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Mastering Heat Pumps Selection for Energy Efficient Distillation

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A practical selection scheme of energy efficient distillation technologies is proposed, with a special focus on heat pumps. The most promising technologies selected are: vapour compression, mechanical or thermal vapour recompression, absorption, compression-resorption and thermo-acoustic heat pumps, heat integrated distillation column, cyclic distillation, Kaibel and dividing-wall column. The scheme considers the type of separation tasks, the product flow and purity specifications, the boiling point differences (ΔT_b), the reboiler duty (Q_{reb}) and its temperature level (T_{reb}) as the main technology selection criteria. The proposed scheme allows considerable savings in time and resources allocated for the selection of eco-efficient chemical processes.

1. Introduction

Several technologies are available to reduce the energy requirements of distillation. Heat pumps (HP) systems can be used to upgrade the low quality energy in the condenser to drive the reboiler of the column. Vapor compression (VC), thermal and mechanical vapor recompression (TVR and MVR), upgrade the heat by compressing vapor or a working fluid (Annakou and Mizsey, 1995; Fonyo and Benko, 1998; Mc Mullan, 2003). Compression-resorption (CRHP) and absorption (AHP) heat pumps increase efficiency by means of absorption equilibrium (Mučić, 1989). Thermo-acoustic heat pump (TAHP) has a broader applicability range (Bruinsma and Spoelstra, 2010), while the heat integrated distillation column (HIDiC) enhances both heat and mass transfer for a better performance (Bruinsma et al., 2011). Cyclic distillation (CyDist) technology reduces energy demand by enhancing tray separation efficiency through pseudo-steady-state operation in separate phase movement (SPM) (Gaska and Cannon, 1961). Dividing-wall column (DWC) and Kaibel distillation columns allow energy savings by avoiding the re-mixing effects in multi-product distillation (Yildirim et al., 2011). Any of these technologies can offer energy savings of 20-50 %, but only when certain conditions are met.
This article is based on an extensive literature survey to allow the selection of the most promising energy efficient distillation technologies. Only the key aspects for the overall efficiency were analyzed: boiling points differences (ΔT_b), or the temperature lift (ΔT_{lift}) to upgrade heat from the source if accounting the driving force ($\Delta T_{lift}=\Delta T_b+20$); nature of the components involved; operating pressures; product distribution and purities; reboiler temperatures (T_{reb}) and duties (Q_{reb}); besides the relative volatility between two components (α_{i-j}) . Efficiency indicators include total annual costs (*TAC*), total operating costs (*TOC*) and the (ideal) coefficient of performance (*COP*) for heat pumps. COP is defined as the ratio between the amount of heat upgraded (Q_b) and the heat pump energy requirements (W): $COP = (Q_b /W) = (T_{reb} /\Delta T_b)$ (Bruinsma and Spoelstra, 2010).

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2. Problem statement

Every energy efficient technology has benefits but only at given specific conditions. Most of these systems are applied in different separation tasks, thus complicating the comparison and selection of these options. Currently this task is assigned to dedicated experts, consuming valuable time and resources. To solve this problem, this study proposes a novel scheme for the selection of energy efficient distillation technologies. The result is a simple technology evaluation scheme that allows the quick selection of the most suitable system to enhance the energy efficiency of any distillation task.

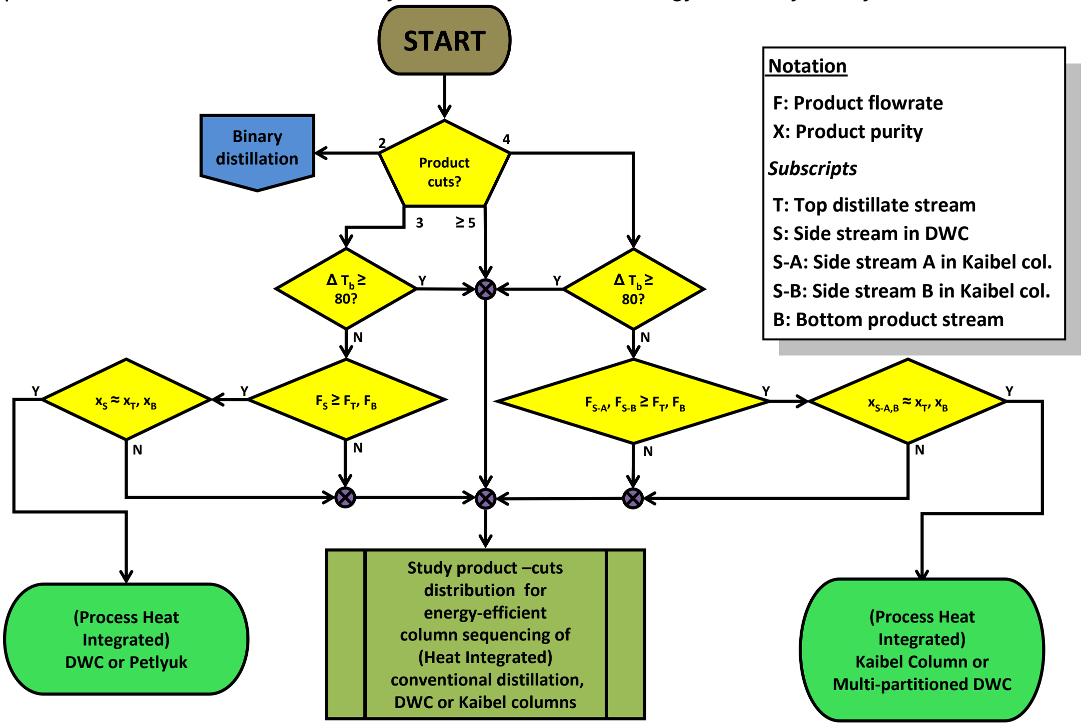


Figure 1. Main selection scheme of energy efficient distillation technologies

3. Results and discussion

Error! Reference source not found. lists the major energy efficient distillation technologies considered in this study, most of them being applied already at industrial scale. Figure 1 illustrates the selection scheme, in which the systems are classified according to the type of separation tasks performed. Before starting the selection, one must ensure that distillation can in fact perform the separation task with greater efficiency (Linnhoff et al., 1983). This selection scheme only intends to present design guidelines towards a sustainable process. Heat integration possibilities within the process, plant or with another distillation column could be also considered (Linnhoff et al., 1983). The selection scheme aims to narrow down the number of alternatives at early design stages. For the main scheme illustrated in Figure 1, the selection criteria include: number of components (or product cuts) to be separated, their boiling points, their flow rates and their purity requirements. First of all, the number of components is reviewed to select the most efficient technology in each case. Then, the temperature span for DWC and Kaibel column is checked. As those columns operate at a single pressure, a reasonable ΔT_b ensures their operability with common utilities. Moreover, the energy savings of the DWC and Kaibel columns are higher at demanding side-stream flow rates and purities, besides equal feed separation between top and bottom parts of the column. Thus, DWC and Kaibel columns are the recommended options for multi-components separations when these favorable conditions are met.

Table 1. Description and performance of energy efficient distillation technologies

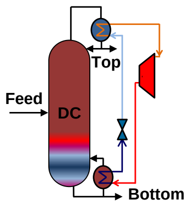
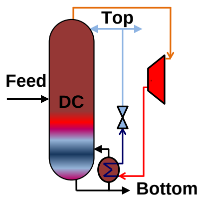
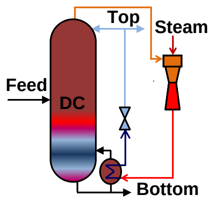
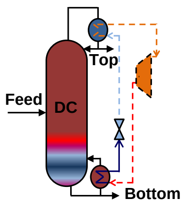
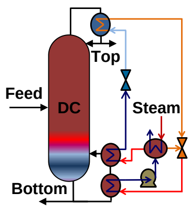
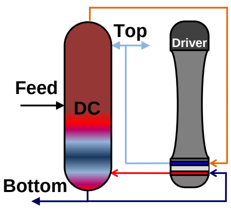
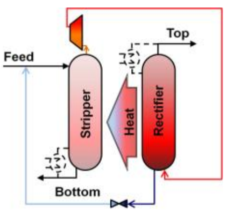
Type	Technology	Remarks on design and performance
Binary		**Vapor Compression HP (VC):** Classic reference system, widely implemented industrially. + Minor column modifications required (Mc Mullan 2003). – Low efficiency. Limited by working fluids (Wallin et al., 1990). Reported results: Methanol-water separation with R114 working fluid yields 3≤*COP*≤4 at 50 °C≤ ΔT_{lift}≤64 °C (Oliveira et al., 2002). Benzene-toluene separation, *COP*≤5 at ΔT_{reb}=30 °C. (Feng et al., 1997; Fonyo et al., 1998; Omideyi et al., 1985; van de Bor and Infante Ferreira, 2011).
Binary		**Mechanical Vapor Recompression HP (MVR):** State-of-the art well implemented industrial system. + Compared with VC, MVR saves one heat exchanger (Wang et al, 2011). – Only slightly higher efficiency than VC (Annakou and Mizsey, 1995). Reported results: For propane-propylene separation (ΔT_{lift}=30 °C) it gives COP~6 and 37 % *TAC* savings (Olujić et al., 2006). For butane-isobutane separation (ΔT_{lift}=35 °C) it yields *COP*~6.4 and 39 % TOC savings (Campbell et al., 2008; van de Bor and Infante Ferreira, 2011).
Binary		**Thermal Vapor Recompression HP (TVR):** Widely implemented only for low heat loads (≤ 2 MW) and aqueous systems (Mc Mullan, 2003). + No rotating parts. Low capital expenditure and maintenance costs. – Ejector design is crucial: very sensitive system (Perry and Green, 1997). Reported applications: Evaporators, steam-stripping, peroxide distillation and other aqueous separations. Usual *COP* is about 1.1 (Feng and Berntsson, 1997; Fonyo and Benko, 1998).
Binary		**Compressor–Resorption Heat Pump (CRHP):** Pilot plants implementation of standalone CRHP (Nordtvedt, 2005; Spoelstra, 2011). + Zeotropic mixtures as working fluid (NH3-H2O) (Zamfirescu et al., 2004). – Wet compression issues: 2-phase flow in dotted lines sections. Reported results: 1000 kW Pilot plant with ΔT_{lift}=30°C to 115°C gets *COP* ~9 (Mučić, 1989). Benzene-toluene diabatic distillation with integrated CRHP results in *COP* ~8. (van de Bor and Infante Ferreira, 2011).
Binary		**Absorption Heat Pump (AHP):** Implementation of standalone pilot plant AHP (Feng and Berntsson, 1997). + Absorption pairs only require pumps: T_{reb} up to 150 °C using LiBr-H2O. – AHP requires 4 heat exchangers, making it expensive for low ΔT_b. Reported results: Modelled i-butane n-butane distillation coupled with AHP yields 30 % higher *TOC* with ΔT_{lift}=11.5 °C. AHP for a depropanizer: *COP* ~1.75 with ΔT_{lift}~55 °C.(van de Bor and Infante Ferreira, 2011).
Binary		**Thermo-Acoustic Heat Pump (TAHP):** Implemented as proof of principle. Scaling up is currently in research (Bruinsma and Spoelstra, 2010). + Wider range of application by using noble gas as heat transfer media. – Slightly lower efficiency than CRHP (Spoelstra and Tijani, 2005) Reported results: A 5 kW burner driven TAHP with argon yields a ΔT_{lift}=60 °C to 100 °C with 200 W acoustic power. Benzene-toluene distillation modelled with electrical TAHP yields *COP* ~4 (Spoelstra, 2011).
Binary		**Heat Integrated Distillation Column (HIDiC):** Implemented pre-commercially (Feed ~15 ktpy) (Nakaiwa et al., 2003; Matsuda et al., 2010). It features enhanced COP but it has complex design. Reported results: Modelled propane-propylene separation: COP~10, 25 % TAC savings against MVR with ΔTlift=6.5 °C (Olujić et al., 2006). Modelled benzene-toluene separation and acetic acid dehydration: ~40 % and ~60 % energy savings, respectively (Bruinsma et al., 2011; Campbell et al, 2008).

Table 1. Description and performance of energy efficient distillation technologies (Continued)

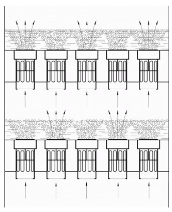
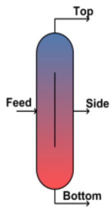
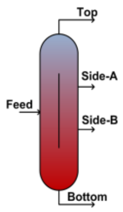
Type	Technology	Remarks on design and performance
Binary		**Cyclic distillation (CyDist):** Implemented in ethanol purification (~20 m^3/day) (Maleta et al., 2011). Enhanced separation efficiency in pseudo-steady-state. Reported results: 0.9 m^3/day of ethanol are recovered with only 50 kW. Bench scale methanol-water cyclic distillation requires 20 % to 50 % less vapor flow (Matsubara et al., 1985). Acetic acid cyclic dehydration: up to 32% energy savings. (Gaska and Cannon, 1961).
Ternary		**Dividing-Wall Column (DWC):** State-of-the-art for distillation of ternary mixtures (Yildirim et al., 2011). + Applicable to extractive, azeotropic and RD (Kiss and Suszwalak 2011) – Limited application range, just one operating pressure Reported results: Revamp of a xylene recovery distillation column reduces *TAC* in 40 %. Aromatics extraction using DWC yield 36 % energy savings. Retrieval of C11-C13 cut from crude kerosene with DWC gives 30 % *TOC* savings (Dejanovic et al., 2011, Dejanovic et al., 2010).
Multi-component		**Kaibel Distillation Column:** Scarce implemented (Dejanovic et al., 2010). + Four products in only one unit giving low Capital expenditure (*CapEx*). – It operates at a single pressure, giving a large temperature span. Reported results: Modelled distillation of lights, benzene, toluene and heavies yields 42 % energy savings. Modelled distillation of benzene, toluene, xylene and heavies yields 17 % lower TOC and CO_2 emissions. (Halvorsen et al., 2010; Yildirim et al., 2011).

Figure 2 provides more details on the binary distillation choices. The following selection criteria are considered here: column operating pressure, nature of the components with respect to corrosiveness and fouling, boiling point differences (ΔT_b), temperature lift (ΔT_{lift}), reboiler duty (Q_{reb}) and temperature (T_{reb}). The efficiency of the selected technologies greatly depends on the ΔT_b between light key and heavy key components. At lower ΔT_b, the efficiency is higher. Thus, a larger number of options is available at lower ΔT_b. TVR is an interesting option to consider if the reboiler duty is low enough and other conditions are met. When the substances to be separated are corrosive or fouling, it is economically wise to avoid contact of these substances with rotating equipment. Thus, heat pump designs that use working fluids/pairs as heat transfer media are preferred. Therefore, it is required to evaluate the reboiler temperature to select the most efficient option. On the contrary, if the substances to be separated do not threaten the equipment, an important parameter to verify is the operating pressure. Some technologies are very efficient options, but they use a compressor for heat upgrading or cause high pressure drops. Consequently, MVR, HIDiC and CyDist are preferable at high pressures. For medium boiling point differences (ΔTb), the choices are limited to three options: CRHP, TAHP and CyDist – giving that some particular conditions are also met. Most of the distillation processes presented in industry fall in this range of differences in boiling points. Therefore, these technologies might accumulate increased know how in the future by its possible massive implementation.
Finally, the separations with higher boiling point differences (ΔTb) require efficient technologies, as the work input is significantly higher. The preferred options are Multi-stage VC, CRHP, TAHP and AHP. CyDist and CRHP are interesting options for higher pressures and relatively close boiling components. Extractive or Azeotrpic distillation, preferably with DWC, is preferred for energy demanding separations (Kiss and Suszwalak 2011). The investment and operating costs of introducing a mass separating agent might offset the huge energy requirements of conventional distillation.

4. Conclusions

This study presents a novel selection scheme for energy efficient distillation to provide guidelines in the design of energy efficient separation processes. Using the scheme, process designers can effectively narrow down the number of technology alternatives that can deliver significant energy savings considering the particular process conditions. The selection scheme features several key issues for the conditions required to successfully apply each technology:

- VC, MVR and TVR usually allow higher savings for low T_{reb} and ΔT_{lift}.
- TAHP and CRHP enhance heat pump applicability range from low to middle ΔT_{lift}.
- Technologies as HIDiC and cyclic distillation are applicable only at higher pressures, mainly for non corrosive compounds, low ΔT_{lift} and $\alpha_{i\text{-}j}$.
- For multi-component distillation, DWC and Kaibel distillation columns are the preferred option for ΔT_b lower than 80 °C and demanding side stream requirements.

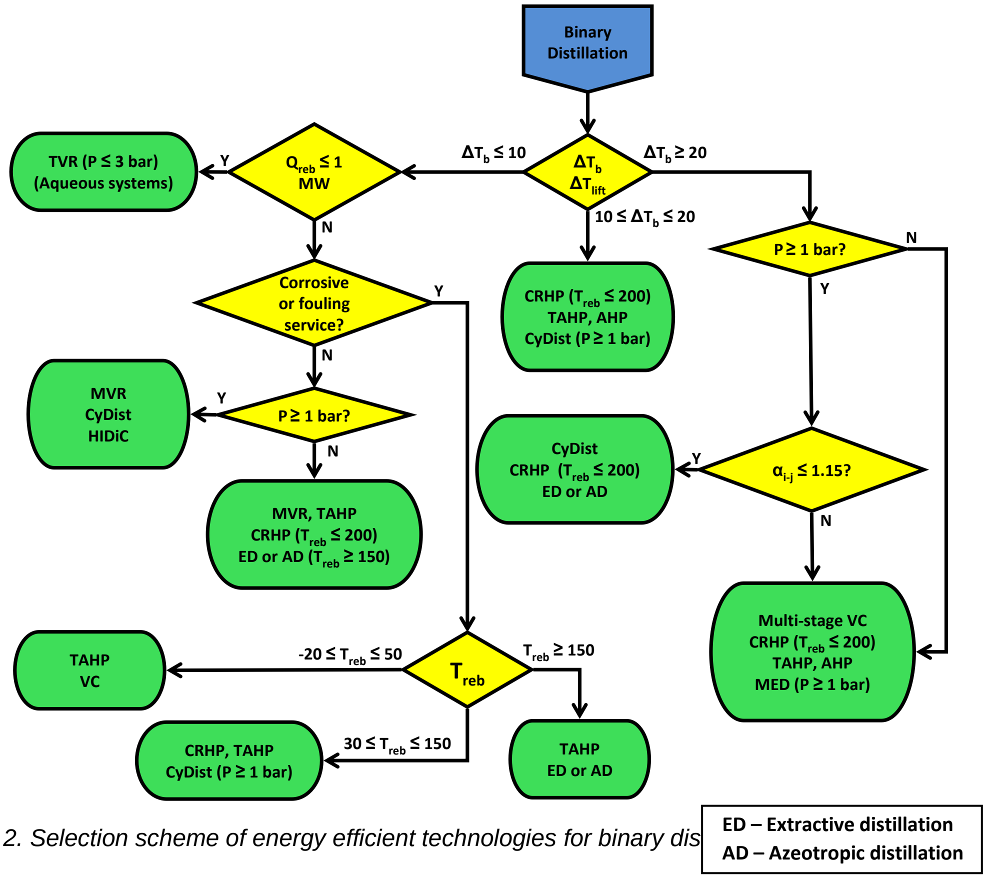


Figure 2. Selection scheme of energy efficient technologies for binary dis

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