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Review

Systematic optimization methodology for heat exchanger network and simultaneous process design

Andreas Psaltis[a], Delphine Sinoquet[b], Alexandre Pagot[b,*]

[a] MTN Cyprus, 87 Kennedy Avenue, 1077, Nicosia, Cyprus
[b] IFP Energies nouvelles, Rond-point de l'échangeur de Solaize – BP 3, 69360 Solaize, Lyon, France

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ABSTRACT

Distillation units require huge amounts of energy for the separation of the multicomponent mixtures involved in refineries and petrochemical industries. The overall efficiency of the distillation column system is determined from the trade-offs of the Operating Expenditures (OPEX) and Capital investment cost (CAPEX), as there is a strong interaction between the distillation columns and the Heat Exchanger Network (HEN) of the interconnecting streams. In this paper, a systematic Mixed Integer Non-Linear Programming (MINLP) optimization methodology for process integration of distillation column complex is presented. The highly nonlinear rigorous models of the distillation column and phase change are being substituted with simple surrogate models that generate operating responses with adequate accuracy. The methodology is applied on two case studies of the aromatics separation PARAMAX complex. The results illustrate significant reductions on the Total Annualized Cost. With a scope limited to the benzene and toluene columns, the gain reaches about 15%.

Contents

1. Introduction

The continuous rising prices in energy and stringent environmental regulations have lead Chemical industries to invest towards energy efficient solutions. Particularly, for Separation industries such as Refineries and Petrochemical plants, which are among the

* Corresponding author.
E-mail address: alexandre.pagot@ifpen.fr (A. Pagot).

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Notation

Indices
k Stage

Sets
HP {i|i = Hot process streams}
CP {j|j = Cold process streams}
REB {j|j = Reboiler streams}
CON {i|i = Condenser streams}
COL {su|su = Distillation column}

Variables
T_i^S Supply temperature of hot stream
T_j^S Supply temperature of cold stream
$T_{i,k}^I$ Input temperature of hot stream at stage *k*
$T_{i,k}^O$ Output temperature of hot stream at stage *k*
$T_{j,k}^I$ Input temperature of cold stream at stage *k*
$T_{j,k}^O$ Output temperature of cold stream at stage *k*
T_i^{AI} Temperature of stream entering AirCooler
T_i^{AO} Temperature of stream exiting AirCooler
T_i^T Target temperature of hot stream
T_j^T Target temperature of cold stream
H_i^S Supply enthalpy of hot stream
H_j^S Supply enthalpy of cold stream
$H_{i,k}^I$ Input enthalpy of hot stream at stage *k*
$H_{i,k}^O$ Output enthalpy of hot stream at stage *k*
$H_{j,k}^I$ Input enthalpy of cold stream at stage *k*
$H_{j,k}^O$ Output enthalpy of cold stream at stage *k*
H_i^{AI} Enthalpy of stream entering AirCooler
H_i^{AO} Enthalpy of stream exiting AirCooler
H_i^T Target enthalpy of hot stream
H_j^T Target enthalpy of cold stream
$q_{i,j,k}$ Heat exchanger duty for process streams
q_j^H Heater duty
q_i^A AirCooler duty
q_j^{Cyl} Cylindrical heater duty
q_j^{Cab} Cabin heater duty
q_j^{HPS} High pressure steam duty
$\delta T_{i,j,k}^{HOCI}$ Hot output-cold input stream temperature difference
$\delta T_{i,j,k}^{HICO}$ Hot input-cold output stream temperature difference
$\delta T_{i,j,k}^{HOCO}$ Hot input-cold output stream temperature difference
$\delta T_{i,j,k}^{HICI}$ Hot input-cold input stream temperature difference
$\delta T_i^{HICI\_A}$ AirCooler input-ambient temperature difference

Binary variables
$Z_{i,j,k}$ Indicates if a heat exchanger exists between hot stream i and cold stream j at stage k
Z_i^A Indicates if an AirCooler exists for hot stream i
Z_j^H Indicates if a heater exists for cold stream j
Z_j^{Cyl} Indicates if a cylindrical heater exists for cold stream j
Z_j^{Cab} Indicates if a cabin heater exists for cold stream j
Z_j^{HPS} Indicates if high pressure steam is used for heating cold stream j

Matrices
L^H $n_i x n_{su}$ matrix
L^C $n_j x n_{su}$ matrix

most energy intensive, a major concern is to minimize the huge operational demands of the distillation columns which are by far the most preferred unit for separation. The low thermodynamic efficiency of the columns, stemming from the higher temperature profile of the reboiler compared to the condenser, has lead researches on improving the performance of HEN between the streams involved in the distillation column complex, by targeting the minimization of the external heat sources and the associated HEN equipment costs.

Over the last decades, several methodologies have been emerged for solving the HEN synthesis problem and can be classified as sequential or simultaneous approaches. The first approach decomposes the problem in a sequence of objectives. Initially the target is to identify the HEN with the minimum utilities demand. Once the energy requirements are met, the second objective is the reduction of capital cost by minimizing the number of Heat Exchangers. Finally, detailed calculations are performed in order to investigate further reductions on the Heat Exchanger Area cost. The Pinch analysis method, developed by Hohmann (Hohmann, 1971) then Linnhoff and co-workers (Linnhoff, 1979; Linnhoff and Hindmarsh, 1983), is among the most influential methodologies of this approach. The energy profile of the process streams is graphically represented on composite curves and according to the heuristic-based value of the minimum allowable temperature difference (ΔT_{min}) the pinch point determines the energy requirements from external sources.

The decomposition of objectives is also being addressed in mathematical programming formulations such as the transshipment methodology of Papoulias and Grossmann (1983) and Floudas et al. (1986). On the other hand, the simultaneous approach methodologies are characterized by the complex mathematical formulations employed for the optimization of the combined sub-objectives of CAPEX and OPEX within well-defined process restrictions. Moreover, potential heat exchange between process streams is examined in superstructures (Yee and Grossman, 1990; Ciric and Floudas, 1991) with the introduction of binary variables, which are used for the realization of existence or not of a heat exchanger. A review of the main literature for HEN synthesis is presented in Furman and Sahinidis (2002) and more recent approaches can be found in Klemeš and Kravanja (2013).

Heat integration methodologies demonstrate remarkable energy savings but are limited to the existing process conditions which are defined during Process design, performed in advance. Bounded by these conditions, the results of the sequential procedure are suboptimal compared to Process integration configuration, namely when process design and Heat integration are optimized simultaneously. Process integration takes into account the strong interaction between the process units and the HEN of their interconnection streams and the best scheme corresponds to the optimum trade-off compromise of the conflicting CAPEX and OPEX criteria. Despite the numerous Heat integration methodologies reported in literature, limited publications addressed the holistic optimization problem, mainly because the increased complexity of the problem provides little margins for heuristics and the mathematical formulations require significant computational