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Conceptual insights to debottleneck the Network Pinch in heat-integrated crude oil distillation systems without topology modifications

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ABSTRACT

Heat exchanger network pinch sets the limitations of heat recovery for existing network topologies. Improving the heat recovery within a pinched-network is independent of the areas of individual exchangers present in the network, rather the topology of the network must be altered. Such a change in the topology can be very capital intensive and in many cases seems not easy to implement. This research aims to overcome the Network Pinch through proposing process operation changes, avoiding network topology alterations; hence, debottlenecks the heat-integrated systems towards further energy savings beyond the maximum heat recovery limitations. A new graphical representation is recently proposed to simulate existing preheat trains/networks with all energy equipment. The recent graphical representation is employed in this work to identify the pinching matches that limit heat recovery. Therefore, such graphs are key tools to identify potential process changes by which the Network Pinch is overcome. New graphs are constructed involving hot stream temperatures against cold stream temperatures. Existing exchangers are described by straight lines, with slopes related to flows of process streams and heat capacities. Exchanger matches touching the line where hot outlet stream temperature equals cold inlet stream temperature are pinching matches; this condition corresponds to absolute maximum heat recovery ($\Delta T = 0$). Potential process changes within a distillation unit are identified to relax the Network Pinch and further heat recovery is maximised. The slope of such an exchanger match is decreased or the location of the pinching match is altered keeping the same slope. These changes are translated into process changes within the crude oil distillation unit. Accordingly, the process changes are determined based on which match is pinched besides its location within the network. An illustrative example shows that process changes overcome the Network Pinch and energy recovery is increased by 14% beyond the maximum level achieved for the existing process conditions. Capital investments imposed are minor compared with substantial energy cost savings.

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1. Introduction

One major obstacle in industrial processes and chemical plants, including refineries, is the energy intensive feature. Typically, in energy-integrated crude distillation systems, large amounts of fuel oil, natural gas, or in some cases part of the crude oil processed are burned in the fired heater to provide the energy required for crude fractionation. Heat exchanger networks (HENs) are essential in the chemical plants to minimise external utility consumption through recovering process heat available at no operating costs. Indeed, literature is rich in addressing HEN synthesis problems, however, there is markedly less contributions on HEN retrofitting which is based on revamping the existing preheat trains [1,2].

Crude distillation units (CDUs) are of major energy consumption in refining industries. Energy of crude oil products and other process hot streams is recovered in preheat trains to reduce external utility requirements (fuel and flue gas consumption). Energy recovery in preheat trains maximises crude temperatures prior to entering the fired heaters. Maximum energy recovery in crude preheat trains is limited by the physical design of the exchanger network and together with the given process conditions. Revamping preheat trains once implies maximising the energy recovery in the network and reducing the external fuel consumption. Exchanger networks characterised with this condition are known as pinched networks or Network Pinch is taking place. Modifying

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Nomenclature

C_{pc}	specific heat of cold stream (kJ/kg·°C)
C_{ph}	specific heat of hot stream (kJ/kg·°C)
CP_c	heat capacity flow for cold stream (kJ/s·°C)
$\overline{CP}_c$	mean heat capacity flow for cold stream (kJ/s·°C)
CP_h	heat capacity flow for hot stream (kJ/s·°C)
$\overline{CP}_h$	mean heat capacity flow for hot stream (kJ/s·°C)
m_c	mass flow rate of cold stream (kg/s)
m_h	mass flow rate of hot stream (kg/s)
Q	heat duty or flow (kW)
T_c	temperature of process cold stream (°C)
T_h	temperature of process hot stream (°C)
T_{in}^h	temperature of inlet hot stream to exchangers (°C)
T_{out}^h	temperature of outlet hot stream from exchangers (°C)
T_{in}^c	temperature of inlet cold stream to exchangers (°C)
T_{out}^h	temperature of outlet cold stream from exchangers (°C)
T_{in}^h	temperature of inlet hot stream to exchangers (°C)
ΔT	temperature driving force of exchanger (°C, K)
ΔT_{min}	minimum temperature approach difference (°C, K)
ΔT_c	temperature difference of cold stream (°C, K)
ΔT_h	temperature difference of hot stream (°C, K)
Abbreviation*c*	
	cold stream
cw	cooling water
h	hot stream
HEN(*s*)	heat exchanger network(s)
hx	exchanger unit
P/*A*	pump-around
hvgo	heavy vacuum gas oil
AGO	atmospheric gas oil

the existing network is thus necessary in order to further increase and improve the heat recovery.

The Network Pinch method revealed the limits of the energy or heat recovery for an existing HEN. The heat recovery for a given network can be increased, providing exchangers exhibit a positive temperature driving force or ΔT. The maximum heat recovery can be possibly achieved whenever some exchangers show a limited temperature approach or absolute zero temperature difference. Several modifications are potentially successful for retrofitting such as relocating exchangers, stream splitting, and adding new units. It is important to say that these modifications are network-based and have been addressed extensively in most previous revamping methods [3–6]. Recent network retrofitting approaches include global optimisation [7], MILP-based iterative method [8], two-level pinching [9], fixed network structure [10], response surface [11], and heat transfer intensified techniques [12]. Yet, to the best of our knowledge, there is no report in literature on overcoming the Network Pinch in energy-integrated systems exploiting process operation changes.

Existing approaches and methods for revamping focus on modifying the exchanger networks. Most of these methods are mainly based on Pinch Analysis principles, Network Pinch, stream splitting or mathematical programming. Pinch Analysis-based methods identified promising modifications to the existing network to recover more energy. In spite of the fact that different methods and approaches have been established for retrofit purposes, more advancement is still needed to ensure thermodynamic feasibility and economic viability simultaneously at the same time [13].

Based on the early generation of graphical methods in Pinch Analysis [14,15], recently, there have been remarkable developments in process integration techniques [16–19] with diverse applications for the sake of energy saving and pollution reduction. Advanced modelling techniques allowed the detailed optimisation of complicated networks. Examples comprise in utility systems [20,21], separation systems [22], heat recovery systems [23,24], scheduling networks [25], heat transfer enhancement [26,27], and total site analysis [28–31]. The aim of these methods was to maximise energy recovery in tight heat-integrated systems [32] and reduce CO_2 emissions [33] through improved process integration strategies.

It is worth-mentioning that the Pinch Analysis has spread to other areas post the success of heat integration. Mass exchange in particular [34] and water pinch [35] as a special case of Mass Exchange Networks (MENs) raised with the target of minimising the consumption of fresh water and the disposal of wastewater through maximising the internal water reuse. Researchers developed methods and improved approaches for mass integration and synthesis of MENs [36] besides the waste water minimisation [37]. Combined mass and heat exchange networks have been also synthesised lately [38].

Applying process integration techniques appeared to be more preferable than the grass-roots design for oil refineries [39]. Other solutions including distillation design modifications and different retrofitting solutions were considered to enhance the distillation yield of petroleum fractionation and to improve the energy efficiency [40,41]. Additionally, short cut models were developed to account for the existing HEN details within the optimisation of existing refinery distillation units [42] with the objective of optimising existing units for energy saving and emission reduction. In the manner now being indicated, there is a continuous interest to find out ways to boost the energy efficiency of energy-integrated systems existing in chemical and petrochemical industries.

As introduced above, previous researches on improving energy efficiencies of existing refining distillations can thus be grouped into two fields. One field that considers the preheat train or HEN within revamping in an isolation from the background process, while the other looks at the process. When it comes to Network Pinch, literature yet does not report work on overcoming such a limitation using the background process. Given the complex nature of the background process together with the associated preheat train, graphical methodologies emerge as a valuable tool for visual-interaction. Such a feature would help in identifying the Network Pinch and pinched matches and then propose potential modifications excluding structural HEN modifications. In the light of this context, the recent graphical method of Gadalla [19] is opted for in the present work to develop a general strategy aiming at overcoming the heat recovery limitations of the Network Pinch with no structural modifications to the existing HEN. The strategy applies the aforementioned graphical method to locate the Network Pinch and identify the pinching exchanger matches that hinder further potential heat recovery. Process operation changes to overcome the Network Pinch are proposed; hence, more heat recovery beyond the maximum limitations is achieved. Distillation process is to be analysed in light of the graphical representation of the HEN and potential process changes are defined, for the first time, to overcome the Network Pinch in such tight systems. The new approach is also applied to increase and improve the energy recovery for an existing refinery plant of atmospheric and vacuum distillation unit associated with its exchanger network.

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