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Internal and external HIDiCs (heat-integrated distillation columns) optimization by genetic algorithm

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A B S T R A C T

HIDiC (Heat-Integrated Distillation Column) is an effective energy-saving configuration especially for the separation of close boiling point mixtures. In this work, the stochastic methodology has been applied for optimization of both internal and external HIDiCs. The use of GA (Genetic Algorithm) to find the optimal HIDiC configuration is presented while the fitness function is set to be the TAC (Total Annual Cost). HIDiC simulation has been performed based on the modified MESH equations using a rigorous thermodynamic model. Introducing a novel integer variable (the Layout number) leading to a more effective solution for the examined case study. This variable can generate systematically more energy efficient candidates for both internal and external HIDiCs. Benzene-toluene separation has been investigated by the proposed optimization procedure. The multivariable problem can be successfully optimized by GA while a good initial estimation is not essential. Based on the final results, up to 6.60% and 9.75% TAC reduction have been accomplished in external and internal HIDiCs optimization using the proposed method compared to the reported solutions in a previous work for the examined case study. However, VRC (Vapor Recompression Column) optimization at the end of presented work results 7.89% TAC reduction rather than optimal HIDiC.

1. Introduction

Distillation is the most popular separation process in chemical industries worldwide. Although over 95% of separation processes utilize distillation units, distillation is still one of the lowest energy-efficient processes (5–20%) [1]. Energy saving in this unit can decrease the required utilities for the trim-condenser and trim-reboiler to provide more profit. Release of greenhouse gases to the environment will also decrease through less energy consumption. These facts make a powerful motivation and priority for the researchers and governments alike to find a better energy-saving configuration for distillation columns.

There are many different heat integration techniques which have been proposed for distillation units. Kiss et al. and Jana have reviewed most of the candidates for heat integration of distillation columns [2,3]. Industrial applications of a number of them (i.e. Petlyuk distillation column or VRC (Vapor Recompression Column)) are growing rapidly. HIDiC (Heat-Integrated Distillation Column) is one of the modern and attractive heat pump-assisted columns for the heat integration of a single distillation column with promising future. Earlier, the merits of the HIDiC have been discussed by Mah et al. as the SRV (Secondary Reflux and Vaporization) [4]. Furthermore, Fitzmorris and Mah compared thermodynamic availability change, work loss, and thermodynamic efficiency of CDiC, VRC and SRV [5]. HIDiC takes advantage of the merits of both VRC and Diabatic distillation columns by making positive heat transfer driving force from the rectifying section to the stripping section. Removing heat on each tray of the rectifier leads to the provision of more internal reflux in this section eventually causing a decrease in external reflux ratio. Similarly, the external boil-up ratio of HIDiC is lower than CDiC due to the heat load added to the stripping section. Required driving force for the heat to be transferred from the rectifying to the stripping section is generated by a pressure raise in the rectifier. A compressor and a throttling valve can be used for pressure adjustment of connected streams of these two sections. A HIDiC flowsheet has been schematically provided in Fig. 1. Unlike the CDiC, distribution of trim-condenser and trim-reboiler heat duties between the trays in HIDiC makes less exergy loss. Ideal HIDiC exists if neither trim-reboiler nor trim-condenser is required under steady-state conditions. Otherwise, it is known as a Partial

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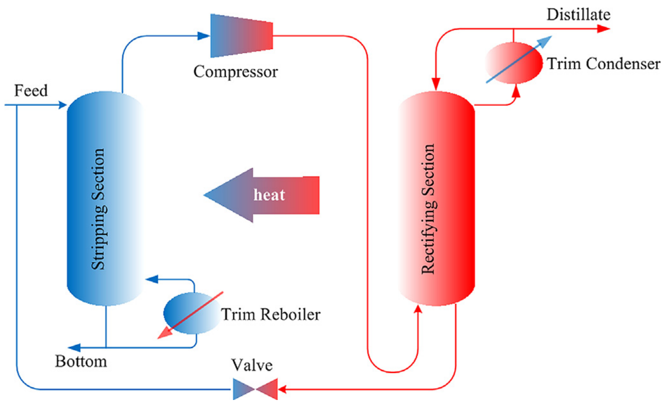

Fig. 1. An Schematic diagram of HIDiC flowsheet.

HIDiC. Nevertheless, external utility will be an essential auxiliary during start-up. It should be noted that in an ideal HIDiC the top product is saturated vapor and a trim-condenser (of a duty equal to the distillate flow rate multiplied its latent heat) will be needed if liquid distillate is necessary for the next unit.

Effect of feed composition on exergy loss of HIDiC and CDiC has studied by Nakaiwa et al. [6]. It has been then shown that partial HIDiC is more flexible for various situations (i.e. different feed flow rates and different product purities) compared to its ideal counterpart [7,8]. Many HIDiCs have been constructed in Japan and Netherland, but none of them is of industrial scale [9–14]. There are two good reviews over the HIDiC progress in the literature [15,16].

There are two major techniques for heat integration in trayed HIDiC: internally and externally. In internal HIDiC, the rectifying section will be inside the stripping. Heat panels prepare the desired heat transfer area which can be located in both sections [13,14]. Gadalla et al. have reported that heat integration in internal HIDiC is feasible if only there is a positive heat transfer driving force (thermodynamic feasibility) and desired heat panel area on each paired tray is available (hydraulic capacity) [17]. Since the number of variables is large, there must be an algorithmic procedure for achieving the most energy-efficient HIDiC. Uniform heat transfer area and uniform heat load distribution are two well-known scenarios for simulation of HIDiCs [18,19]. It should be noted here that there is no optimization during these scenarios and the procedure just comprises repetitive simulations. Unlike internal HIDiC, its external counterpart has two separate columns for the rectifying and stripping sections connected by heat exchangers outside [16,19–22]. External heat exchangers can supply more heat transfer area than internal ones, so it is possible to have a large amount of heat duty in a single stage thus reducing the number of paired stages drastically. It is also obvious that external coupling facilities assist the HIDiC construction. Economical analysis through various case studies has been done for comparison between the two heat integration scenarios. The lesser heat exchangers number in HIDiC, the more energy saving will be accomplished [16,19–22].

Most of the optimal design procedures for different separation missions lead to non-linear multivariable problems and have a non-convex objective function (i.e. thermodynamic or economical criterion) with many local optima [23,24]. Several optimization techniques have been developed to find the global optimum in the field of chemical engineering [25–30]. The deterministic and stochastic (random) methods are the main categories in global optimization. The first class of methods is based on gradient computation while implementation of stochastic methods includes random ingredients. Global optimization will be guaranteed by gradient-based techniques if the fitness function is differentiable and convex. However, this type of technique might require much more computational time (compared to stochastic methods) and reformulation of the problem through the optimization. Rigorous thermodynamic models and complex structures (e.g. Petlyuk distillation column), however harden the convergence of the larger and non-convex problems encountered. On the other hand, if the mixed integer variables (i.e. number of trays), binary (i.e. existence of a trim-reboiler, trim-condenser, or column) variables, or discontinuous formulations (i.e. cost estimation functions) are also included in the search space, solving procedure will be that much more difficult. Good initial guess for optimizing variables near the optimum solution, which is not always easy to find, is a common way to compensate the aforementioned severities.

GA (Genetic Algorithm), proposed by Holland, is one of the most popular methods for complex system optimization problems [27]. The GA has many features that make this algorithm the most favorite one among the stochastic optimization techniques: (i) there is no need for explicit mathematical model or its derivatives, (ii) generally, the final result is independent of the initial guess, (iii) GA is able to provide multi-objective optimization, and (iv) it can be used in parallel processing to search multi-dimensional solution with a large search space.

There are researches about rigorous optimization of HIDiC which show that the number of variables and constraints is more than CDiC or VRC. Owing to the non-linearity of the TAC (Total Annual Cost) as the objective function of optimization and being a multivariable problem including integer, binary, and continuous variables, HIDiC problem is a complicated MINLP (Mixed Integer Non-Linear Programming) problem. In a Propane–Propylene separation case study, Schmal et al. optimized an internal HIDiC both in the terms of operation and economy, followed by a comparison of the result with an existing VRC [8]. In his investigation, since the number of variables is large, it has been assumed that heat-integrated trays are variables between 1 to 10 and 50 to 57 of the stripping section, while for tray numbers of 11–20 a linear function has been considered and heat loads at the remaining stages (21–49) have been assumed constant. Suphanit later on used continuous variables of heat loads in each paired tray as well as the rectifying pressure [20]. In his work, optimal configurations of both internal and external HIDiCs have been defined when PP splitter is the optimization case study leading to the introduction of Linde double columns with side rectifier. Finally, Harwadt and Marquardt introduced an excellent model for HIDiC considering more complex configurations with more heat integration possibilities taking advantage of reformulations to work only with continuous variables [22]. These simplifying assumptions in three aforementioned works lead to dealing with NLP (Non-Linear Programming) instead of MINLP problems. Because of the large search space with many local optima, usually using derivative optimization methods for optimization of NLP leads to being trapped in local optima unless a very good initial guess, which is not always available, is used. This makes the assessment of stochastic methods, such as genetic algorithm, a necessity to reach a better solution.

In this work, some improvements have been achieved on the optimum solution on HIDiC configurations. A new integer variable called Layout number has been introduced. Using the Layout number will eventuate the analysis of more heat integration opportunities for HIDiC. In addition, pressure ratio, heat load on each tray, binary variables to account existence of heat integration on the trays, as well as the Layout number contribute to a multivariable MINLP optimization problem. GA is then employed for optimization of both internal and external HIDiCs. The optimization objective function is considered to be TAC. Furthermore, the effects of trim-reboiler duty of partial HIDiC have also been studied.