Separation and Purification Technology 209 (2019) 18–25

Contents lists available at ScienceDirect

Separation and Purification Technology

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

# Performance analysis of a heat integrated column with heat pumping

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ARTICLE INFO

*Keywords:*
Dividing wall column
Vapor recompression
Ternary separation
Energy savings
Economics

ABSTRACT

In this work, a heat pump system in the form of vapor recompression (VRC) is introduced in the dividing wall column (DWC) to further improve its thermal efficiency performance. It is a fact that the temperature difference is reasonably large between the top and bottom of a DWC, which typically produces at least a single side product. This may lead to a very large compression ratio (CR), with which, the operation of VRC in the DWC becomes quite complicated and may not be economically so attractive. To improve this situation, the vapor recompression mechanism is further proposed between the side stream and reboiler drum of the DWC column. Utilizing the latent heat of a vapor stream from an intermediate tray in liquid reboiling of the stripper, this side vapor recompressed DWC (SVR-DWC) configuration can reduce the utility consumption and thus improves its energetic and economic potential substantially. This proposed thermally integrated scheme is finally illustrated by a ternary system.

## 1. Introduction

As climate changes and resource crisis have emerged as global threats, the capability to deal with environment and energy issues is indeed an important index in determining the future of the national economy [1]. There are a handful of policies framed at the national and international levels targeting to decrease the emissions of greenhouse gases, reduce the dependency on fossil fuels and mitigate the climate change. In this light, the European Union (EU) has set the goals through the 20-20-20 targets in 2007 with a reduction in greenhouse gas emissions of at least 20% below 1990 levels, a consumption of 20% out of renewable energy sources and an increase in energy efficiency by 20% within 2020 [2]. This work is concerned with the thermal integration that is typically used for improving the energy efficiency. Here, a century old chemical unit, namely distillation column, is selected as a potential candidate that shows a maximum thermodynamic efficiency of 20% [3].

Presently, more than 80% of the global energy demand is met by fossil fuels [4]. In the United States, distillation alone accounts for an about 10% of the total industrial energy consumption. Keeping its large energy demand and low thermal efficiency, several heat integration techniques have been scrutinized seeking lower utility consumption and better profitability. The most popular schemes include the vapor recompression (VRC) [5] heat pump system and the dividing wall column (DWC) [6]. It is observed that [7] the former configuration performs well for the separation of close-boiling mixtures because of the requirement of a low compression ratio (CR) in VRC operation.

As far as DWC is concerned, it has been known for several decades since the first patent filed in 1949 [8]. Then Petlyuk et al. [9] have developed a fully thermally coupled distillation column (FTCDC) that consists of a prefractionator and a main column, which is popularly known as Petlyuk column. Actually, the DWC column follows the concept of FTCDC by accommodating both the prefractionator and the main tower in a single shell [10]. It should be noted that the first industrial application of DWC was established by BASF in 1985 [11]. Currently, more than 100 DWC units are being used in industry [11].

Compared to a conventional system with direct or indirect sequence of distillation columns, the DWC scheme can achieve up to 30% savings in capital as well as operating cost [12,13]. Interestingly, this configuration requires a single reboiler and a condenser, whereas for example, a conventional two column system (CTCS) used in separating a ternary mixture requires two reboilers and two condensers. Reducing utility consumption as well as number of equipment (i.e., heat exchangers) leads to lower the capital and operating cost of DWC.

This apart, the DWC column can also reduce the installation space up to 40% compared to the conventional sequences [14]. This savings in space requirements is owing to the reduced number of heat exchangers and associated equipment such as pumps, their supports etc. Because of these potential benefits, the DWC has emerged as a promising technology in boosting the thermodynamic reversibility of distillation in the current scenario of competition and environmental concerns.

The application of DWC has been extended to the azeotropic and extractive distillations [15]. Subsequently, the vapor recompression

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https://doi.org/10.1016/j.seppur.2018.07.011
Received 26 March 2018; Received in revised form 28 June 2018; Accepted 6 July 2018
Available online 07 July 2018
1383-5866/ 

**Nomenclature**

*Abbreviation*

| | |
|---|---|
| bhp | brake horsepower |
| CI | capital investment |
| CR | compression ratio |
| CTCS | conventional two column system |
| CW | cooling water |
| DWC | dividing wall column |
| EWE | ethanol/water/ethylene glycol (E/W/EG) system |
| FTCDC | fully thermally coupled distillation column |
| hp | horsepower |
| M&S index | Marshall and Swift cost index |
| NRTL | nonrandom two-liquid model |
| OC | operating cost |
| OVR-DWC | overhead vapor recompressed DWC |
| SVR-DWC | side vapor recompressed DWC |
| TAC | total annual cost |
| VRC | vapor recompression |
| VRC-DWC | vapor recompressed DWC |

*Symbol*

| | |
|---|---|
| $A$ | heat transfer area, $m^2$ ($ft^2$ in heat exchanger cost estimating formula) |
| $D_c$ | column diameter, m (ft in column cost estimating formula) |
| $F$ | feed flow rate, kmol/h |
| $H$ | enthalpy, J/mol |
| $k$ | phase equilibrium constant, dimensionless |
| $L$ | liquid flow rate, kmol/h |
| $L_c$ | column height, m (ft in column cost estimating formula) |
| $m$ | liquid holdup in a tray, kmol |
| $N_C$ | total number of components |
| $P$ | pressure, kPa |
| $P_t$ | total pressure, kPa |
| $P^0$ | vapor pressure, kPa |
| $Q$ | heat duty, kW |
| $Q_{Comp}$ | compressor duty, hp |
| $Q_{Cons}$ | total heat consumption, kW |
| $Q_E$ | external energy supplied to the reboiler, kW |
| $Q_R$ | reboiler duty, kW |
| $S$ | side stream flow rate, kmol/h |
| $T$ | temperature, C |
| $t$ | time, h |
| $V$ | vapor flow rate, kmol/h |
| $\upsilon_f$ | flooding vapor velocity, m/s |
| $\upsilon_{op}$ | operating vapor velocity, m/s |
| $x$ | liquid composition, mole fraction |
| $y$ | vapor composition, mole fraction |
| $z$ | feed composition, mole fraction |
| $\gamma$ | activity coefficient, dimensionless |
| $\mu$ | polytropic coefficient, dimensionless |
| $\rho$ | density, $kg/m^3$ |
| $\lambda$ | latent heat, J/mol |

*Subscript/superscript*

| | |
|---|---|
| *Comp* | compressor |
| *CV* | compressed vapor |
| *F* | feed |
| *i* | component index |
| *in* | inlet |
| *L* | liquid |
| *n* | tray index |
| *out* | outlet |
| *R* | rectifier |
| *S* | stripper |
| *V* | vapor |

heat pump system is introduced in the traditional DWC to acquire the benefits of both of them. The overhead vapor from rectifying section is thermally integrated with the reboiler content under the VRC framework. This hybrid VRC-DWC scheme is tested on an azeotropic column with a reasonable performance improvement in energy and cost savings [16]. Although, it leads to reduce the use of external utility in the reboiler but this hybrid configuration runs at a reasonably large compression ratio (CR), involving a huge investment for the compression system and an increased degree of operational complexity. To reduce the compressor work, they [16] have proposed to add a preheater to cut down the compressor pressure ratio and to split the top stream to decrease the feed flow of the compressor.

To address this issue concerning large compression ratio, in this contribution, an alternative strategy is proposed by introducing the vapor recompression between a vapor stream from an intermediate stage, from where a side product is taken out, and the reboiler content. This side vapor recompressed DWC (SVR-DWC) can provide a better economic performance and operational flexibility over the overhead vapor recompressed DWC (OVR-DWC). With a ternary system, both the proposed VRC based DWC configurations are illustrated. Based on our knowledge, there is no work exploring the techno-economic feasibility of such heat pumping, particularly between side and bottom streams, integrated in the DWC column.

## 2. Dividing wall column: Basic configuration and operating principle

The separation of multicomponent systems is very common in chemical and allied industries. A train of distillation columns is connected either in direct or indirect sequence for fractionating a wide variety of multicomponent mixtures. For instance, for separating a system of three species into pure products, at least a sequence of two conventional distillation columns is required. Interestingly, both the columns require separate rectifying and stripping sections along with their respective condenser and reboiler.

Aiming to improve the energy efficiency, a fully thermally coupled distillation system (FTCDS), also referred to as Petlyuk column (Fig. 1), is subsequently appeared in literature [9]. This configuration mainly consists of a prefractionator and a main column. The prefractionator may not have a reboiler and condenser, and the liquid and vapor streams are fed from the main column at its top and bottom stage, respectively. In most cases, the concept of Petlyuk column is implemented through the dividing wall column structure, which is built by accommodating the prefractionator and the main column in a single shell separated by a vertical wall. As shown in Fig. 2, the rectifying and stripping operations are carried out at the top and bottom sections, respectively. The middle portion of the shell is left for vertical division by a wall. One side of this dividing section receives fresh feed and the other side discharges intermediate or side product. Moreover, the distillate and bottoms are collected from the top of rectifier and the bottom of stripper, respectively. Now it becomes obvious that the DWC uses one reboiler and one condenser, while, as stated before, a conventional two column system (CTCS) requires two reboilers and two condensers. Consequently, the DWC would reduce not only the utility consumption but also the space and capital investment compared to the CTCS.