Energy 74 (2014) 662–674

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Feasibility study of heat-integrated distillation columns using rigorous optimization

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ARTICLE INFO

Article history:
Received 19 January 2014
Received in revised form
2 July 2014
Accepted 9 July 2014
Available online 30 July 2014

Keywords:
Genetic algorithm
Heat exchangers arrangement
Heat-integrated distillation column
Optimization
Vapor recompression column

ABSTRACT

In this work, rigorous optimization of HIDiC (Heat-Integrated Distillation Column) and VRC (Vapor Recompression Column) is implemented by GA (Genetic Algorithm) to find an alternative for CDiC (Conventional Distillation Column). The objective function is TAC (Total Annual Cost). Three different case studies are investigated, being composed of benzene-toluene, propane-propylene, and methanol-water. A novel strategy is proposed to consider all the heat integration possibilities resulting in more efficient search space than our previous attempt. It is observed that the heat exchangers arrangement of optimum HIDiCs are very similar to VRCs in ideal case studies. Although CDiC is the optimum configuration in the benzene-toluene separation, 6.6% reduction is achieved for the presented HIDiC compared to previous work. For propane-propylene splitter, VRC is the economical alternative with a 44.1% decrease in the TAC of CDiC. Moreover, VRC and HIDiC optimizations leads to 25.5% and 4.4% reductions in TAC compared to previous work, respectively. However, for the non-ideal methanol-water separation, which has a wide boiling point range, the TAC of optimum HIDiC is surprisingly lower than CDiC and optimum VRC by 3.4% and 31.2%, respectively.

1. Introduction

Distillation is the most widely used separation process in chemical industries. In an industrial plant, the distillation process consumes 40–70% of operating costs and capital investment [1]. Low efficiency of CDiCs (Conventional Distillation Columns) and the global warming have urged companies and governments to find an alternative technology which demands less energy. Since elimination of distillation process from industries is impossible in our modern and competitive world, researchers have focused on finding new effective technologies in the view of thermodynamic and economic. To do so, many heat-integrated configurations have been introduced since 1950s as alternatives. A number of these configurations like VRC (Vapor Recompression Column), DWC (Divided-Wall Column), and petlyuk column have been successfully commercialized and their industrial applications are growing constantly [2].

One of the latest configurations in this field is HIDiC (Heat-Integrated Distillation Column) which is a combination of VRC and diabatic distillation columns. Initially, Mah et al. presented HIDiC as SRV (Secondary Reflux and Vaporization) and specifications of an appropriate distillation process in which HIDiC can outperform CDiC [3]. It was also reported that HIDiCs have less entropy production compared to CDiCs [4]. Ever since, many experimental, simulation, and optimization studies have been conducted on HIDiCs and they have been compared with VRCs and CDiCs. There are comprehensive reviews by Nakaiwa et al. [5], Jana [2], Shenvi et al. [6], and Kiss et al. [7].

Simplified schematic diagrams of VRC and HIDiC are shown in Fig. 1. By compressing the overhead vapor of column, this stream is able to be the heating source of the heat-integrated reboiler/condenser in VRCs (see Fig. 1(A)). There is a rise in temperature profile across distillation columns from the top to the bottom; therefore, the compressor pressure ratio must be high enough for the desired direction of heat transfer. Available latent heat of the high-pressure stream is usually more than required duty in the heat-integrated heat exchanger. Utilizing cooling water, this additional heat can be absorbed in order to entirely condensate the high-pressure stream.

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http://dx.doi.org/10.1016/j.energy.2014.07.032
0360-5442/

Nomenclature

CDiC	conventional distillation column
CoD	compressor duty (kW)
DWC	divided-wall column
GA	genetic algorithm
HIDiC	heat-integrated distillation column
LMTD	logarithmic mean temperature difference (°C)
MILP	mixed integer linear programming
MINLP	mixed integer non-linear programming
n	last tray of distillation column
N	number of trays
NLP	non-linear programming
NRTL	non-random two-liquid
P	pressure (kPa)
PCD	product condenser duty (kW)
Q	heat duty (kW)
r	number of trays in the rectifying section
RCD	reflux condenser duty (kW)
ReD	reboiler duty (kW)
s	number of trays in the stripping section
SQP	sequential quadratic programming
SRK	soave-redlich-kwong
SRV	secondary reflux and vaporization
T	temperature (°C)
TAC	total annual cost (\$ yr^{-1})
VRC	vapor recompression column

Greek letter

α	number of heat-integrated heat exchangers (integer variable)
β	heat exchangers arrangement matrix
γ	heat exchangers heat load distribution matrix

Subscripts

i	tray counter
j	coupled heat exchanger counter
r	the rectifying section
s	the stripping section
T	Total

On the other hand, by dividing a distillation column into its rectifier and stripper sections and increasing the rectifier operating pressure, transferring heat from the rectifier to the stripper will be feasible (see Fig. 1(B)). As a result, the whole column sections can be applied to heat integration, and there will be also more options for installation of heat-integrated heat exchangers. Furthermore, lower pressure ratio is required to run HIDiCs compared to VRCs, for the same case study due to having more suitable position for the compressor. Under these conditions, HIDiCs are expected to be the most efficient candidate. It should be noted that recycling of the high-pressure stream to the low-pressure column is possible only by passing it through a throttling valve in both VRCs and HIDiCs. It is possible that the heat integration leads to complete elimination of condenser and reboiler in steady-state condition referred to as ideal HIDiC [8,9]. If heat integration leads to elimination of only one or none of them, the structure would be called partial HIDiC [8,9].

Some Researchers have focused on the internal heat integration of trayed HIDiC in their experiments and simulation studies [9–13]. Gadalla used thermo-hydraulic analysis for internal HIDiC simulation for the first time [14,15]. In the thermodynamic analysis part of his study, temperature profiles of the rectifying and stripping sections were checked to have enough heat transfer driving force in each heat panel. In the hydraulic analysis part of his study, physical limitations of each heat-integrated tray were checked, consisting of their dimensions and maximum available heat transfer area in each tray and each section. Heat panels will be then installed in either the rectifier or the stripper depending on space availability. It was also reported that it is preferred to limit the heat integration to trays with higher temperature differences [14]. On the other hand, some researchers have focused on the internal heat integration of packed HIDiC in their experiments [16–19], while they have considered trayed HIDiCs in their simulation studies [8,20]. Their efforts have been led to a pilot plant HIDiC with a 27 m height and 1.4 m diameter column [18].

It has been recently shown that construction of external HIDiCs is much easier and they are comparatively more energy efficient than their internal counterparts [6,21–24]. External HIDiCs do not require expensive heat panels with physical limitations, and there

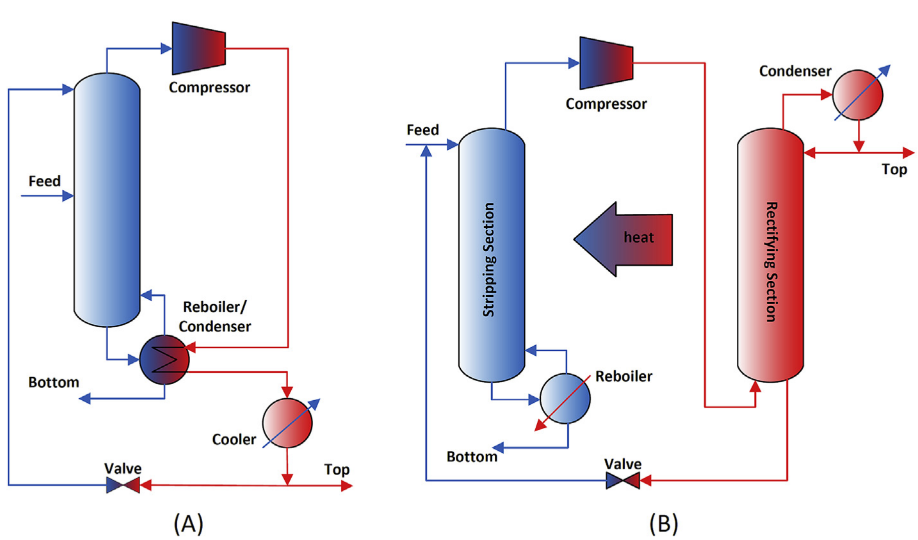

Fig. 1. Schematic diagram of a VRC (A) and a HIDiC (B).