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RESEARCH ARTICLE

Energy efficiency of diabatic distillation schemes for an acetone–toluene–*n*-butanol mixture with an entrainer in the first column

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Abstract

Objectives. *To investigate the effectiveness of various options for organizing the process of diabatic distillation in the separation of a mixture of acetone–toluene–n-butanol by extractive distillation (ED) with dimethylformamide as an entrainer in a scheme where an entrainer is used in the first column.*
Methods. *Mathematical modeling in the Aspen Plus v. 12.1 software package was used as the primary research method. The local Non-Random Two Liquid composition equation was used as a model for describing vapor–liquid equilibrium. Parametric optimization of diabatic schemes was carried out according to the criterion of reduced energy costs.*
Results. *Based on ED scheme for an acetone–toluene–n-butanol mixture with an entrainer in the first column, four options for organizing diabatic distillation schemes were considered, both with and without increasing the temperature of the flows due to compression.*
Conclusion. *It is shown that the use of diabatic schemes in the ED of an acetone–toluene–n-butanol mixture with dimethylformamide can decrease energy consumption by 11–17%. While the maximum reduction in energy consumption is achieved in a scheme using a compressor, the efficiency of schemes without a compressor is slightly lower. Nevertheless, the technological design of the latter is much simpler.*

Keywords: *extractive distillation, heat integration, diabatic distillation, energy saving*

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НАУЧНАЯ СТАТЬЯ

Оценка энергетической эффективности схем неадиабатической ректификации смеси ацетон–толуол–*н*-бутанол с использованием экстрактивного агента в первой колонне

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Аннотация

Цели. *Исследовать эффективность применения различных вариантов организации процесса недиабатической ректификации при разделении смеси ацетон–толуол–н-бутанол экстрактивной ректификацией с диметилформамидом в схеме с использованием экстрактивного агента в первой колонне.*
Методы. *Математическое моделирование проводилось в программном комплексе Aspen Plus v. 12.1. Для моделирования парожидкостного равновесия применяли уравнение локальных составов Non-Random Two Liquid. Параметрическая оптимизация неадеабатических схем проводилась по критерию приведенных энергетических затрат.*
Результаты. *На основе схемы экстрактивной ректификации смеси ацетон–толуол–н-бутанол с использованием разделяющего агента в первой колонне было рассмотрено четыре варианта организации схем неадиабатической ректификации, как с применением повышения температуры потоков за счет сжатия в компрессоре, так и без него.*
Выводы. *Показано, что применение неадиабатических схем в экстрактивной ректификации смеси ацетон–толуол–н-бутанол с диметилформамидом позволяет снизить приведенные энергетические затраты на 11–17%, при этом максимальное снижение энергозатрат достигается в схеме с использованием компрессора. Однако эффективность схем без компрессора ниже незначительно, но технологическое оформление таких решений существенно проще.*
Ключевые слова: *экстрактивная ректификация, теплоинтеграция, недиабатическая ректификация, энергосбережение*

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INTRODUCTION

Extractive distillation (ED), which represents a method for separating azeotropic mixtures and mixtures of components having a relative volatility close to 1, is widely used in large-tonnage processes of basic organic and petrochemical synthesis. Since, like conventional distillation, this process is characterized by its low thermodynamic efficiency, reducing energy costs involved in its implementation is an important task. Among the various approaches for increasing the energy efficiency of ED, one can note the selection of separating agents (entrainers) with high selectivity [1], the optimization of separation schemes [2], as well as various options for internal and external heat integration.

Internal heat integration technologies described in publications [3–5] include the use of partially and fully thermally coupled distillation sequences. Several recent studies describe thermally coupled sequences in ED of various mixtures [6–9]. An empirical criterion for preliminary assessment of the energy efficiency of partially thermally coupled distillation sequences in ED has been proposed [10]; various algorithms for their optimization have been developed [9]. The use of a fully thermally coupled distillation sequences in the ED is considered, for example, in [11, 12].

External heat integration can be realized by organizing the heating of the reboiler of one column with the heat removed in the condenser of the other column; here, the temperature difference necessary for heat exchange is achieved by selecting the pressure in the columns. Such approaches are considered in [13–15]. Another option for the implementation of external heat integration is the use of heat pumps, considered, for example, in [16–19].

An interesting variant of heat integration is the use of complexes of the heat integrated distillation column (HIDiC) type. Instead of transferring heat from the top of the column to the reboiler as in a heat pump, heat transfer in HIDiC is carried out between the plates of the rectifying and stripping sections of the column, providing a continuous or stepwise supply or removal of heat in each of the sections. In this case, to ensure a positive temperature difference between the respective plates, the stripping section must operate at a higher pressure than the rectifying section.

The concept of internal heat integration was already considered in detail in 1977 [20]. The application of such schemes in ED processes is considered in [21, 22]. While the effectiveness of HIDiC schemes has been tested and confirmed experimentally [23], ensuring effective heat exchange between sections remains a rather challenging structural task. In various works, it is proposed to use concentric, multi-tube, separated by partitions with heat exchange panels [24] or other [25] configurations. Additional difficulties in the practical implementation of schemes with HIDiC are associated with the low controllability of the process [26].

Another possible option for the implementation of heat integration is the use of diabatic distillation schemes, which imply an external supply (or removal) of heat to the column plates due to the integration of heat flows between different scheme devices. The main advantage of such solutions as compared with HIDiC complexes lies in the simplicity of the organization of heat exchange, for which standard heat exchange equipment is sufficient. As compared with schemes using heat pumps, diabatic distillation schemes allow the use of compressors having a lower compression ratio, as well as, in some cases, doing away with them altogether. However, the use of diabatic distillation schemes has clearly not been sufficiently considered to date [27].

Therefore, the present study aims to evaluate the energy efficiency of the use of diabatic distillation schemes in the process of ED of a mixture of acetone–toluene–*n*-butanol using dimethylformamide (DMF) as an entrainer. The acetone–toluene–*n*-butanol mixture is a mixture of solvents used in the production of stabilene-9, which is used as a polyamide heat stabilizer. This azeotropic system has one azeotrope with a minimum boiling point in the binary component toluene–*n*-butanol. To separate this mixture, L.A. Pirog[1] has proposed to use an ED with a heavy-boiling entrainer DMF. In this paper, diabatic distillation schemes obtained on the basis of one of two possible separation schemes proposed by Pirog are considered. The conventional scheme is shown in Fig. 1.

CALCULATION SECTION

Mathematical modeling and computational experiment were used as the main research method, with all calculations carried out in the AspenPlus v.12.1 software package (*Aspen Technology*, USA). The modeling and optimization of the

[1] Pirog L.A. *Evaluation of efficiency agents in the separation of non-ideal mixtures of extractive distillation.* Cand. Sci. Thesis (Eng.). Moscow; 1987. 204 p. (in Russ.).

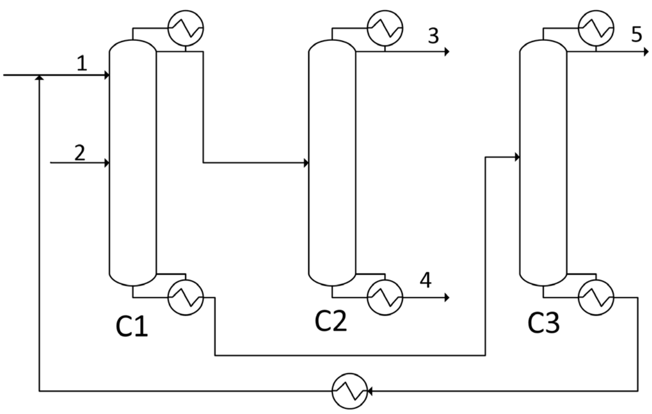


Fig. 1. Conventional scheme of extractive distillation for an acetone–toluene–*n*-butanol mixture with dimethylformamide (DMF) as an entrainer: Hereinafter: C1 – extractive distillation column, C2 – acetone–toluene separation column, C3 – entrainer regeneration column; 1 – entrainer (DMF); 2 – feed; 3 – acetone; 4 – toluene, 5 – *n*-butanol.

conventional ED scheme of the acetone–toluene–*n*-butanol mixture with DMF presented in Fig. 1 were carried out by E.A. Anokhina[2]. We took these data as a source for the development of diabatic distillation schemes. One model for describing vapor–liquid equilibrium in the acetone–toluene–*n*-butanol system with DMF is the Non-Random Two Liquid (NRTL) equation with parameters published by Anokhina (Footnote 2).

We considered the separation of an initial mixture containing 71.3 wt % acetone, 14.7 wt % toluene and 14 wt % *n*-butanol (power supply speed is 1000 kg/h; temperature is 61.8°C; pressure is 101.3 kPa). The pressure of the top of the columns was assumed to be 101.3 kPa. Columns with theoretical plates were considered. Calculations were carried out in the design and verification mode assuming a fixed product flow quality. The concentration of acetone and *n*-butanol in the product streams was set constant and equal to 99.5 wt %; toluene concentration equal to 99.6 wt %; DMF concentration equal to 99.99 wt % The operating parameters of the conventional scheme are presented in Table 1.

One of the key conditions for the organization of diabatic distillation schemes is the temperature difference ΔT of the heat flow (source), as well as the temperature on the plates of the distillation section of the columns into which this heat is directed (heat receiver), which must be sufficient to provide the driving force of heat exchange. On this basis, ΔT between the heat source and receiver was assumed to be at least 10°C for the purposes of modeling schemes. For a preliminary assessment of the possibility of implementing a diabatic ED scheme with specified heat transfer parameters and selecting the required compression ratio E_{comp} in the compressor, it is necessary to evaluate the temperature profiles of all columns of the traditional scheme. The corresponding temperature profiles are shown in Fig. 2.

It can be seen that the highest temperatures are observed in the reinforcing section of the C3 column. Although the temperatures of the top of columns C1 and C2 are quite close, the distillate of column C2 contains practically pure acetone, while the distillate of column C1 is a mixture of acetone and toluene. When using such a flow to ensure heat transfer, its composition may change, which in turn will entail a change in the operating mode of the C2 column. Therefore, the synthesis of diabatic distillation schemes is carried out using only the upper steam flows of the C2 and C3 columns. Based on the analysis of profiles, the following variants of diabatic ED schemes can be proposed:

– Scheme I. To heat the column C2, the steam flow of the top of the column C3 is used. In this case, the flow temperature is sufficient to ensure heat transfer without using a compressor (Fig. 3a).

– Scheme II. Column C1 is heated by steam flow from the top of column C3. Heat supply to the 24th plate is possible without the use of a compressor; for heat supply below, it is necessary to increase the temperature by compressing steam in a compressor with compression ratios from $E_{comp} = 1.1$ to $E_{comp} = 2.0$ (Fig. 3b).

– Scheme III. Heating of column C1 by steam flow of the top of column C2. In this case, the compression ratio of steam in the compressor should be greater than 3.1 (Fig. 3c).

– Scheme IV. Heating of column C1 by steam flows of the top of columns C2 and C3. Since “hot” compressors are expensive equipment, the use of more than one compressor in the scheme is likely to be economically impractical. Therefore, a variant is considered in which the heat of the steam flow of column C3 is supplied to the 24th plate of column C1; the compressor is installed only on the steam flow of column C2 (Fig. 3d).

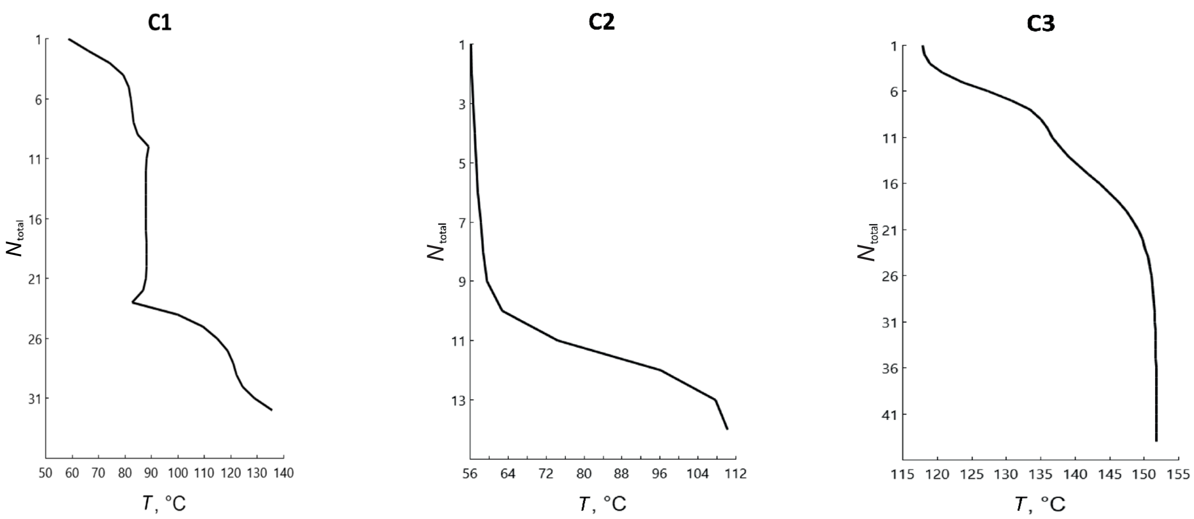
The above-mentioned variants of diabatic schemes are presented in Fig. 3. In the schemes where the compressor is used, to prevent possible cavitation, a preheater is installed in front of it, the heat duty of which is indicated by Q_{PH}.

[2] Anokhina E.A. *Extractive distillation in complexes with partially coupled heat and material flows*. Dr. Sci. Thesis (Eng.). Moscow; 2020. 549 p. (in Russ.).

Table 1. Operating parameters of conventional extractive distillation scheme (Footnote 2)

Parameters	C1	C2	C3
N_{total}	32	14	44
N_F	23	8	10
N_S	10	–	–
Q_{reb}, kW	200	151	59.3
Q_{cond}, kW	185	148	59.1
R	0.55	0.46	1.6
T_{cond}, °C	58.7	56.2	117.8
T_{reb}, °C	135.7	110.2	151.8
S, kg/h	190.68	–	–
T_S, °C	60	–	–
Q_{total}, kW	410		

Note: C1 is the extractive distillation column; C2 is the acetone separation column; C3 is the entrainer regeneration column; N_{total} is the total number of plates in a column; N_F is the feed plate number in a column; N_S is the number of the plate with the entrainer in a column; Q_{reb} is the reboiler heat duty; Q_{cond} is the condenser heat duty; R is the reflux ratio; T_{cond} is the condenser temperature; T_{reb} is the reboiler temperature; S is the entrainer flow rate; T_S is the entrainer temperature; Q_{total} is the total heat duty.



(a) (b) (c)

Fig. 2. Temperature profiles of columns of conventional extractive distillation scheme: (a) column C1, (b) column C2, (c) column C3.

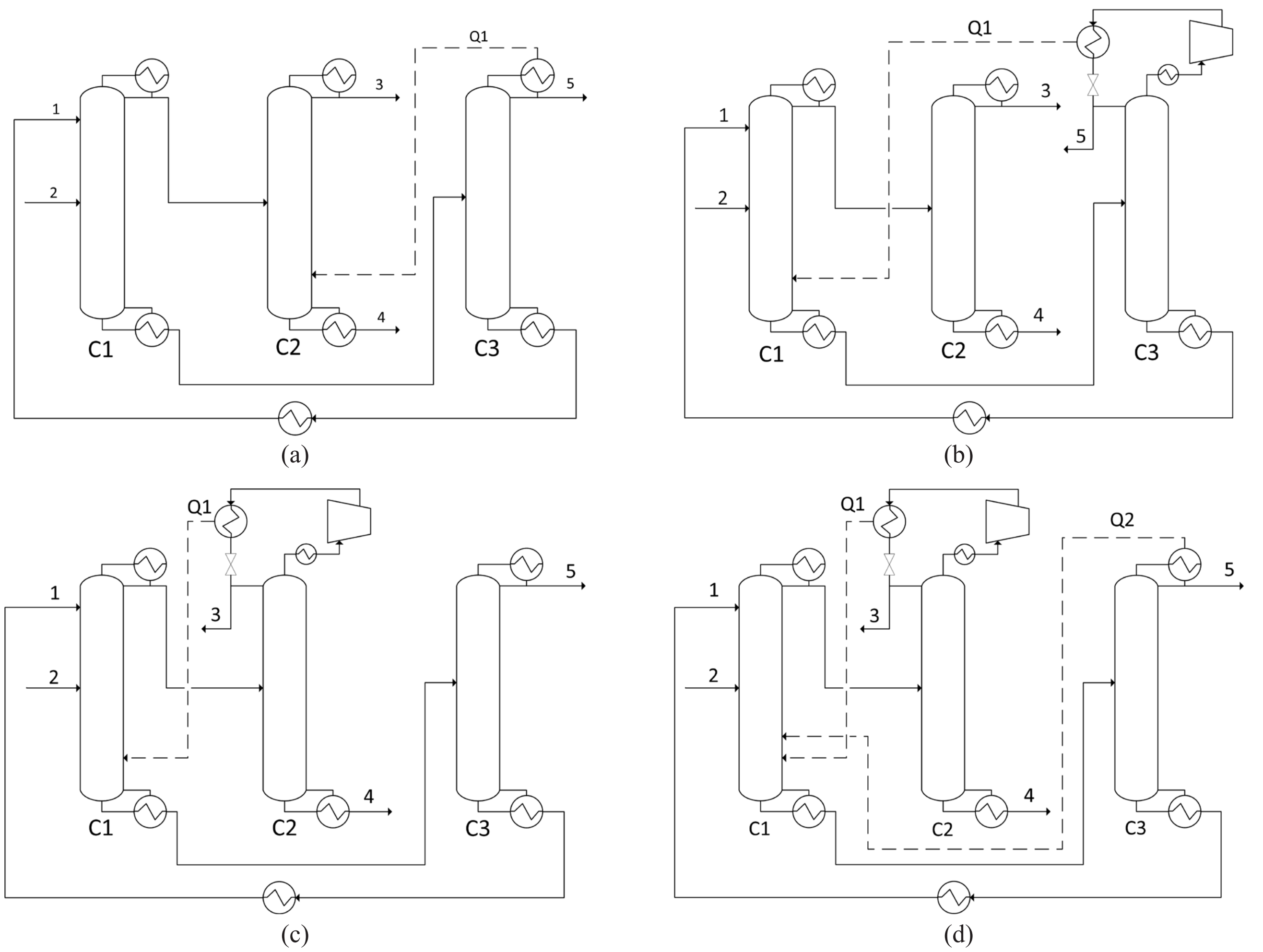


Fig. 3. Diabatic extractive distillation schemes: (a) Scheme I, (b) Scheme II, (c) Scheme III, (d) Scheme IV.

As in schemes with heat pumps, in diabatic schemes there are "hot" compressors and additional heat exchange equipment, while an electric motor is usually used to drive the compressor. In the case of the use of heat pumps in distillation processes, the authors [28] proposed a simple formula for evaluating energy efficiency through the reduced energy costs (Q_{cons}):

$$Q_{cons} = Q_{total} + 3W_{comp}, \quad (1)$$

where Q_{total} is the total energy costs in the column reboilers, kW, and W_{comp} is the power consumed by the compressor, kW.

This method can also be used to estimate energy costs in other distillation schemes that include compressors, including diabatic schemes.

The optimization of diabatic schemes was carried out according to the criterion of the reduced energy consumption Q_{cons}. Here, the optimization parameters were as follows: position of the heat supply plate to the distillation section of the column – N_{HE}; amount of heat supplied – Q_{HE}; necessary degree of steam compression in the compressor to ensure the accepted ΔT value – E_{comp}. The optimization procedure itself, however, had some differences for each of the schemes under consideration. So, in Scheme I, the temperature of the flow coming out of the top of the C3 column (T_{cond} = 117.8°C) allows for heat supply to any of the plates of the C2 column, while all the heat given off by the flow at full condensation can be used, i.e., 59.1 kW. Thus, the optimization of this scheme is reduced to the selection of the optimal position of the heat supply plate N_{HE}. The result of such a selection is presented in Table 2.

It can be seen that the most effective is the heat supply to the bottom plate of the column. When heat is supplied to the plates of the distillation section located above the 13th, the reflux ratio in the column increases slightly, as does the duty on the reboiler; however, there is no significant effect on the operating mode of the column. The optimal operating parameters of Scheme I are given in Table 3.

In Scheme II (Fig. 3b), the heat supply of the upper flow of the C3 column without the use of a compressor is possible only to the upper (24th) plate of the distillation section of the C1 column; this case is given in Table 4 as E_{comp} = 1. In other cases, to achieve the necessary temperature difference, it is necessary to increase the pressure as well as determine the necessary compression ratios. It follows from formula (1) that the maximum energy efficiency will be achieved with a minimum W_{comp}, and, accordingly, with a minimum E_{comp}, at which the necessary temperature difference is provided. It should be noted that, at E_{comp} = 2, it is already possible to supply heat to the reboiler of the column C1—that is, the implementation of an adiabatic scheme with a heat pump. The optimization results are presented in Table 4.

It can be seen that the maximum reduction in the duty on the column reboiler is achieved when heat is supplied to the 30th plate. However, the lowest energy consumption is characterized by the option with heat supply to the 24th plate and without a compressor. The operating parameters of this option are presented in Table 5.

Table 2. Optimization of operation parameters for diabatic Scheme I

N_{HE}	Q_{HE}, kW	Q_{reb}^{C2}, kW	R^{C2}
9	59.1	93.80	0.48
10	59.1	92.26	0.47
11	59.1	91.87	0.46
12	59.1	91.74	0.46
13	59.1	91.66	0.46

Note: N_{HE} is the heat supply plate number in the heat exchanger; Q_{HE} is the exchanger heat duty; C2 is the acetone separation column; Q_{reb}^{C2} is the reboiler heat duty in C2; R^{C2} is the reflux ratio in C2.

Table 3. Optimal operation parameters for diabatic Scheme I

Parameters	C1	C2	C3
N_{total}	32	14	44
N_{HE}	–	13	–
Q_{reb}, kW	200	91.7	59.3
R	0.55	0.46	1.6
Q_{HE}, kW	–	59.1	–
Q_{cons}, kW	351		

Note: N_{total} is the total number of plates in the column; N_{HE} is the heat supply plate number in the heat exchanger; Q_{reb} is the reboiler heat duty; R is the reflux ratio; Q_{HE} is the exchanger heat duty; Q_{cons} is the reduced energy consumption in the scheme with thermal integration.

Scheme III was optimized in a similar way (Fig. 3c). However, here it was found that for each plate N_{HE} there is a limit amount of supplied heat Q_{HE}^{max}, above which it becomes impossible to obtain a distillate of a given quality. At the same time, the higher the plate N_{HE} is located in the column, the smaller the value of Q_{HE}^{max}. This is probably because, at a fixed N_{HE}, the total concentration of *n*-butanol and DMF increases on the plates of the reinforcing section with an increase in Q_{HE}; moreover, the closer the heat supply level is located to the extractive section, the more noticeable the influence of Q_{HE} on this concentration.

Table 4. Optimization of operation parameters for diabatic Scheme II

E_{comp}	W_{comp}, kW	N_{HE}	Q_{HE}, kW	Q_{reb}^{C1}, kW	Q_{PH}, kW	Q_{cons}, kW
1.0	0	24	59.1	134.0	0	134.0
1.1	0.6	25	59.3	132.6	0.4	134.8
1.2	1.1	26	58.2	133.0	0.4	136.7
1.3	1.6	27	58.0	132.8	0.4	138.0
1.4	2.1	28	57.5	132.6	0.4	139.3
1.5	2.5	30	57.4	132.0	0.6	140.1
1.7	3.3	31	56.9	132.1	0.7	142.7
2.0	4.4	32	56.7	131.3	0.9	145.4

Note: E_{comp} is the compressor compression ratio; W_{comp} is the compressor power consumption; N_{HE} is the heat supply plate number in the heat exchanger; Q_{HE} is the exchanger heat duty; C1 is the extractive distillation column; Q_{reb}^{C1} is the reboiler heat duty in C1; Q_{PH} is the heat duty in the preheater; Q_{cons} is the reduced energy consumption in the scheme with thermal integration.

Table 5. Optimal operation parameters for diabatic Scheme II

Parameters	C1	C2	C3
N_{total}	32	14	44
N_{HE}	24	–	–
Q_{reb}, kW	134	151	59.3
R	0.50	0.46	1.6
Q_{HE}, kW	59.1	–	–
Q_{cons}, kW	344		

Note: N_{total} is the total number of plates in the column; N_{HE} is the heat supply plate number in the heat exchanger; Q_{reb} is the reboiler heat duty; R is the reflux ratio; Q_{HE} is the exchanger heat duty; Q_{cons} is the reduced energy consumption in the scheme with thermal integration.

The optimization results are presented in Table 6, and the optimal operating parameters are shown in Table 7.

When modeling Scheme IV (Fig. 3d), as already mentioned, it was assumed that only one compressor was used in the scheme. Since it is only possible to bring the heat of the steam flow of the column C3 to the 24th plate without additional compression, the value of the plate number of the first flow supply N_{HE}^1 is fixed. Then, during optimization, it is necessary to determine both the optimal position of the heat supply plate from the steam flow of the column C2, N_{HE}^2, the compression ratio Ecomp, as well as the optimal ratio of the first and second heat flows Q_{HE}^1 and Q_{HE}^2. In this case, optimization was performed by a combination of sequential quadratic programming methods and the *Sensitivity Analysis* automatic iteration utility built into the *Aspen Plus* software package. The optimization result is presented in the Table 8; the optimal operating parameters are shown in Table 9.

RESULTS AND DISCUSSION

During the conducted studies, four different variants of heat integration between the columns of the ED scheme of a mixture of acetone–toluene–*n*-butanol with DMF as an entrainer were considered. A comparison of the proposed schemes of diabatic distillation with the traditional ED scheme of two selected columns according to the criterion of the above energy consumption is presented in Table 10. The reduction of the reduced energy consumption ΔQ_{cons} was calculated by the formula:

$$\Delta Q_{cons} = (Q_{total} - Q_{cons}) / Q_{total} \times 100\%, \quad (2)$$

where Q_{total} is the total energy costs in the reboilers of the columns of the traditional ED scheme, and Q_{cons} is the reduced energy costs of the scheme with heat integration.

As shown in Table 10, the maximum reduction in the reduced energy consumption is achieved in Scheme IV. However, in order to ensure the operability of Scheme IV, the use of a compressor with a high (E_{comp} = 5) compression ratio is required, which may negatively affect the cost of such an installation. In turn, for the operation of Schemes I and II, an increase in flow pressure—and consequent use of expensive compressor equipment—is not required; here, reduced energy consumption compared to the traditional scheme of Schemes I and II is commensurate with Scheme IV.

Table 6. Optimization of operation parameters for diabatic Scheme III

E_{comp}	W_{comp}, kW	N_{HE}	Q_{HE}, kW	Q_{reb}^{C1}, kW	Q_{PH}, kW	Q_{cons}, kW
3.0	15.2	24	61.7	133.2	0.5	179.3
4.0	19.5	26	75.5	119.3	0.5	178.3
4.3	20.9	27	84.8	109.6	0.5	172.8
4.6	21.7	28	97.4	97.4	0.6	163.1
4.8	26.5	29	114.9	79.6	0.7	159.8
5.0	32.6	30	137.4	55.9	0.8	154.5
5.4	34.3	31	136.5	62.4	0.8	166.1
6.3	37.8	32	134.5	65.5	0.8	179.7

Note: E_{comp} is the compressor compression ratio; W_{comp} is the compressor power consumption; N_{HE} is the heat supply plate number in the heat exchanger; Q_{HE} is the exchanger heat duty; C1 is the extractive distillation column; Q_{reb}^{C1} is the reboiler heat duty in C1; Q_{PH} is the heat duty in the preheater; Q_{cons} is the reduced energy consumption in the scheme with thermal integration.

Table 7. Optimal operation parameters for diabatic Scheme III

Parameters	C1	C2	C3
N_{total}	32	14	44
N_{HE}	30	–	–
Q_{reb}, kW	55.9	151	59.3
R	0.50	0.46	1.6
Q_{HE}, kW	137.4	–	–
Q_{PH}, kW	0.8	–	–
E_{comp}	5.0	–	–
W_{comp}, kW	32.6	–	–
Q_{cons}, kW	365		

Note: N_{total} is the total number of plates in the column; N_{HE} is the heat supply plate number in the heat exchanger; Q_{reb} is the reboiler heat duty; R is the reflux ratio; Q_{HE} is the exchanger heat duty; Q_{PH} is the heat duty in the preheater; E_{comp} is the compressor compression ratio; W_{comp} is the compressor power consumption; Q_{cons} is the reduced energy consumption in the scheme with thermal integration.

Table 8. Optimization of operation parameters for diabatic Scheme IV

E_{comp}	W_{comp}, kW	N_{HE}^2	Q_{HE}^1, kW	Q_{HE}^2, kW	Q_{reb}^{C1}, kW	Q_{PH}, kW	Q_{cons}, kW
3.5	17.4	25	27	35	126	0.8	178
4	19.4	26	16	55	123	0.8	181
4.3	20.5	27	14	76	113	0.8	175
4.6	21.5	28	16	93	99	0.8	164
4.8	24.8	29	13	105	83	0.8	157
5	32.6	30	25	136	31.7	0.8	130
5.4	34.2	31	27	136	37	0.8	140

Note: E_{comp} is the compressor compression ratio; W_{comp} is the compressor power consumption; N_{HE}^2 is the second flow plate number in the heat exchanger; Q_{HE}^1 is the first flow heat duty in the heat exchanger; Q_{HE}^2 is the second flow heat duty in the heat exchanger; C1 is the extractive distillation column; Q_{reb}^{C1} is the reboiler heat duty in C1; Q_{PH} is the heat duty in the preheater; Q_{cons} is the reduced energy consumption in the scheme with thermal integration.

Table 9. Optimal operation parameters for diabatic Scheme IV

Parameters	C1	C2	C3
N_{total}	32	14	44
N_{HE}	24/31	–	–
Q_{reb}, kW	31.7	151	59.3
R	0.49	0.46	1.6
Q_{HE}, kW	137/25	–	–
Q_{PH}, kW	0.8	–	–
E_{comp}	5.0	–	–
W_{comp}, kW	32.6	–	–
Q_{cons}, kW	341		

Note: N_{total} is the total number of plates in the column; N_{HE} is the heat supply plate number in the heat exchanger; Q_{reb} is the reboiler heat duty; R is the reflux ratio; Q_{HE} is the exchanger heat duty; Q_{PH} is the heat duty in the preheater; E_{comp} is the compressor compression ratio; W_{comp} is the compressor power consumption; Q_{cons} is the reduced energy consumption in the scheme with heat integration.

Table 10. Energy efficiency of various variants of extractive distillation schemes

Parameters	Scheme				
	Convent.	I	II	III	IV
Q_{total}, kW	410	351	344	266	242
W_{comp}, kW	0	0	0	32.6	32.6
Q_{cons}, kW	410	351	344	365	341
ΔQ_{cons}, %	0	14	16	11	17

Note: Q_{total} is total energy costs in reboilers of the columns in the conventional scheme; W_{comp} is the compressor power consumption; Q_{cons} is the reduced energy consumption in the heat integration scheme; ΔQ_{cons} is the decrease in the reduced energy consumption in the heat integration scheme.

CONCLUSIONS

The application of diabatic schemes in the ED mixture of acetone–toluene–*n*-butanol with DMF is considered. The use of such schemes is shown to reduce applicable energy costs by 11–17%. While the maximum reduction in energy consumption is achieved in Scheme IV using a compressor, the efficiency of schemes without a compressor is slightly lower. However, the technological design of such solutions is significantly simpler, making them more attractive from the perspective of their practical implementation. Thus, an unconventional scheme of external heat integration for ED processes using a diabatic process in one or several columns is proposed. Given certain characteristics of the separated mixture, the proposed solution can be used in the absence of heat pumps or forced pressure increases in individual sections or columns of the scheme.

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Authors' contributions

P.S. Klauzner – planning and conducting research, analyzing research materials, writing the manuscript;

D.G. Rudakov – conducting research, analyzing research materials;

E.A. Anokhina – management and scientific consulting;

A.V. Timoshenko – formulation of the scientific concept, general management.

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