Chemical Engineering and Processing xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Chemical Engineering and Processing: Process Intensification

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

# Selecting suitable energy-saving distillation schemes: Making quick decisions

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ARTICLE INFO

*Article history:*
Received 28 April 2016
Accepted 23 May 2016
Available online xxx

*Keywords:*
Heat pump assisted distillation
Multi-effect distillation
Double-effect distillation
Shortcut method
Energy saving performance
Simulation

ABSTRACT

More and more frequently, chemical engineers need to make quick decisions when selecting suitable energy-saving distillation schemes, for example, choosing between double effect and heat pump. Having endured this situation for years, the authors try to introduce, in this paper, shortcut methods to help choose between heat pump-assisted distillation and multi-effect distillation by evaluating energy efficiency in comparison with a conventional distillation column without any heat integration. To verify the accuracy of the shortcut methods, five binary systems with different relative volatilities, namely, methyltrichlorosilane-dimethyldichlorosilane, 2-methylbutane-*n*-pentane, benzene-toluene, methanol-water and cyclohexane-cyclohexanol, are studied using the shortcut methods with the aid of rigorous simulations. The energy efficiency results are presented in terms of standard oil versus atmospheric relative volatilities for both double-effect distillation and mechanical vapor recompression assisted distillation. Systems with lower relative volatilities perform best with the heat pump option, while systems with higher relative volatilities perform better with heat integration. The aim of the shortcut methods—to simplify and speed up the decision using only easily accessible data such as relative volatility and utility prices—is achieved.



**Nomenclature**

Acronyms

| | |
|---|---|
| CDiC | Conventional distillation column |
| COP | Coefficient of performance |
| DWC | Divided-wall column |
| FS | Feed splitting |
| HIDiC | Heat integrated distillation column |
| HPAD | Heat pump assisted distillation |
| HPC | High-pressure column |
| LPC | Low-pressure column |
| LSF | Light split forward |
| LSR | Light split reverse |
| MED | Multi-effect distillation |
| MVR | Mechanical vapor recompression |
| ORC | Organic Rankine cycle |
| VC | Vapor compression |

Roman letters

| | |
|---|---|
| $a$ | Antoine parameter |
| $B$ | Bottom product molar flow rate |
| $b$ | Antoine parameter |
| $c$ | Antoine parameter |
| $D$ | Top product molar flow rate |
| $E$ | Corrected energy consumption based on standard oil |
| $F$ | Feed molar flow rate |
| $H$ | Enthalpy |
| $N$ | Number of effect |
| $N^*$ | Set of positive integers |
| $p$ | Pressure |
| $Q$ | Heat duty |
| $q$ | Thermal condition of feed |
| $R$ | Reflux ratio |
| $T$ | Temperature |
| $W$ | Compression work |

Greek letters

| | |
|---|---|
| $\alpha$ | Relative volatilities of mixtures |
| $\beta$ | Economic correction factor for compression work |
| $\omega$ | Energy saving rate |

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http://dx.doi.org/10.1016/j.cep.2016.05.009

$\lambda$ The ratio of real reflux ratio over minimum reflux ratio
$\eta$ Energy margin coefficient
$\theta$ Common root of underwood equation
$\delta$ Iteration factor
$\varepsilon$ Economic correction factor of energy quality

## 1. Introduction

Despite accounting for an estimated 3% of world's energy consumption and more than 50% of plant operating costs, distillation remains one of the most important thermal separation techniques in the chemical process industry [1–3]. The major drawback of a conventional distillation column (CDiC) is its low thermodynamic efficiency, requiring high-quality energy in the reboiler while rejecting a similar amount of low-grade heat in the condenser [4]. To improve its energy efficiency, numerous heat-integrated distillation processes have been suggested [5], including heat pump-assisted distillation (HPAD) [1,6], the internally heat-integrated distillation column (HIDiC) [7], the divided-wall column (DWC) [8,9] and multi-effect distillation (MED) [10–18], which attempt to lower thermodynamic irreversibility by means of a compressor, intermediate heat exchanger, heat transfer through a dividing wall and extra distillation column, respectively.

HPAD is a state-of-the-art industrial technology for higher energy efficiency in CDiCs. It utilizes a heat pump to upgrade low-grade vapor heat discharged from the top of a CDiC to drive the boilers, thus reducing the consumption of hot utilities at the cost of a smaller amount of electrical power of higher quality. HPAD is usually estimated, under certain conditions, to provide energy savings of approximately 20–50% [19]. However, this choice usually calls for an expensive compressor that requires considerable procurement capital, installation and maintenance investments. As a result, the energy savings are not always welcomed by the industrial community because they do not always result in overall economic savings [1].

HIDiC (Fig. 1) is developed by effectively integrating the heat pump principle into a CDiC. In contrast to HPAD, HIDiC involves heat integration between the whole rectifying and stripping sections and therefore has a high potential for energy savings [7]. Although bench-scale experiments and rigorous simulations have confirmed that HIDiC is much more energy efficient than a CDiC, the separation of multicomponent mixtures and the control strategy remain challenges for its commercialization [7,20–22]. As a result, reported industrial applications of HIDiC are few, and relevant engineering experience is still in demand.

A DWC (Fig. 1) is thermodynamically equivalent to a Petlyuk column. By introducing a vertical wall in a distillation column to partition the prefractionator and the main column in a variation of the Petlyuk column [23], a DWC can separate a ternary mixture into pure products with only one distillation column, one condenser and one reboiler, hence reducing the number of units and lowering capital expenditures by approximately 30% [24]. For a crude feed containing four or more components, a DWC can achieve separation with multiple vertical walls [25]. It is predicted that a DWC, by effectively avoiding remixing effects as completely as a Petlyuk column [26], could provide energy savings of approximately 20–50% compared with a CDiC. However, due to numerous difficult controllability problems, some of the expected savings in capital and operational expenditures have to be forgone for stable operation and increased safety margins [24]. Consequently, the DWC still requires a more elaborate, reliable and inexpensive automatic control scheme before it can finally be implemented in the chemical process industry [27].

MED utilizes multiple columns instead of a single column to improve energy efficiency. Its basic concept is to use the overhead vapor from the high-pressure column (HPC) to drive the subsequent bottom of the low-pressure column (LPC), combining the condenser of the former with the reboiler of the latter, eliminating a heat exchanger as well as the corresponding utilities. Because MED does not require extra rotating machinery that consumes electrical power, it has become the preference of the majority of researchers [28]. For a CDiC, the heat duties associated with condensation and reboiling are approximately identical. Therefore, the total heat duty of MED can be calculated as the heat load of a CDiC with the same total feedstock and separation targets divided by the number of effects $N$, leading to a simple assessment:

$$Q_{MED} = Q_{CDiC}/N \tag{1}$$

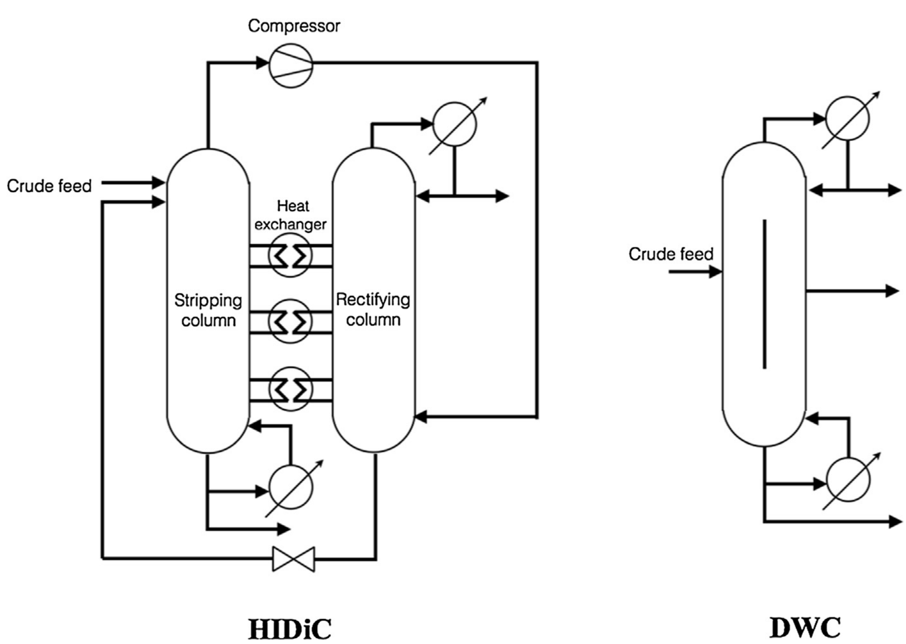


**Fig. 1.** A schematic representation of the internally heat-integrated distillation column and dividing wall column.

Please cite this article in press as: C. Cui, et al., Selecting suitable energy-saving distillation schemes: Making quick decisions, Chem. Eng. Process. (2016), http://dx.doi.org/10.1016/j.cep.2016.05.009