A SHORT NOTE ABOUT ENERGY-EFFICIENCY PERFORMANCE OF THERMALLY COUPLED DISTILLATION SEQUENCES

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In this work, we present a comparative study of the energy-efficiency performance between conventional distillation sequences and thermally coupled distillation arrangements (TCDs) for the separation of ternary mixtures of hydrocarbons under the action of feedback control loops. The influence of the relative ease of separation of the feed mixture and its composition was analyzed. The feedback analysis was conducted through servos tests with individual charges in the set points for each of the three product streams. Standard PI controllers were used for each loop. The results show an apparent trend regarding the sequence with a better dynamic performance. Generally, TCDs systems performed better for the control of the extreme components of the ternary mixtures (A and C), while the conventional sequences offered a better dynamic behavior for the control of the intermediate component (B). The only case in which there was a dominant structure for all control loops was when the feed contained low amount of the intermediate component and the mixture had similar relative volatilities. The Petlyuk columns provided the optimal choice in each case, which contradicts the general expectations regarding its control behavior. In addition, the energy demands during the dynamic responses were significantly lower than those observed for the other distillation sequences. TCDs options, therefore, are not only more energy efficient than the conventional sequences, but there are cases in which they also offer better feedback control properties.

On présente dans ce travail une étude comparative de la performance d'efficacité énergétique entre les séquences de distillation conventionnelles et les configurations de distillation couplées thermiquement (TCDs) pour la séparation de mélanges ternaires d'hydrocarbures sous l'action de boucles de contrôle d'asservissement. L'influence de la facilité relative de séparation du mélanges d'élaboration et de sa composition est analysée. L'analyse de redimensionnement est réalisée grâce à des tests d'asservissement avec des changements individuels dans les points de consigne pour chacun des trois produits de sortie. Des contrôleurs PI standards ont été utilisés pour chaque boucle. Les résultats montrent une tendance apparente pour le séquence ayant une meilleure performance dynamique. Généralement, les options TCDs sont meilleures pour le contrôle des composantes extrêmes du mélanges ternaire (A et C), tandis que les séquences conventionnelles offrent un meilleur contrôle dynamique pour le contrôle de la composante intermédiaire (B). L'unique cas où il y a une structure dominante pour toutes les boucles de contrôle, c'est lorsque l'alimentation contient de faibles quantités de la composante intermédiaire et le mélanges a la même volatilité relative. La colonne Petlyuk est le choix optimal dans ce cas, ce qui contredit les attentes générales concernant son comportement de contrôle. En outre, les demandes d'énergie pendant les réponses dynamiques sont significativement plus faibles que celles observées pour les autres séquences de distillation. Ainsi, non seulement les options TCDs sont plus efficaces que les séquences conventionnelles, mais il y a des cas où elles offrent également de meilleures propriétés de contrôle d'asservissement.

Keywords: conventional distillation sequences, thermally coupled distillation, energy-efficiency performance

Distillation is widely used separation method in the process industries and it is the largest energy consumer among individual process units. Improvements of energy efficiency in distillation systems is still an active research field. Among the issues concerned with the improvement of energy efficiency of distillation systems, the optimal design and synthesis of multicomponent distillation schemes is still one of the most challenging problems. The optimal design of distillation systems of multicomponent separations, thermally coupled distillation

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systems, TCDS (which is achieved through the implementation of interconnecting liquid and vapour streams between two columns) is considered to be more promising due to its potential savings in both energy and capital costs (Pelnikov et al., 1995; Fitt, 1993). A good number of publications have been reported on TCDS structures, especially for ternary mixtures. The three TCDS schemes that have been studied more in detail are the system with a side rectifier (TCDS-SS, Figure 1b), the scheme with a side stripper (TCDS-SS, Figure 1b), and the fully thermally coupled distillation system (or Pelnikov column, Figure 1c). These schemes can offer energy savings of around 30% in contrast to the conventional distillation trains (Figure 2) widely used in the chemical industry for the separation of feeds with low or high content of the intermediate component (Boddoo and Rudd, 1978; Klone and Malone, 1988; Antilous and Mazuy, 1996; Teomann and Grossmann, 2000). Most of these results were obtained through energy consumption calculations at minimum reflux conditions and have spawned the development of more formal design procedures. Hernández and Jiménez (1996, 1999a) have reported the use of optimization strategies for TCDS schemes to design designs with minimum energy consumption. TCDS options are more efficient because the remaining in the intermediate component, presented naturally in the conventional distillation sequences and translated into higher energy consumption, is reduced significantly, thus reducing energy requirements (Fattah and Smith, 1992; Hernandez et al., 2003). When comparing the energy savings of the integrated schemes, it has been found that in general the Pelnikov column offers better savings than the systems with side columns. Even though the Pelnikov column, the most important TCDS sequence, was introduced some 50 years ago (Brguna, 1937), its use has been limited because of potential control problems (Fellows and Kolkowitzki, 1990; Serra et al., 2003). Recent research efforts have been conducted to understand the operational properties of TCDS. The works of Wolt and Shogekact (1995), Abdul-Mutallib and Smith (1998), Hernandez and Jiménez (1999b), Jiménez et al. (2001) and Segovia-Hernández et al. (2002) have shown that some of these integrated options are controllable, so that their potential implementation would probably not be at the expense of control problems. Recently, motivated by the expected savings in both energy and capital investment, industrial implementations of TCDS in companies such as BASF have been reported (Kahle and Schuemann, 2002).

It is important to mention that TCDS options have been used for the separation of hydrocarbon mixtures and air into oxygen, nitrogen and argon (Fitt, 1993), but a common result is that important savings in energy can be obtained in contrast to conventional distillation sequences. The most used complex distillation sequence is the fully thermally coupled distillation sequence, or Pelnikov column, which can be implemented in industrial practice by using a divided-wall distillation column. TCDS has implemented this Pelnikov-type column obtaining savings in both energy and capital costs. Also, Grossmann et al. (2005) have reported the use of mathematical programming for the synthesis of complex distillation columns for the separation of nonracemic and racemize mixtures. Their results show that significant energy savings can be obtained.

In this paper we present a comparative study of the energy efficiency performance between conventional distillation sequences and TCDS for the separation of ternary mixtures of hydrocarbons under the action of feedstock control loops.

**DESIGN PROCEDURE**

The design and optimization of the conventional distillation sequences are well known. In this work the conventional distillation sequences (Figure 2) were designed and optimized using the process simulator Aspen Plus II.13. In the case of TCDS the design and optimization is more complicated because of recycle streams between the two distillation columns. The optimized design is obtained in two stages: (i) the conventional distillation sequences of Figure 2 were used to provide an initial tray structure; (ii) then, recycle streams were introduced between columns as indicated in Figure 1. For the TCDS-SS (Figure 1c), a vapour recycle (VR) stream is taken from the first column and introduced in the bottoms of the second column (removing the residue). The recycle stream was varied until minimum energy consumption in the recollier of the first column was detected for
Table 1. Energy requirements (kW) for the separation of the ternary mixtures

<table>
<thead>
<tr>
<th>Feed</th>
<th>Direct sequence</th>
<th>Indirect sequence</th>
<th>TCDS-SR</th>
<th>TCDS-SS</th>
<th>Petyuk column</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixture M1</td>
<td>956.3</td>
<td>1039.3</td>
<td>738.6</td>
<td>820.0</td>
<td>920.9</td>
</tr>
<tr>
<td>Mixture M2</td>
<td>1202.1</td>
<td>1275.6</td>
<td>927.9</td>
<td>920.9</td>
<td>628.9</td>
</tr>
<tr>
<td>Mixture M3</td>
<td>2177.2</td>
<td>2313.4</td>
<td>2082.3</td>
<td>2020.5</td>
<td>1846.0</td>
</tr>
<tr>
<td>Mixture M4</td>
<td>2290.2</td>
<td>2151.8</td>
<td>2072.6</td>
<td>2038.1</td>
<td>1799.8</td>
</tr>
<tr>
<td>Mixture M5</td>
<td>1139.0</td>
<td>1666.4</td>
<td>1651.1</td>
<td>1825.5</td>
<td>703.1</td>
</tr>
<tr>
<td>Mixture M6</td>
<td>1686.5</td>
<td>1553.0</td>
<td>1131.0</td>
<td>1311.2</td>
<td>762.1</td>
</tr>
</tbody>
</table>

Table 2. Mixture results for mixture M1, composition H1

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Component A</th>
<th>Component B</th>
<th>Component C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td>7.9244 X 10^-3</td>
<td>5.2856 X 10^-3</td>
<td>2.9796 X 10^-3</td>
</tr>
<tr>
<td>Indirect</td>
<td>4.3076 X 10^-3</td>
<td>3.4576 X 10^-3</td>
<td>2.6487 X 10^-3</td>
</tr>
<tr>
<td>TCDS-SR</td>
<td>3.5136 X 10^-3</td>
<td>2.7214 X 10^-3</td>
<td>7.9523 X 10^-4</td>
</tr>
<tr>
<td>TCDS-SS</td>
<td>7.6185 X 10^-4</td>
<td>8.9276 X 10^-4</td>
<td>3.8084 X 10^-4</td>
</tr>
<tr>
<td>Petyuk</td>
<td>1.4924 X 10^-4</td>
<td>3.4927 X 10^-4</td>
<td>2.1067 X 10^-4</td>
</tr>
</tbody>
</table>

ENERGY DEMANDBS

The results on energy requirements were obtained after the optimization procedure described earlier was carried out on the recycle streams for the three integrated sequences. Table 1 shows the energy requirements for each integrated scheme and conventional sequence. When mixture M1 was considered, the Petyuk system showed the best potential, offering savings in energy consumption of up to 30% with respect to the conventional distillation sequences. The TCDS-SR and TCDS-SS sequences required between 14 and 20% less energy consumption than the conventional sequences. The superior behavior on energy efficiency of the Petyuk column was also observed for mixtures M2 and M3 (Table 1). In the case of mixture M2 the Petyuk column can offer savings in energy consumption of up to 15% with respect to the conventional sequences, while the savings achieved by the TCDS-SR and TCDS-SS schemes are in the order of 10%. In the case of mixture M3 the Petyuk column requires between 40 and 50% less energy consumption, whereas the TCDS-SR and TCDS-SS options offered energy savings of up to 30% with respect to the conventional sequences. In general, the Petyuk column showed the highest energy savings with respect to the direct and indirect conventional distillation sequences for all the case studies considered.

ENERGY-EFFICIENCY DYNAMIC PERFORMANCE

The dynamic performance of the energy-efficient designs of TCDS was analyzed following the responses to set point changes for product composition on each of the three product streams. The three control loops for each conventional and TCDS were assumed to operate under closed loop operation. Mixture M1

The IAE values obtained (Feed F1) for each composition control loop of the distillation sequences under analysis is shown in Table 2. It is observed that the Petyuk column offers the best
dynamic behaviour, which is reflected in the lowest values of TAE, for the control of the three product streams. The dynamic response of each control loop when the Petlyuk column was considered is displayed in Figure 3. A comparison is made to the response of the widely-used direct distillation sequence. One may notice in particular how the direct sequence is unable to control the composition of the intermediate component, while the Petlyuk column provides a smooth response, with a relatively short settling time. It is interesting to notice that for this mixture with an ESI = 1 and a low content of the intermediate component in the feed, the Petlyuk column offers the highest energy savings and also shows the best dynamic performance from the five distillation sequences under consideration. When the content of the intermediate component in the feed was raised from 20 to 70% (feed F2), significant changes in the dynamic responses of the distillation systems were observed. The first remark is that the Petlyuk column does not provide the best choice from an operational point of view. A second observation is that the best choice depends on the control loop of primary interest. When the control of the light (A) or the heavy (C) component of the ternary mixture is of primary concern, then the TCDS-SS scheme provides the best option since it offers the lowest TAE values for these control loops. However, if the control policy calls for the composition of the intermediate (B) component, the indirect sequence shows the best behaviour, with the lowest value of TAE. Overall, it may be stated that for this type of mixture, the TCDS-SS may offer a good compromise, providing energy savings with respect to conventional sequences and good dynamic properties. In these cases, the control valves showed a quick adjustment towards the new steady state of the manipulated variables, which may also be interpreted as a lower energy consumption (in other words, lower control effort) in the dynamic behaviour of the sequences.

Other Mixtures
The analysis was completed with the consideration of the other four cases of studies. Some trends were observed (Tables 1 and 2). For one thing, the best option depends on the amount of intermediate component. Also, it was found that the best sequence, based on the TAE criterion, for the control of the light component was also the best choice for the control of the heavy component, but a different separation scheme provided the best option for the control of the intermediate component. If the feed contains less amounts of the intermediate component, the Petlyuk column shows the best dynamic behaviour for the control of the light and heavy components, while the indirect sequence provides the best responses for the control of the intermediate component. For feed mixtures with high content of the intermediate component, sequences with side columns showed the best responses for the control of light and heavy components, and conventional sequences were better for the control of the intermediate component. The case of separability index also shows some effect on the topology of the preferred separation scheme when the feed contains a high amount of the intermediate component. For mixtures with ESI higher than 1, the separation systems with two top distillate streams (TCDS-SS or the direct sequence) provide the best dynamic responses, which may also be interpreted as a lower energy consumption (the control valves show a quick adjustment towards the new steady state). Finally, we consider the Petlyuk type column, or
From energy considerations the Pellyuk column was shown to provide in general the best option. Although the results from the dynamic analysis do not show a dominant option, some trends were observed. One factor that affects the feedback behaviour of the distillation systems is the amount of intermediate component, and the other one is the control point under consideration. Integrated sequences showed a better feedback behaviour when the control points were set at the lightest of the heaviest components. For most cases, the influence of the amount of intermediate component as follows: the Pellyuk column performed better for feed mixtures with a low amount of component B, while the sequences with side columns provided the best dynamic performance when the amount of the intermediate component was high. When the control was focused on the intermediate component, the results changed noticeably since the conventional sequences performed better than the integrated options. The results of the study have shown that the incentive for the use of TCDIS provided by their lower energy requirements, should not be overlooked in the case of their dynamic properties. The lower control efforts required by TCDIS for some of the case studies indicate that these options may also provide a more efficient use of energy during its transient times.

**NOMENCLATURE**

- ABC: ternary mixture
- A: light component
- B: intermediate component
- C: heavy component
- ESI: easy of separation index
- IAE: integral of the absolute error
- LF: long-term feasibility
- TCDIS: thermally coupled distillation sequences

**REFERENCES**


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