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

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
v_f	flooding vapor velocity, m/s
v_{op}	operating vapor velocity, m/s
x	liquid composition, mole fraction
y	vapor composition, mole fraction
z	feed composition, mole fraction
γ	activity coefficient, dimensionless
μ	polytropic coefficient, dimensionless
ρ	density, kg/m^3
λ	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.

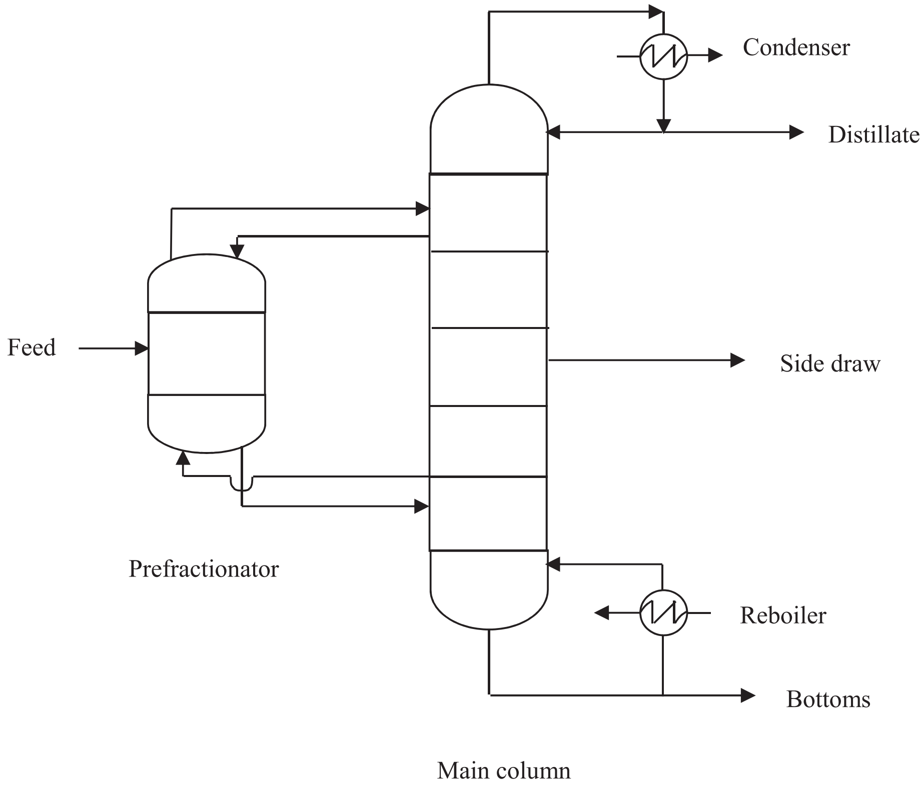

Fig. 1. A schematic representation of a fully thermally coupled distillation system (FTCDS).

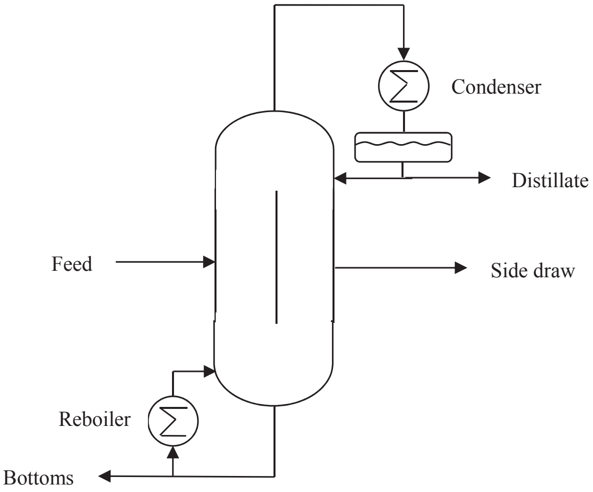

Fig. 2. A schematic representation of a dividing wall column (DWC).

3. Introducing heat pump system in DWC: The proposed scheme

In order to ensure the optimal use of internal heat source, a heat pump system in the form of vapor recompression is introduced in the DWC column. Now this VRC arrangement is developed by two ways with thermally linking: (i) top and bottom streams, and (ii) side and bottom streams. Here, the former scheme is named as overhead vapor recompressed DWC and the later scheme as side vapor recompressed DWC, and both of them are elaborated below.

3.1. Overhead vapor recompressed DWC (OVR-DWC)

As shown the configuration in Fig. 3, the vapor stream leaving the top of rectifier is employed as a heat source for liquid reboiling at the bottom of stripper. Since the temperature of heat source is lower than the heat sink (i.e., reboiler content), the overhead vapor is subjected to compression for elevating its pressure (i.e., temperature) to create a certain thermal driving force. Here, target is made to maintain this driving force at least 10 °C [17]. In this external thermal loop, the compressed vapor changes its phase by releasing latent heat in the stripper reboiler. Subsequently, the condensed overhead stream is flashed back to the reflux drum. Because of pressure reduction in the throttling valve, a part of the condensate gets vaporized and thus, an overhead condenser is installed coupling with the reflux accumulator. This thermally integrated OVR-DWC configuration can be developed by externally fitting the VRC loop around the DWC column, which indicates a possibility of retrofitting.

3.2. Side vapor recompressed DWC (SVR-DWC)

It is well known that the DWC is used for separating a mixture of three or more components. For a system of three components, the column is usually designed for three products, one at the top (distillate), second one from an intermediate stage (side draw) and last one at the bottom (bottoms). As mentioned earlier, the vapor recompression column performs well for close-boiling mixture separation. However, the use of heat pump between the top (heat source) and bottom (heat sink) products of the OVR-DWC, keeping the intermediate one untouched, seems to form a scheme that separates a wide-boiling mixture. In such a case, the vapor recompression involves a large CR, making the operation complex and economically unattractive.

To overcome this situation of heat pumping that involves a large CR, attempt is made further to introduce the vapor recompression between a side stream and the reboiler content. Actually, a vapor stream is withdrawn from an intermediate stage and then as usual, its pressure is elevated before using it as a heat source against the reboiler liquid that acts as a heat sink. Releasing the latent heat in the reboiler, the side stream is throttled for pressure reduction that leads to a partial vaporization. An intermediate cooler is thus used for condensing the

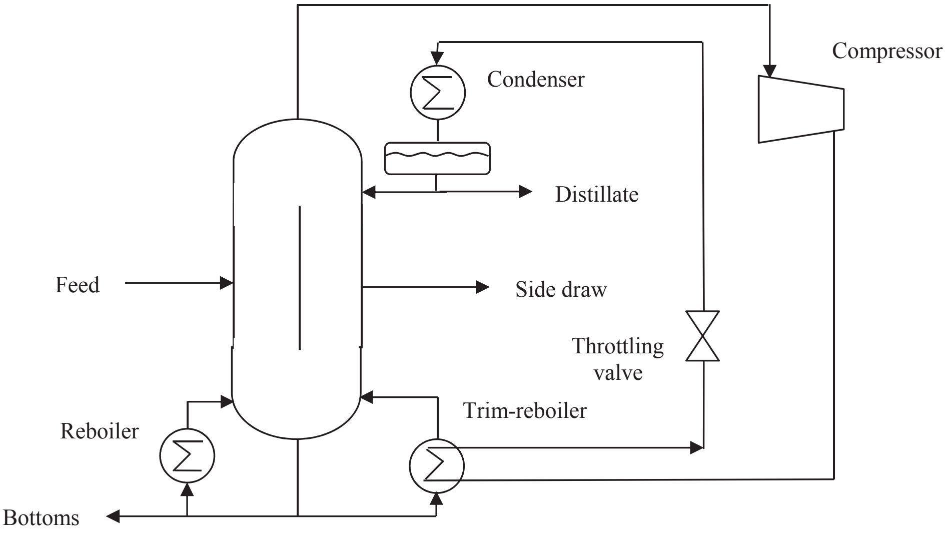

Fig. 3. Overhead vapor recompressed dividing wall column (OVR-DWC).

vaporized fraction. Finally, the entire stream is withdrawn as a side product. This configuration is called here as side vapor recompressed dividing wall column (SVR-DWC) and schematically depicted in Fig. 4.

It is now obvious that the SVR-DWC involves a lower CR than the OVR-DWC. The internal energy provided by VRC in these two hybrid configurations mainly depends on the desired distillate (equivalently, overhead vapor) rate in case of OVR-DWC and side stream (equivalently, side vapor) rate for SVR-DWC. At this point, it should be noted that when the compression ratio exceeds 4, it is quite common in practice to use a multi-stage vapor recompression system.

In both the vapor recompression based DWC configurations proposed above, an internal heat source (i.e., latent heat of compressed vapor) is utilized for liquid reboiling in the stripper. By this way, these hybrid schemes lead to reduce the utility consumption in the reboiler by releasing the latent heat and that in the condenser by the occurrence of subsequent condensation. As a consequence, these schemes require reduced size condenser and reboiler, and thus further lowering the capital investment (CI). This qualitative analysis clearly indicates that the VRC based DWC schemes would outperform the DWC-alone and the CTCS.

However, the VRC-DWC columns additionally involve a compressor and a throttling valve. It is known that both the capital and operating costs involved in vapor recompression are reasonably high. These cost indices are mostly affected by the CR at which the VRC needs to be operated. It is further noticing that the compressor consumes electricity which is several times more expensive than the thermal utility used to run the heat exchangers (i.e., reboiler and condenser). Keeping these issues in mind, a quantitative analysis is conducted in this study.

4. Distillation column modeling

The following assumptions have been considered in modeling a distillation column:

A1. Perfect mixing and equilibrium on each stage
A2. No heat loss to the surroundings
A3. Nonideal liquid phase (NRTL model used later in the illustrative ternary system)
A4. Fast energy dynamics
A5. Isentropic compression system

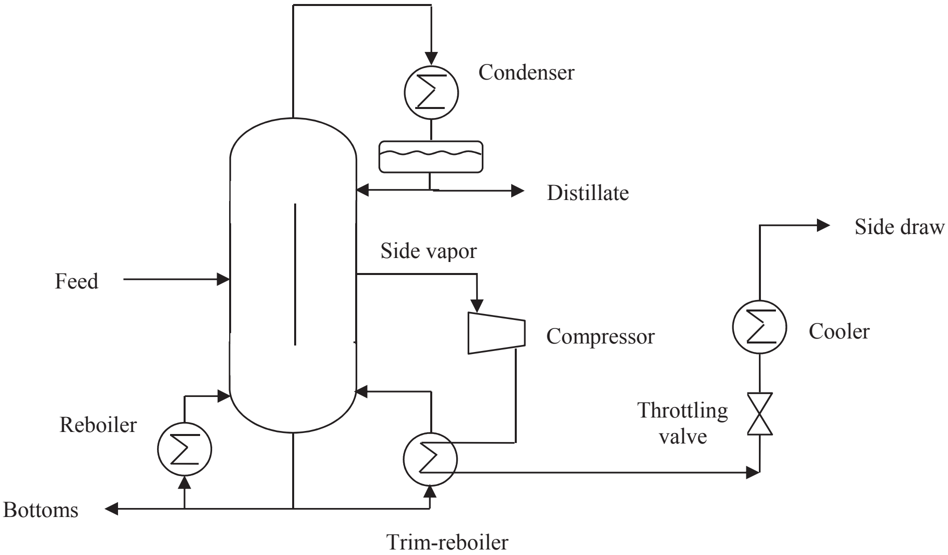

Fig. 4. Side vapor recompressed dividing wall column (SVR-DWC).

A6. Minimum thermal driving force of 10 °C [17] required for complete phase change in a heat exchanger
A7. No subcooling/superheating occurred in the compressor
A8. Adiabatic flashing occurred in the throttling valve
A9. No heat transfer occurred across the insulated wall

Here, the modeling equations are developed for a representative *n*th tray, depicted in Fig. 5, which are applicable to all the distillation columns, including the prefractionator one. It is quite straightforward to extend this model to the entire column.

Total mole balance

$$\frac{dm_n}{dt} = L_{n-1} + V_{n+1} + F_n - (L_n + S_n^L) - (V_n + S_n^V) \tag{1}$$

Component mole balance

$$\frac{d(m_n x_{n,i})}{dt} = L_{n-1}x_{n-1,\,i} + V_{n+1}y_{n+1,\,i} + F_n z_{n,\,i} - (L_n + S_n^L)x_{n,\,i} - (V_n + S_n^V)y_{n,\,i} \tag{2}$$

Energy balance

$$\frac{d(m_n H_n^L)}{dt} = L_{n-1}H_{n-1}^L + V_{n+1}H_{n+1}^V + F_n H_n^F - (L_n + S_n^L)H_n^L - (V_n + S_n^V)H_n^V \tag{3}$$

Equilibrium

$$y_{n,\,i} = k_{n,\,i}x_{n,\,i} = \gamma_{n,\,i}\frac{P_{n,\,i}^0}{P_t}x_{n,\,i} \tag{4}$$

Summation

$$\sum_{i=1}^{NC} x_{n,\,i} = 1 \tag{5a}$$

$$\sum_{i=1}^{NC} y_{n,\,i} = 1 \tag{5b}$$

All the notations used in the aforementioned equations are defined later (see Nomenclature section).

5. Performance indicators

To quantify the performance improvement of different variants of the DWC column with reference to its conventional analogous (i.e., CTCS), two performance indicators are used. They are thermal energy savings and payback time [18], both of which are elaborated in the following.

5.1. Thermal energy savings

The proposed vapor recompressed DWC column has two energy components, namely reboiler and compressor. The compressor duty (Q_{Comp}) is determined in hp from the following expression [17]:

$$Q_{Comp} = 3.03 \times 10^{-5}\frac{\mu}{\mu-1}VP_{\text{in}}\left[(\text{CR})^{\frac{\mu-1}{\mu}} - 1\right] \tag{6}$$

The compression ratio (CR) is expressed as:

$$\text{CR} = \frac{P_{\text{out}}}{P_{\text{in}}} = \left(\frac{T_{\text{out}}}{T_{\text{in}}}\right)^{\mu/(\mu-1)} \tag{7}$$

Here, T_{in} and T_{out} are the inlet and outlet temperatures, respectively, with reference to the compressor. Note that in the above equations, the pressure (inlet pressure, P_{in} and outlet pressure, P_{out}) is in $\text{lb}_\text{f}/\text{ft}^2$, and the vapor stream subjected to compression (V) is in ft^3/min.

To determine the polytropic coefficient (μ), the following form is used:

$$\frac{1}{\mu-1} = \sum_{i=1}^{NC}\frac{y_i}{\mu_i - 1} \tag{8}$$

in which, μ_i denotes the polytropic coefficient of species *i*.

Now, one can estimate the total energy consumed by a VRC-based scheme as:

$$Q_{Cons}^{VRC} = Q_E + 3Q_{Comp} \tag{9}$$

in which,

$$Q_E = Q_R - Q_{CV} \tag{10}$$

$$Q_{CV} = V_{CV}\lambda_{CV} \tag{11}$$

Here, $Q_R$denotes the reboiler duty of the DWC-alone, and Q_{CV} corresponds to the latent heat (λ_{CV}) released by compressed vapor (V_{CV}) in the reboiler. In Eq. (9), a conversion factor (from electrical energy to thermal energy) of 3 is assumed [19].

Like the CTCS, the DWC-alone has no compression element. So, the total heat consumption of these schemes (Q_{Cons}^{CTCS} and Q_{Cons}^{DWC}) is equal to their respective reboiler duty (Q_R). Knowing the total heat consumed by a DWC column and its conventional counterpart, one can easily find the energy savings achieved through thermal integration.

5.2. Payback period

It is fairly true that the energy savings is typically reflected through the estimation of operating cost (OC). In practice, this savings in OC is usually achieved at the expense of capital investment (CI). Keeping this point into consideration, it is further adopted a second performance indicator, namely payback period, which takes into account both the OC and CI. It can be expressed for a DWC column with respect to a CTCS as:

$$\text{Payback period} = \frac{\text{CI}^{\text{DWC}} - \text{CI}^{\text{CTCS}}}{\text{OC}^{\text{CTCS}} - \text{OC}^{\text{DWC}}} \tag{12}$$

Here, the OC is computed by adding the cost of cooling water (CW) used in the condenser, steam in the reboiler and electricity in the compressor. These three utilities have their respective cost as 0.03$/t, 13$/t and 0.1$/kW h [20]. The operating cost of the compressor is found out with the bhp (= hp/0.72) [21]. It is further considered that the column operates for about 8000 h in a year.

The proposed thermally integrated configuration is typically equipped with the following major elements: column shell and trays, heat exchanger, including condenser and reboiler, and compressor. The installed costs of all these components are estimated based on the formulae given in Douglas [17] and they are documented in Table 1.

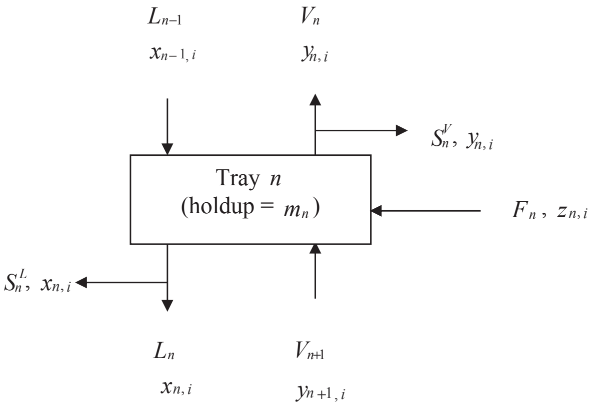

Fig. 5. A typical *n*th tray.

Table 1
Cost estimating formula and parameter value.

Column shell

Installed cost (\$) = $\left(\frac{M\,\&\,S}{280}\right) 101.9 D_c^{1.066} L_c^{0.802} (c_{in} + c_m c_p)$

where, D_c is the column diameter (ft), L_c the column height (ft), $M\&S = 1569$, and the coefficients $c_{in} = 2.18$, $c_m = 3.67$ and $c_p = 1.05$.

Column tray

Installed cost (\$) = $\left(\frac{M\,\&\,S}{280}\right) 4.7 D_c^{1.55} L_c (c_s + c_t + c_m)$

where, the coefficients $c_s = 1$, $c_t = 1.8$ and $c_m = 1.7$.

Heat exchanger

Installed cost (\$) = $\left(\frac{M\,\&\,S}{280}\right) 101.3 A^{0.65} (c_{in} + c_m (c_t + c_p))$

where, A is the heat transfer area (ft^2), and the coefficients $c_{in} = 2.29$, $c_m = 3.75$, $c_t = 1.35$ and $c_p = 0$.

Compressor

Installed cost (\$) = $\left(\frac{M\,\&\,S}{280}\right) 517.5 (bhp)^{0.82} (2.11 + F_d)$

where $F_d = 1.0$.

6. A case study

6.1. The conventional system

To demonstrate the proposed thermal integration with a heat pump, a ternary system of ethanol/water/ethylene glycol (E/W/EG or EWE) is adopted. As a reference system, the conventional two column system (CTCS) is first simulated having the diameters of 1.1 and 0.52 m, with their respective theoretical stages of 30 and 7. Their respective shell heights are 21.88 and 4.81 m. Note that the trays are counted from top down.

The feed specifications for the sample EWE system are same for both the CTCS and DWC, and they are reported in Table 2. The operating pressure of both the columns in CTCS is 1 atm (= 101.3 kPa) with a shell pressure drop of 4 kPa and they have total condensers. With these, the process model, consisting of coupled differential algebraic equations, is simulated developing our own computer code using FORTRAN 90 language. The fourth-order Runge-Kutta method is used for solving the ordinary differential equations and the Newton-Raphson method for bubble-point calculation.

This simulated system produces the top, side and bottom products with a purity of 82.92 mol% ethanol, 99.48 mol% water and 84.64 mol % ethylene glycol, respectively. All these product flow rates of CTCS are kept identical with those of DWC as documented in Table 2. It should be stressed that the same conventional column configuration is considered by Chew et al. [14] as a basis.

At this point, it should be noted that the column diameter (D_c) is determined from [22]:

$$D_c = \sqrt{\frac{4V}{\pi\ \rho_V v_{op}}} \tag{13}$$

with

$$v_{op} = 0.8 v_f \tag{14}$$

$$v_f = 0.07 \sqrt{\frac{\rho_L - \rho_V}{\rho_V}} \tag{15}$$

where V denotes the vapor flow rate (kg/s), ρ the density (kg/m^3), and v_{op} and v_f the operating and flooding vapor velocity (m/s), respectively.

Again, the other process parameters, including total number of trays, reboiler duty and reflux ratio, are determined through the sensitivity tests (conceptual design). For this, one parameter is varied keeping others fixed. Running a couple of such cycles, one can get nearly optimal parameter values. For this, the concerned column given in Chew et al. [14] has been considered as a basis.

6.2. Comparing the example conventional process with the azeotropic processes

The representative conventional two column system (CTCS) used to illustrate the proposed heat integration mechanism is being used in industrial practice for the separation of a ternary ethanol/water/ethylene glycol mixture, as mentioned in Ref. [22]. Basically, the product purity obtained from this CTCS is close to the azeotropic composition of ethanol/water and this mixture needs to be further fractionated using an azeotropic or extractive distillation. A somewhat similar study is conducted by Kunnakorn et al. [23]. Purifying ethanol/water mixture, they [23] have further employed azeotropic distillation with the use of both benzene and cyclohexane separately as an entrainer. Table 3 provides a systematic comparison between them with respect to the CTCS configuration used in this study. It is evident that the CTCS secures a better performance in terms of energy consumption/kg of ethanol produced.

6.3. Development of DWC

As stated previously, the dividing wall column consists of three sections, namely rectifying section at the top, dividing section at the middle and stripping section at the bottom. They have total 17, 9 and 9 theoretical stages, respectively. Actually, the rectifier has 16 trays and a total condenser, and the stripper has 8 trays and a reboiler. As stated before, the trays are numbered from top to bottom. Accordingly, for example, the top tray is Stage 1 and the bottom one is Stage 16 for the rectifying column. Like a CTCS column, the all three sections in DWC have a column pressure drop of 4 kPa.

The simulation results and column specifications are briefly documented in Table 2. As shown, the DWC produces distillate from the top rectifier with a flow rate of 183 kmol/h having 82.89 mol% ethanol, side product from the dividing section with a flow rate of 80.8 kmol/h having 99.5 mol% water and bottoms from the stripper with a flow rate of 236.2 kmol/h having 84.65 mol% ethylene glycol.

The DWC has several parameters that need to be fixed by the physical equipment at the time of construction. They include the total

Table 2
Specifications of DWC column.

System	ethanol (E)/water (W)/ethylene glycol (EG)
Total number of theoretical stages	35
Number of stages (top/middle/bottom)	17/9/9
Column diameter, m	2.5
Column height, m	25
Reboiler duty, kW	4561.45
Feed (saturated liquid)	
Temperature, C	96
Pressure, kPa	150
Flow rate, kmol/h	500
Composition (E/W/EG), mol%	30/30/40
Distillate	
Temperature, C	42.1
Pressure, kPa	20
Flow rate, kmol/h	183
Composition (E/W/EG), mol%	82.89/17.11/0.0
Side draw product	
Temperature, C	70.5
Pressure, kPa	33.7
Flow rate, kmol/h	80.8
Composition (E/W/EG), mol%	0.5/99.5/0.0
Bottoms	
Temperature, C	127.5
Pressure, kPa	44
Flow rate, kmol/h	236.2
Composition (E/W/EG), mol%	0.0/15.35/84.65

Table 3
A comparison of CTCS with the existing configuration.

Configuration	Ethanol purity (wt%)	Energy required[a] (MJ/kg ethanol)
CTCS[b]	92.53[c]	4.317
Distillation [23]	94	8.18
Azeotropic distillation with benzene[d] [23]	99	8.18 + 10.02
Azeotropic distillation with cyclohexane[d] [23]	98.90	8.18 + 9.958

[a] In the reboiler.
[b] Exampled in this study.
[c] Equal to 82.89 mol%.
[d] Distillation column followed by azeotropic distillation.

number of theoretical stages in all four sections, the location of the fresh feed and side stream withdrawal point, and the vapor split between the two sides of the wall. The first six parameters are adopted from Chew et al. [14]. The vapor split ratio (= V_P/V_S) along with the liquid split ratio (= L_P/L_R) are found out through the sensitivity tests as 0.7 and 0.5 so that all three product purities and productivities remain close, if not same, to their desired values as mentioned above. Note that V_P and L_P represent the vapor and liquid flow rate, respectively, fed to the prefractionator (left) side of the wall. Here, $V_S$represents the total vapor leaving the top tray of the stripper and $L_R$the total liquid leaving the bottom tray of the rectifier.

6.3.1. Performance improvement

As indicated earlier, the performance improvement of all the DWC schemes is to be quantified with reference to the conventional two column system in terms of energy consumption and payback period. In this regard, a detailed comparative cost analysis is carried out in Table 4. It is fairly true that the CTCS consumes a thermal utility in both the columns that lead to a total reboiler duty of 6859.51 kW. While, for the DWC structure, it reduces to 4561.45 kW, securing a 33.5% savings in energy consumption and 25.46% in operating cost. Note that this energy efficiency improvement is achieved at the expense of a 38% increase in capital investment (CI). Overall, the DWC column for the example ternary system provides a payback period of 1.15 yr that is calculated taking both the CI and OC into consideration.

6.4. Development of OVR-DWC and its performance

To improve the energetic potential of the DWC column further, it is proposed to introduce a vapor recompression heat pump between the top and bottom of that column. For the representative EWE system, the temperature difference between the two ends of the DWC is 84.87 °C. Adding a thermal driving force of 10 °C between the heat source and heat sink, the compressor needs to be operated for a pressure elevation that is equivalent to a temperature difference of 94.87 °C (= 84.87 + 10). Expectedly, this leads to a large CR of 6.4, yielding the compressor duty of 835.23 kW. Now using Eq (9), one can see that the proposed OVR-DWC secures an energy savings of 61.45% over the CTCS and 27.95% over the DWC configuration. Because of the involvement of a large CR, it requires a multi-stage compression system, leading to a 84.76% increase in CI compared to the CTCS. Except its complicated heat pump operation, it is evident from Table 4 that this OVR-DWC scheme outperforms the DWC-alone in terms of both energy savings (i.e., 61.45%) and payback time (i.e., 1.04 yr).

However, it is logical to use the same DWC reboiler in the OVR-DWC column because of their identical start-up operation. Moreover, one may think of proposing the heat pump arrangement to retrofit with an existing DWC column, which may lead to keep the reboiler unaltered. In such a case, the payback time of the OVR-DWC has increased from 1.04 to 1.46 yr, showing a worse performance than the DWC-alone.

6.5. Development of SVR-DWC and its performance

The quantitative analysis made above reveals that the overhead vapor recompressed heat pump operates at a reasonably large CR, making the compression operation prohibitively expensive and complicated. Therefore, the OVR-DWC configuration may not be that attractive from industrial perspective, irrespective of achieving any performance improvement (e.g., energy savings) over the DWC-alone. Motivated by this, attempt is made to explore the techno-economic feasibility of an alternative approach of heat pumping in the DWC scheme, namely the SVR-DWC.

Based on its operating principle discussed before, the SVR-DWC column is developed for the representative EWE system. The temperature difference existed between the heat source (i.e., a vapor stream from a side/intermediate tray) and heat sink (i.e., reboiler content) is 55.6 °C. It leads to a CR of 1.69 and a compressor duty of about 50 kW. Now, one can calculate from Eq. (10) that the supply of external energy to the reboiler (Q_E) of the SVR-DWC column is equal to 3649.58 kW, which yields an energy savings of 44.6%. A detailed cost calculation is performed in Table 4, in which it is evident that this hybrid column secures a 41.55% savings in OC at the expense of a 36.13% increase in CI with respect to the CTCS scheme.

The attractiveness of the proposed SVR-DWC column can also be quantified in terms of its very low payback time (i.e., 0.67 yr). However, if one continues to use the same reboiler that is operated in conjunction with the DWC-alone for the reasons stated before, the payback time of this hybrid column has increased a little from 0.67 to 0.76 yr, which is still significantly low compared to that of all other schemes reported before and in Table 4.

With reference to the DWC column, the OVR-DWC scheme secures a 27.95% more energy savings at the expense of a 26.96% increased payback time. On the other hand, the SVR-DWC configuration shows its superiority over the DWC column, lowering both the energy consumption by 11.1% and payback time by 33.91%. Overall, the SVR-DWC is the best economic performer among the all DWC-based configurations. Furthermore, the SVR-DWC provides a reduced complexity in compressor operation over the OVR-DWC.

Table 4
Comparative economic evaluation.

	Conventional scheme	DWC	OVR-DWC	SVR-DWC
Capital cost (in thousands of USD ($))				
Column shell	428.30	673.60	673.60	673.60
Column tray	78.33	92.12	92.12	92.12
Reboiler	624.65	504.45	51.99	436.36
Condenser	212.80	517.40	239.58	378.66
Side cooler	–	–	–	46.56
Compressor	–	–	1358.68	135.02
Wall	–	67.36	67.36	67.36
Total	1344.08	1854.93	2483.33	1829.68
Operating cost (in thousands of USD ($)/yr)				
Steam	1639.51	1090.18	33.06	872.30
Cooling water (condenser)	112.41	215.75	66.00	112.87
Cooling water (side cooler)	–	–	–	5.31
Electricity	–	–	561.28	33.60
Total	1751.92	1305.93	660.34	1024.08
Payback period, yr	–	1.15	1.04[a]	0.67[b]
External reboiler duty, kW	6859.51	4561.45	138.33	3649.58
Compressor duty, kW	–	–	835.23	50.00
Energy savings, %	–	33.5	61.45	44.6

[a] 1.46 yr when the reboiler that is attached with DWC-alone is used here.
[b] 0.76 yr when the reboiler that is attached with DWC-alone is used here.

7. Conclusions

In this article, the vapor recompression heat pump is introduced in the DWC column to reduce the heat irreversibility of distillation operation. There are two types of thermal coupling proposed under the VRC mechanism between the heat source and heat sink. They are the overhead vapor recompressed and the side vapor recompressed DWC. The former scheme operates the VRC at a very large CR because of its involvement between the two ends of the column. As a consequence, the OVR-DWC structure may not be so attractive proposition from industrial perspective, although it can show a better energy efficiency performance over the DWC-alone at the expense of an increased cost and complicated compression operation. On the other hand, in the SVR-DWC configuration, the CR remains reasonably low because of its thermal pairing between the intermediate and bottom streams, which would lead to secure a remarkable savings. For the representative ethanol/water/ethylene glycol system, the DWC-alone shows a reasonable energy household and a better economic figure than the conventional two column system (CTCS). Further, it is observed that the OVR-DWC provides a better energy savings but a worse economic performance over the DWC-alone. Finally, it is investigated that the proposed SVR-DWC configuration is superior in the aspects of both energy consumption as well as payback time. Furthermore, the SVR-DWC provides a reduced complexity in compressor operation over the OVR-DWC.

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