *HCU* constant yearly cost for per hot-utility-duty unit ($/yr·kW)
- $HFCP_{ex}$ heat-flow capacities (the multiplication between heat capacity and flow-rate) of hot stream in exchanger *ex* (kW/°C)
- $HMF_{ex}$ flow fraction of hot stream in exchanger *ex*
- $HSTI_{hs}$ network inlet temperatures of hot stream *hs* (°C)
- $HSTO_{hs}$ network outlet temperatures of hot stream *hs* (°C)
- $HTI'_{ex}$ initial inlet temperatures of hot streams in exchanger *ex* (°C)
- $HTO'_{ex}$ initial outlet temperatures of hot streams in exchanger *ex* (°C)
- $ID_{ex}$ outer tube diameter of exchanger *ex* (m)
- $k_{ex,1}$ constants of calculating $MAX\ \theta_{ex}$ (1/h)
- $k_{ex,2}$ constants of calculating $MAX\ \theta_{ex}$ (1/h)
- $k_{tube}$ tube conductivity (kW/m °C)
- $LMTD'_{ex}$ initial logarithmic mean temperature difference in exchanger *ex* (°C)
- *M* a sufficient large positive number
- *MAXCAEK* maximum energy cost when an exchanger is cleaned ($)
- $MAXPD_{ex}$ maximum tube-side pressure drop in exchanger *ex* (kPa)
- *MAXT* maximum acceptable time for exchanger operating (yr)
- $MAX\ \theta_{ex}$ maximum fouling surface coverage in tube side exchanger *ex*
- $MINU_{ex}$ lower bound of $DTUD_{ex}$ ($(kW/m^2\,°C)^{-1}$)
- $OCPD_{ex}$ original pump power cost associated with pressure drop in exchanger *ex* per year ($/yr)
- $OCTI_{ex}$ inlet temperature of cold stream in exchanger *ex* in original HEN (°C)
- $OD_{ex}$ inner tube diameter of exchanger *ex* (m)
- $ODTU_{ex}$ reciprocal values of original tube-side designed heat transfer coefficient for exchanger *ex* ($(kW/m^2\,°C)^{-1}$)
- *OEXLC* original total cost related to exchanger cleaning ($)
- $OHTI_{ex}$ inlet temperature of hot stream in exchanger *ex* in original HEN (°C)
- $OPD_{ex}$ tube-side original pressure drop for exchanger *ex* (kPa)
- $PD'_{ex}$ initial tube-side pressure drop for exchanger *ex* (kPa)
- *POP* plant operating period (yr)
- $Pr_{ex}$ Prandlt number of tube-side fluid
- *R* universal gas constant (kJ/mole °C)
- $R'_{f,ex}(Re_{e,ex})$ initial tube side fouling rate after using tube inserts in exchanger *ex* ($m^2\,°C/kW\,h$)
- $R'_{f,ex}(Re_{ex})$ initial tube side fouling rate before using tube inserts in exchanger *ex* ($m^2\,°C/kW\,h$)
- $Re_{e,ex}$ tube-side Reynolds numbers after using tube inserts
- $Re_{ex}$ tube-side Reynolds numbers before using tube inserts
- $r_{ex}$ constants for calculating $k_{ex,2}$ ($s^{-0.2}\,m^{-0.8}$)
- $RP'$ assumed retrofit profit value ($)
- $SRF_{ex}$ shell-side fouling resistance in exchanger *ex* ($m^2\,°C/kW$)
- $SUD'_{ex}$ initial shell-side designed heat transfer coefficient in exchanger *ex* ($kW/m^2\,°C$)
- $T'_{ex}$ initial exchanger operational time (h)
- $TRF'_{ex}$ initial tube-side fouling resistance ($m^2\,°C/kW$)
- $TUD'_{ex}$ initial tube-side designed heat transfer coefficient in exchanger *ex* ($kW/m^2\,°C$)
- $U'_{ex}$ initial overall required heat transfer coefficient of exchanger *ex* ($kW/m^2\,°C$)
- $u_{ex}$ tube-side flow velocity (m/s)
- $VR_{ex}$ tube-side fluid volumetric flow rate in exchanger *ex* ($m^3/s$)
- $WT'_{ex}$ initial wall temperature in exchanger *ex* (K)
- $\alpha_{ex}$ constants for calculating $R'_{f,ex}(Re_{ex})$ ($m^2\,°C/kW\,h$)
- $\gamma_{ex}$ constants for calculating $R'_{f,ex}(Re_{ex})$ ($m^2\,°C/kW\,h$)
- $\eta$ pump efficiency

*Variables continuous*
- $ADTU_{ex}$ positive variable, differences between initial and updated values of $DTU_{ex}$ ($(kW/m^2\,°C)^{-1}$)
- $ADU_{ex}$ positive variable, differences between initial and updated values of $DU_{ex}$ ($(kW/m^2\,°C)^{-1}$)
- $AEB_{ex}$ positive variable, energy balance differences between hot stream and cold stream in exchanger *ex* (kW)