Application of the Christiansen Dividing-wall Column Configuration for Multicomponent System Separation

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Abstract

Dividing wall distillation columns (DWC) represent a significant advancement in the process industry, promoting sustainability and reducing overall CO_2 emissions in continuous separation processes. Currently, DWC applications are mostly limited to three-product configurations, with a single known commercial implementation for four products in the so-called Kaibel configuration, which uses a single vertical dividing wall. While this simplified structure offers advantages in terms of implementation, its structural limitations lead to a reduced degrees of freedom for process control. This limitation is particularly evident in the main fractionator, where the central section between the two side products must operate in total reflux mode. Maintaining this mode in practice can be challenging, especially during process disturbances, often resulting in degraded quality of the two side products. To address this operational issue, a novel configuration is proposed, featuring a horizontal partition between the two side products, and a heat exchanger to maintain thermal coupling between the newly formed sections of the main fractionator. This configuration, referred to as the "|- column" in the literature, was first introduced by Atle C. Christiansen. It effectively eliminates remixing of the middle components, and allows for additional introduction or removal of thermal energy, enabling both sections of the prefractionator to operate near their optimal conditions. Theoretically, this enables more flexible column operation and decoupling of the two sections.

Keywords

Dividing wall distillation, Kaibel column, Christiansen's column

1 Introduction

Requirements for reducing carbon dioxide emissions are placing increasing pressure on energy-intensive industries such as natural gas, petroleum refining, and bulk chemicals manufacturing. This is driving these sectors to consider the adoption of advanced distillation technologies, since distillation is responsible for a large part of total energy use in the chemical process industry.[1] Among these, the Dividing Wall Column (DWC) technology stands out as the most promising, having demonstrated in over 300 applications worldwide its ability to reduce energy consumption, capital investment, and plot area by about 30 % compared to conventional distillation methods. The use of more complex four-product DWCs can result in savings of up to 50 %.[2] Studies by Dejanović et al.[3,4] have shown that these configurations are viable from both design and construction perspectives, applicable to new designs as well as retrofits aimed at energy savings and capacity increases for existing plants. Nonetheless, concerns about controllability – particularly the lack of proven methods to reliably control vapour flowrates on either side of the partition wall – remain a significant barrier to widespread adoption. One approach to mitigating this concern is the simplification of the internal structure of the four-product DWC, with the main goal of reducing the number of vapour splits in the DWC, as well as the length of column sections with three parallel channels containing trays or packing beds. Simplifications can be done with or without maintaining the energy efficiency of the Petlyuk sequence, depending on the separation task. Fig. 1 shows the full Petlyuk four-product DWC sequence, sometimes known as the "2-3-4" configuration according to the key component splitting sequence, together with different simplifications aiming to either reduce complexity ("s2-3-4" and "2-2-4") or improve controllability using a second condenser ("2-3-3"). All structures presented were conceptually developed using Vmin diagram analysis for the same separation task described in this paper, optimised, sized, and published previously.[3,4] None of the configurations have been built and operated to date, except for a pilot-plant of 2-2-4 configuration, currently in operation at the Ulm University.[5] The only known industrial application of a four-product DWC is the Kaibel (or 2-2-4) configuration, which cannot achieve the same energy efficiency as the Vmin configurations shown in Fig. 1. However, the Kaibel configuration's simpler internal structure results in fewer uncertainties in both design and operation.[6]

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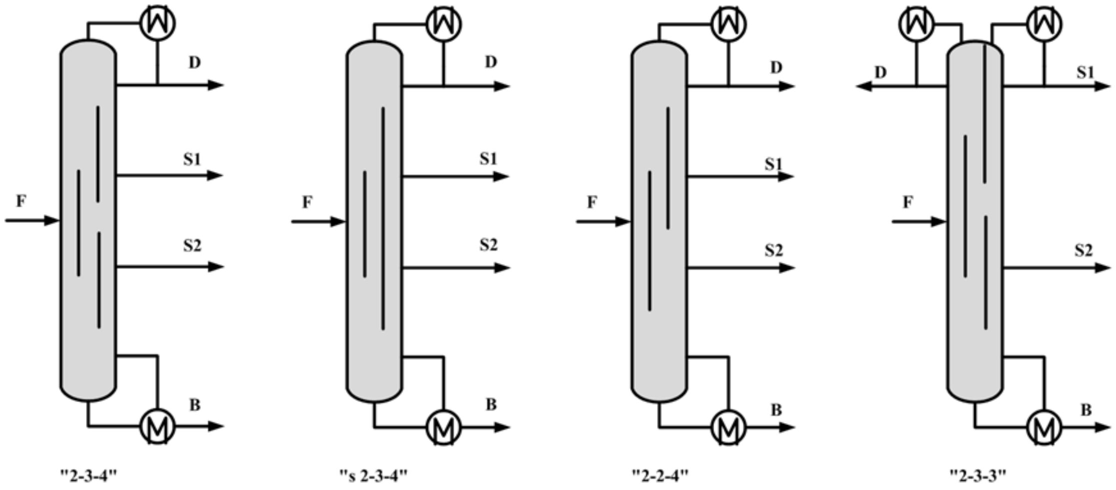

Fig. 1 – Feasible internal structures of a four-product DWC

Slika 1 – Moguće unutarnje strukture DWC-a za četiri proizvoda

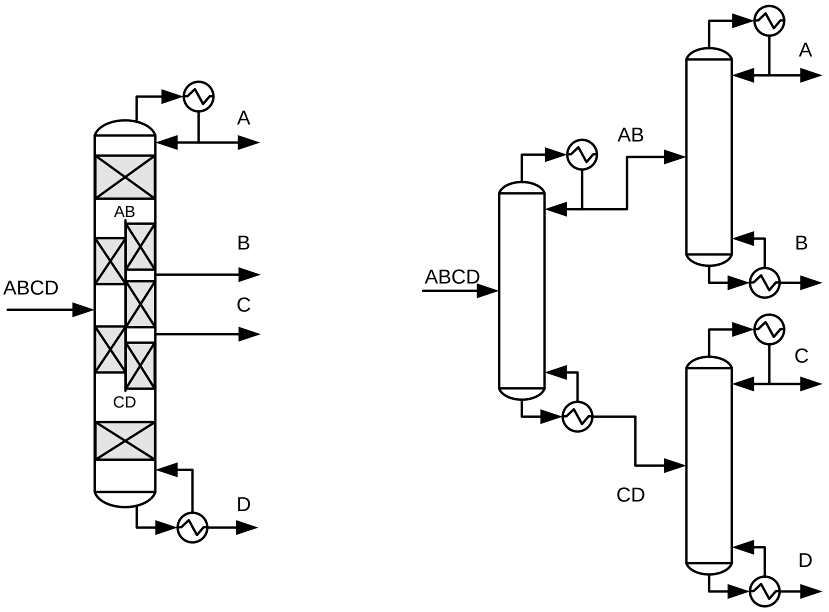

Fig. 2 – Kaibel DWC and its comparable sequence of ordinary columns

Slika 2 – Kaibelova kolona i usporediv niz jednostavnih destilacijskih kolona

1.1 Kaibel DWC

The Kaibel, or "2-4" configuration, shown in Fig. 2, is a thermally coupled three-column sequence, where a sharp split between the two middle boilers, B and C, is performed in the prefractionator. This differs from the Petlyuk sequence, where only the easiest separation task is allowed in each sub-column. This means that the prefractionator performs a sharp AD split, while key components B and C distribute between products. The top and bottom sections of the main column are thermally coupled by a section of trays or packings between the top and bottom side products. This coupling section operates in a total reflux mode, meaning that the internal liquid and vapour flows are equal (L=V). As a result, there is no net transport of material through the section; only heat is transferred from the vapour phase to the liquid phase through direct contact. However, there are certain downsides to this approach. In addition to lower thermodynamic efficiency, there are operational control challenges due to the reduced degrees of freedom compared to the Petlyuk sequence. The section between the two side products is especially critical, as it operates in total reflux mode to prevent remixing effects. This makes composition control of the two side products difficult, since the two control loops are highly coupled.

1.2 Christiansen DWC

A potential improvement of the concept, proposed by *Atle C. Christiansen*,[7] involves replacing the direct heat coupling with a horizontal dividing wall between the two side-product streams and adding a heat exchanger. This design prevents remixing of the two intermediate key components, while the two main column sections remain thermally coupled. The basic principle, shown in Fig. 3, offers only limited improvements due to the inability to directly control the heat duty of the single intermediate heat exchanger.

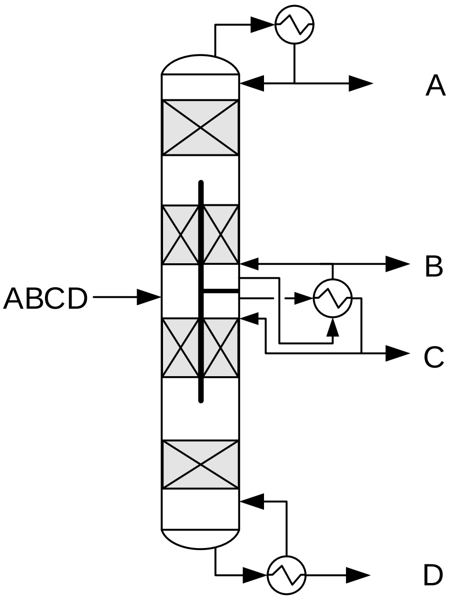

Fig. 3 – Christiansen DWC
Slika 3 – Christiansenova kolona

This work aims to demonstrate, through steady-state simulations and sensitivity studies using the HYSYS process simulator, that the Christiansen column with multiple heat exchangers (as shown in Fig. 5), offers improved controllability compared to the Kaibel column. This improvement is primarily due to the decoupling of the compositions of the two side products.

2 Experimental

2.1 Separation task

The feed and product specifications are based on a real industrial process – the fractionation of reformed gasoline, using a conventional, indirect sequence of distillation columns. The real feed comprises a large number of components in relatively small proportions. For the purposes of the simulation, the feed composition was simplified to the 15 most prevalent components, as shown in Table 1. The product specifications are as follows:

Distillate, **D** (light hydrocarbons): max. 1.5 wt% benzene;
Upper side product, **S1** (benzene rich cut (BRC)): 65.0 – 70.0 wt% benzene;
Lower side product, **S2** (fraction rich in toluene): min. 98.0 wt% toluene;
Bottom product, **B** (ethylbenzene and heavier hydrocarbons): max. 0.1 wt% toluene.

Table 1 – Feed composition
Tablica 1 – Sastav pojne smjese

Components	Mass fraction
n-butane	0.0194
i-pentane	0.0641
n-pentane	0.0453
2-methylpentane	0.0804
n-hexane	0.0425
benzene	0.0854
3-methyhexane	0.0203
toluene	0.2474
ethylbenzene	0.0351
p-xylene	0.0425
m-xylene	0.0549
o-xylene	0.1218
1,4-ethylbenzene	0.0167
1-methyl-3-ethylbenzene	0.0469
1,3,5-methylbenzene	0.0773

2.2 Simulation setup

To examine and compare the controllability of the Kaibel and Christiansen columns, a series of simulations involving parametric sensitivity studies were conducted. Since a dedicated DWC model is not available in HYSYS, both configurations were modelled using thermodynamically equivalent sequences of ordinary columns, which is based on the assumption that the effects of heat transfer through the dividing wall can be neglected. While the effects of trans-wall heat transfer can be both beneficial and detrimental, the latter can be minimised by insulating the wall (*e.g.*, with a sandwiched construction using perlite filling). A model of the Kaibel column is shown in Fig. 4, and the Christiansen column is shown Fig. 5. The parameters of the Kaibel (or 2-4) configuration were determined and published previously.[2–4] The Christiansen's column model parameters were derived from the Kaibel configuration by simply removing the section containing equilibrium stages between the two side-products and adding a heat exchange system model. Sensitivity studies were conducted by introducing various input disturbances – linear changes in one of the side streams flow rates, and recording the open-loop composition changes of benzene in the S1 and toluene in the S2 product.

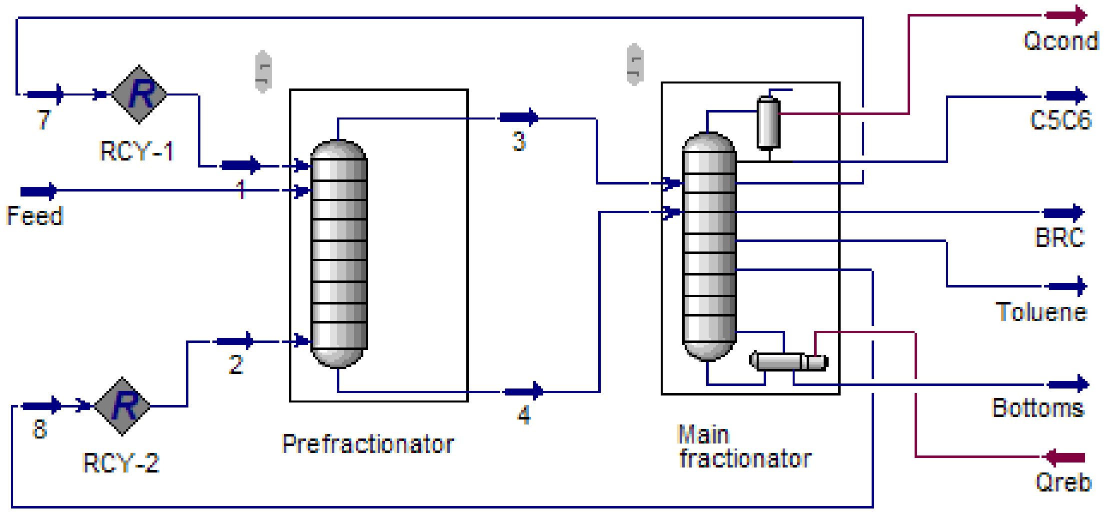

Fig. 4 – Kaibel column model in HYSYS

Slika 4 – Model Kaibelove kolone u HYSYS-u

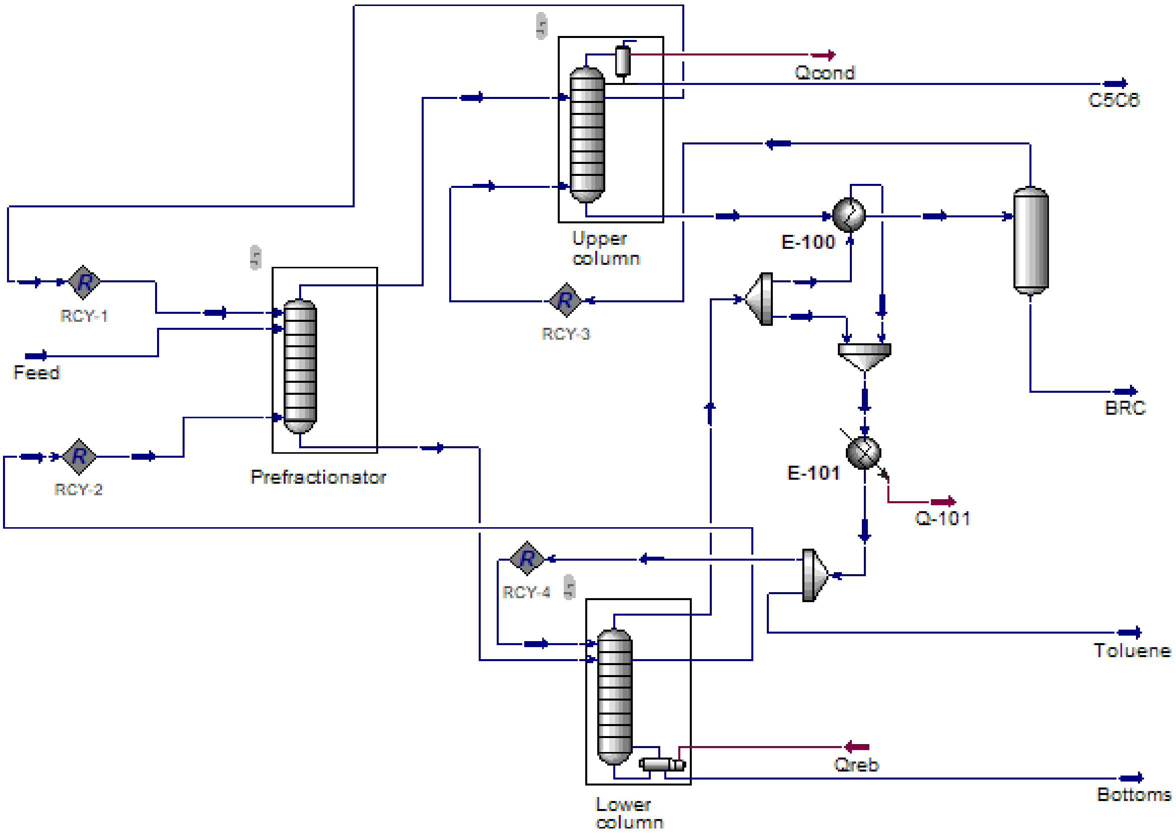

Fig. 5 – Christiansen column model in HYSYS

Slika 5 – Model Christiansenove kolone u HYSYS-u

The parameters for both configurations models are provided in Table 2. In addition to the main heat exchanger (E-100 in the simulation scheme), which can be considered as a reboiler for the upper main fractionator column and the condenser for the lower main fractionator column, the Christiansen column configuration includes two additional components. These are expected to increase the number of available degrees of freedom while maintaining the same energy consumption. The first is the E-100 bypass stream on the tube side (the overhead stream of the lower main column), and the second is an additional cooler for the lower column reflux stream (E-101).

Table 2 – Design data
Tablica 2 – Parametri i ulazne varijable modela

	Kaibel column	Christiansen column
Number of stages, *N*	186	168
Reflux ratio, top	5.72	5.60
Reflux ratio, middle	–	2.25
V/*B*, bottom	5.15	5.14
V/*B*, middle	–	6.62
Total reboiler heat duty	5.66 MW	5.66 MW
Total condenser heat duty	−4.99MW	−4.99 MW
Middle heat exchanger heat duty	–	2.47 MW
Feed flow rate	31.73 t h^{-1}	31.73 t h^{-1}
Distillate flow rate	7.46 t h^{-1}	7.46 t h^{-1}
Side 1 flow rate	3.88 t h^{-1}	3.87 t h^{-1}
Side 2 flow rate	7.95 t h^{-1}	7.96 t h^{-1}
Bottom flow rate	12.43 t h^{-1}	12.44 t h^{-1}

Their purpose is to enable manipulation of the E-100 heat duty and to investigate the effect of the lower column reflux subcooling.

One of the advantages of the Christiansen column compared to the Kaibel column is its ability to minimise interactions between the two side products, effectively achieving decoupling.

Therefore, several scenarios were examined, and the performance of the two columns was compared by estimating the following:

- The effect of a change in the toluene product (S2) flow rate on the purity of the BRC product (S1);
- The effect of a change in the BRC product (S1) flow rate on the purity of the toluene product (S2);
- The effect of changes in the lower main fractionator's reflux temperature (subcooling).

3 Results and discussion

The first step was to compare the temperature profiles of both configurations in their base-case states, to confirm that they performed the same separation tasks. The temperature profiles of both columns at their initial operating points are shown in Fig. 6. For easier comparison, the temperature profile of the lower main fractionator of the Christiansen column was moved to the right by the exact number of stages in the Kaibel column’s section between the two side products.

It can be observed that the temperature profile of the Christiansen column closely matched that of the Kaibel column, meaning that the composition profile also matched, except for the section between products S1 and S2, which was replaced with a heat exchange system. Minor differences between the two temperature profiles can be observed only in their prefractionator sections. This supports the primary concept of the Christiansen column – that the section between the two side-products in the Kaibel column can be replaced using only heat exchange, without direct material exchange. This was further confirmed by the product compositions obtained from the steady-state simulation of the base case, shown in Table 3.

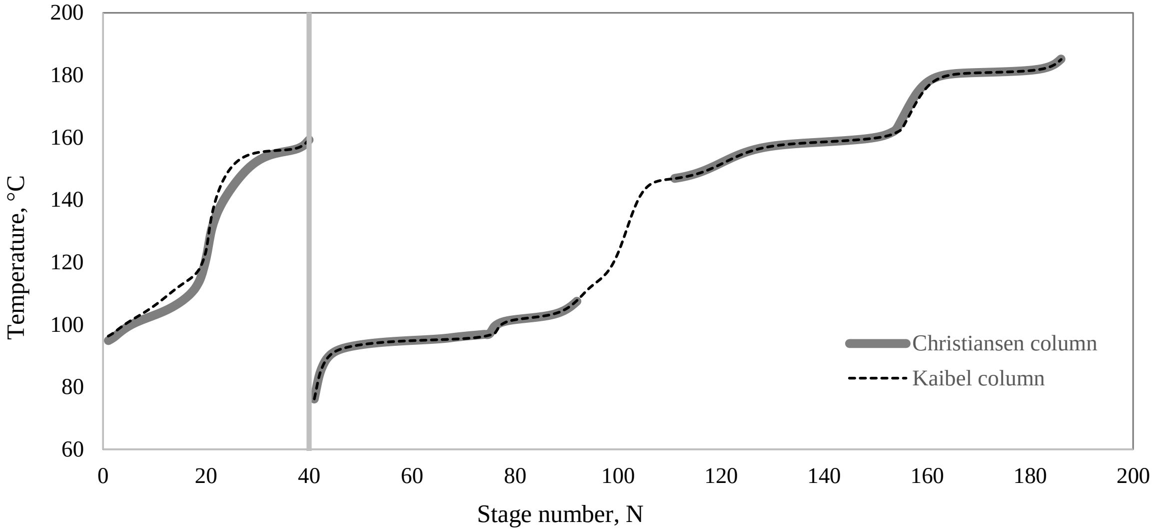

Fig. 6 – Superimposed temperature profiles of Christiansen and Kaibel columns
Slika 6 – Usporedba temperaturnih profila Christiansenove i Kaibelove kolone

Table 3 – Product stream compositions of the Kaibel and Christiansen columns
Tablica 3 – Sastavi proizvoda Kaibelove i Christiansenove kolone

	Kaibel column				Christiansen column			
Component mass %	D	S1	S2	B	D	S1	S2	B
n-butane	8.25	–	–	–	8.25	–	–	–
i-pentane	27.20	–	–	–	27.23	–	–	–
n-pentane	19.26	–	–	–	19.28	–	–	–
2-methylpentane	33.74	0.84	–	–	33.81	0.78	–	–
n-hexane	10.35	14.82	–	–	10.09	15.41	–	–
benzene	**1.20**	**67.50**	0.01	–	**1.34**	**67.50**	0.01	–
3-methyhexane	–	16.29	0.14	–	–	16.11	0.26	–
toluene	–	0.56	**98.50**	**0.00**	–	0.20	**98.50**	**0.00**
ethylbenzene	–	–	1.03	8.30	–	–	0.95	8.35
p-xylene	–	–	0.19	10.71	–	–	0.17	10.72
m-xylene	–	–	0.13	13.92	–	–	0.11	13.92
o-xylene	–	–	0.01	31.10	–	–	–	31.07

3.1 Sensitivity to changes in S1 flow rate

Sensitivity of both side product purities to changes in the S1 mass flow rate is shown in Fig. 7. In the analysis of the Christiansen column, the S1 flow rate was changed by decreasing the heat duty in E-100, achieved through partial bypassing of the lower column overhead past E-100. Since the bypassed portion of the lower column overhead remained in the vapour phase, heat exchanger E-101 was utilized to ensure total condensation of the lower column overhead. The upper column reflux ratio, liquid and vapour splits, main column reboiler heat duty, and S2 flow rate were maintained at constant values, as in the base case. No subcooling was applied in E-101. In the analysis of the Kaibel column, the flow rate of S1 was independently changed, while the main column reflux ratio, liquid and vapour splits, S2 flow rate, and reboiler heat duty were kept constant.

As shown in Fig. 7, the Kaibel column exhibited a substantial negative impact of the S1 flow rate on the toluene product (S2) purity – only 1.5 % change in the BRC flow rate was sufficient to cause the toluene product to go off-specification. In contrast, in the Christiansen column, changes in the S1 flow rate had virtually no effect on the toluene product (S2) purity. Both configurations displayed similar behaviour regarding the relationship between the S1 flow rate and its benzene content: increasing the flow rate of a product stream decreases its purity due to the decreasing value of the internal reflux. However, for the same S1 flow rate, the Christiansen column showed a slightly lesser effect on S1 purity.

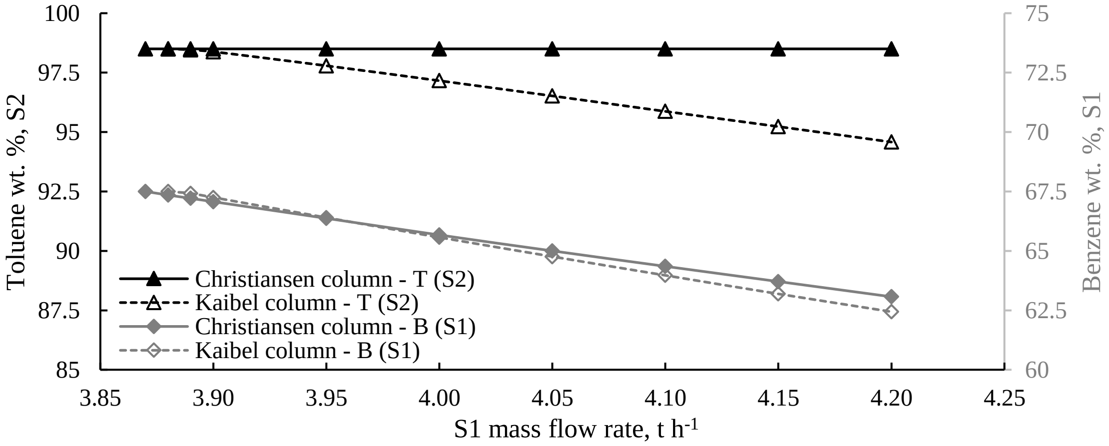

Fig. 7 – Sensitivity of side product purities to changes in S1 mass flow rate

Slika 7 – Osjetljivost čistoće bočnih proizvoda o masenom protoku S1

3.2 Sensitivity to changes in S2 flow rate

Sensitivity of both side product purities to changes in the S2 mass flow rate is shown in Fig. 8. In the analysis of the Christiansen column, the toluene product flow rate was changed independently, allowing the reflux ratio of the lower fractionator to change freely. The upper column reflux, liquid and vapour splits, main column reboiler heat duty, and S1 flow rate were kept constant, as in the base case. There was no subcooling in E-101, and no flow through the E-100 bypass line.

For the Kaibel column analysis, the flow rate of S2 was independently changed, while the main column reflux ratio, liquid and vapour splits, S1 flow rate, and reboiler heat duty were kept constant.

In both cases, changing the toluene product (S2) flow rate clearly influenced its purity – higher product flow rates led to decreased purities and vice versa. Both models encountered convergence difficulties when toluene product purities reached higher values (> 99.5 wt.%), suggesting that further investigation in a dynamic environment could be beneficial. The Kaibel column exhibited a minor influence of S2 flow rate changes on S1 purity. In comparison, the Christiansen column exhibited some influence of changing the S2 flow rate on S1 purity, though it remained well within the required specifications. Increasing the S2 flow rate in the Christiansen column shifted its composition towards heavier components, raising the heat capacity and temperature of the lower column overhead. Since this stream served as the heating medium for the upper column, its increased heat duty and boil-up ratio slightly reduced the S1 flow rate while increasing its purity. This change in S1 purity can be entirely avoided by bypassing a small fraction of the lower column overhead past E-100 to maintain the desired heat duty. Simulation results indicate that at a toluene flow rate of 8.5 t h^{-1} (rightmost data point in Fig. 8), BRC (S1) purity could be restored to its original value of 67.5 wt.% by bypassing 4.3 % of the overhead past E-100. However, this is impractical to further investigate in a steady-state environment, suggesting that a dynamic, pressure-driven simulation is the obvious next step. For the same toluene product (S2) flow rate, its purity is slightly higher in the Christiansen column.

3.3 Sensitivity to changes in the lower reflux subcooling

Sensitivity of both side product purities to changes in the degree of the lower reflux subcooling is shown in Fig. 9. During the analysis of the Christiansen column, the lower column reflux temperature was adjusted using heat exchanger E-101, while the E-100 bypass was not used. The upper column reflux ratio, liquid and vapour splits, main reboiler heat duty, and S2 flow rate were kept constant.

Under the condition of a fixed S2 flow rate, subcooling the lower column reflux had no effect on its purity but influenced only S1 purity. This effect can be explained by the unchanged internal reflux value of the lower column. During reflux subcooling, once steady state had been reached, the lower column operated with the same distillate rate (since the S2 flow rate was fixed) but with a reduced reflux flow rate, effectively operating with a lower measured reflux ratio. However, since the reflux stream was subcooled, some vapours at the topmost stage condensed as soon as the subcooled refluxed material entered the column and contact was made between the two phases.

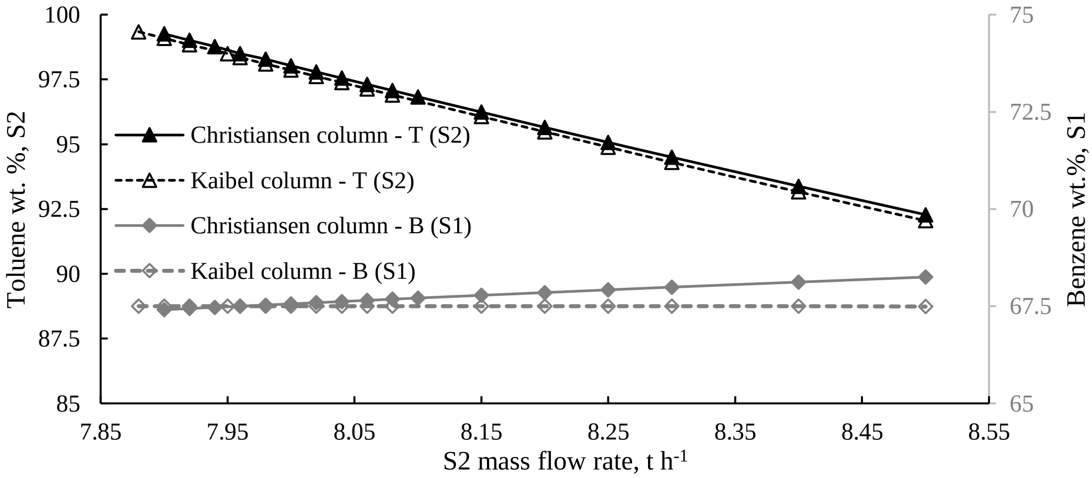

Fig. 8 – Sensitivity of side product purities to changes in S2 mass flow rate

Slika 8 – Osjetljivost čistoće bočnih proizvoda o masenom protoku S2

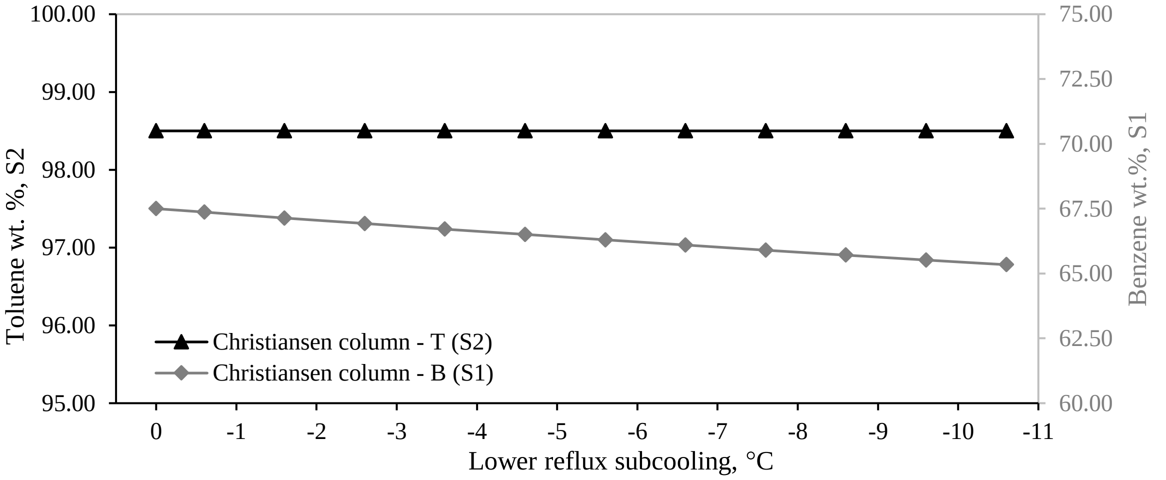

Fig. 9 – Sensitivity of side product purities to changes in the lower reflux subcooling degree

Slika 9 – Osjetljivost čistoće bočnih proizvoda o stupnju pothlađenja donjeg pretoka

This means that the column's internal reflux ratio remained unchanged and that the internal liquid flow rates at which the column operates will ultimately remain unchanged, provided that column heat duty and capacity remain unchanged, which is the case here. Internal operation of the column was basically unchanged; the only difference was the location where part of the overhead vapours had condensed. Since now a part of the vapour phase was condensed at the very top of the lower column, less vapour was available as a heating medium in E-100, causing the upper column to operate at a reduced heating duty. This effect is identical to increasing the S1 flow rate. This behaviour of the Christiansen column provides an additional degree of freedom for the independent control of S1 purity, particularly when there is an upper limit on the content of a key component, as is the case in this study.

4 Conclusions

The goal of this study was to investigate the steady-state performance of the Christiansen column and compare it to that of the Kaibel variant. The results confirm that replacing the section between the two side products of the Kaibel column with a simple heat exchange setup provides the same separation performance while reducing the overall height of the column. Moreover, the Christiansen column offers additional degrees of freedom that allow for more efficient operational control. In this sense, the primary advantage of this configuration is the improved and more independent control of the side product purities, which was the focus of this steady-state study. The results suggest that the Christiansen column effectively decouples product purities, allowing for changes in only one product with minimal impact on the other. Due to the limitations of steady-state simulations for this arrangement, further analyses in a dynamic and pressure-driven environment are necessary to fully understand the column's performance and potential, especially in cases of process upsets, disturbances, or changes in vapour and liquid splits.

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SAŽETAK

Primjena Christiansenove izvedbe kolone s razdjelnom stijenkom za separaciju višekomponentnih sustava

Goran Lukač, *Ivan Bilmez* i *Igor Dejanović* *

Primjena kolona s razdjelnom stijenkom (KRS) u procesnoj industriji važan je korak naprijed prema održivosti i smanjivanju ukupnih emisija CO_2, kojima ona značajno doprinosi. Zasad se primjena KRS-a u najvećoj mjeri svodi na izvedbe za tri proizvoda s tek nekoliko izvedbi za četiri proizvoda u tzv. Kaibelovoj izvedbi, sa samo jednom razdjelnom stijenkom. Iako je to prednost s aspekta primjene, njezina jednostavna struktura ipak donosi i određena ograničenja – smanjeni broj stupnjeva slobode za upravljanje. To se naročito odnosi na glavni frakcionator, čiji središnji dio između dvaju bočnih proizvoda mora raditi u uvjetima totalnog pretoka. U praksi je to problematično održavati, naročito uslijed procesnih poremećaja, pa često dolazi do degradacije kvalitete dvaju srednjih proizvoda.

Kao moguće rješenje ovog operativnog problema nameće se uporaba horizontalne stijenke između dvaju bočnih proizvoda te primjena izmjenjivača topline da bi obje novonastale sekcije glavnog frakcionatora i dalje bile toplinski povezane. Takvu konfiguraciju, koja se u literaturi označava i kao "|– kolona", prvi je predložio Atle C. Christiansen. Ona u potpunosti sprječava mogućnost pojave ponovnog miješanja dviju komponenti te omogućuje dodatno dovođenje ili odvođenje toplinske energije, što u teoriji omogućuje fleksibilniji rad kolone, odnosno tzv. *decoupling* dvije sekcije.

U ovom radu uspoređeni su stacionarni simulacijski rezultati obje izvedbe kolone dobiveni detaljnim modelima destilacije. Kao primjer separacije upotrijebljena je višekomponentna smjesa ugljikovodika s 15 različitih komponenti, koja se oštro separira na četiri proizvoda.

Ključne riječi

Kolone s razdjelnom stijenkom, Kaibelova kolona, Cristiansenova kolona

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