Two Alternatives to Thermally Coupled Distillation Systems with Side Columns

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DOI 10.1002/aic.10209
Published online in Wiley InterScience (www.interscience.wiley.com).

Keywords: distillation, thermally coupled distillation, energy integration

Thermally coupled distillation systems (TCDS) have been proposed to perform distillation separation tasks with the incentive of achieving lower energy consumption levels with respect to conventional distillation sequences. Through the implementation of a vapor–liquid interconnection between two columns, a condenser or a reboiler of one of the columns is eliminated, and if a proper search on the operating conditions is performed, such an interconnection can provide energy savings (Hernández and Jiménez, 1999; Triantafyllou and Smith, 1992). TCDS for ternary mixtures have particularly been analyzed with special interest. Two of the schemes that have received special attention are systems with side columns (Finn, 1993; Hernández and Jiménez, 1996): the thermally coupled system with a side rectifier, TCDS-SR, and the coupled system with a side stripper, TCDS-SS. Those systems are shown in Figure 1.

Many times, the design of integrated systems creates operational and control problems with respect to simpler designs. In particular, the presence of recycle streams for TCDS schemes has influenced the notion that control problems might be expected during the operation of those systems with respect to the rather well-known behavior of conventional distillation sequences. That has been one of the main reasons for the lack of industrial implementation of TCDS schemes. Recently, Agrawal (2000) proposed two arrangements that emerge from modifications to the systems shown in Figure 1. Such new systems are shown in Figure 2. The first modified arrangement [a direct sequence with a side stream (DSS) from the first column] eliminates the recycle stream of the TCDS-SR by reproducing the bottom section (section 4) of the first column within the second column, which affects the structure of the original side rectifier. For the second choice [an indirect sequence with a side stream (ISS) from the first column], the vapor interconnection of the TCDS-SS is eliminated and the top section of the first column (section 3) is added to the second column, affecting the original side stripper. Therefore, the new arrangements eliminate the intercolumn vapor transfer and do not contain recycle streams, and the second column of each sequence is transformed into a conventional distillation column. The resulting new structures thus seem to provide simpler systems to control and operate.

In this work we analyze the energy performance of the new arrangements and compare them to the behavior of the original integrated systems with side columns.

Design Method and Case Studies

For the design of the TCDS arrangements, conventional sequences were first obtained (the direct sequence for the TCDS-SR, and the indirect sequence for the TCDS-SS). The sections performing similar tasks between the two types of systems were identified to produce the tray arrangement of the thermally coupled design. Such a design was then tested and optimized for energy consumption through rigorous simulations. Further details on the design procedure are given by Hernández and Jiménez (1996).

The new schemes were then obtained directly from the TCDS arrangements following the simple tray section analogies depicted in Figures 1 and 2. The new systems were also subjected to an optimization procedure to detect the values of the side stream flow rates from the first column that minimized their energy consumptions. It should be noted that the range for the search procedure for these structures is more restricted than that for the TCDS structures because of mass balance considerations. The bounds for columns with side streams have been explained by Glinos and Malone (1985).

To compare the behavior of the sequences with and without thermal coupling, three ternary mixtures with different values of the ease of separability index (ESI = α_{AB}/α_{BC}), as defined by Tedder and Rudd (1978), were considered. A description of the mixtures is given in Table 1; the feed flow rate was 45.36

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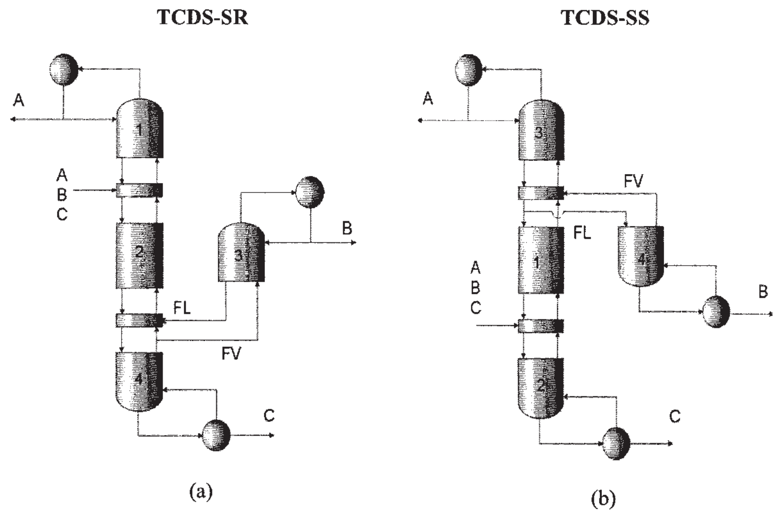

Figure 1. Thermally coupled distillation sequences with side columns.

(a) With a side rectifier, (b) with a side stripper.

kmol h^{-1}. The design pressure for each separation was chosen to ensure the use of cooling water in the condensers. Three feed compositions were assumed for each mixture (Table 2), to reflect the effect of the content of the intermediate component. The design of each sequence was carried out to meet a recovery of 98% of the components for each of the feed mixtures considered.

Results and Discussion

Table 3 shows the results obtained for the TCDS schemes after the interconnection flows for each scheme were optimized; energy values refer to the total energy supplied to the reboilers for each sequence. It can be observed that the TCDS with side stripper provides higher energy savings than that of the system with side rectifier in most cases. A comparison with the heat duties required by the conventional sequences yields savings of about 20% for feed streams with low content of the intermediate component; those savings gradually decrease as the concentration of component B in the feed increases.

Table 4 shows the heat duties required by the new sequences with no recycle streams. For mixture M1, heat duties are observed similar to those required by the systems with thermal coupling, except for the feed with a high content of component B, in which case the new arrangements provide a more efficient choice. For mixture M2 (ESI $>$ 1), the DSS option slightly improves the energy savings provided by the TCDS-SR; however, the ISS requires a higher energy level than that of the TCDS-SS for all feeds considered (about 13% higher). In the case of mixture M3 (ESI $<$ 1), DSS shows heat duties about 11% higher than those of TCDS-SR, and ISS shows heat requirements similar to those of TCDS-SS, with slight savings for equimolar mixtures. Overall, it can be observed that the new arrangements provide similar or better energy performances than those of the original TCDS arrangements in most

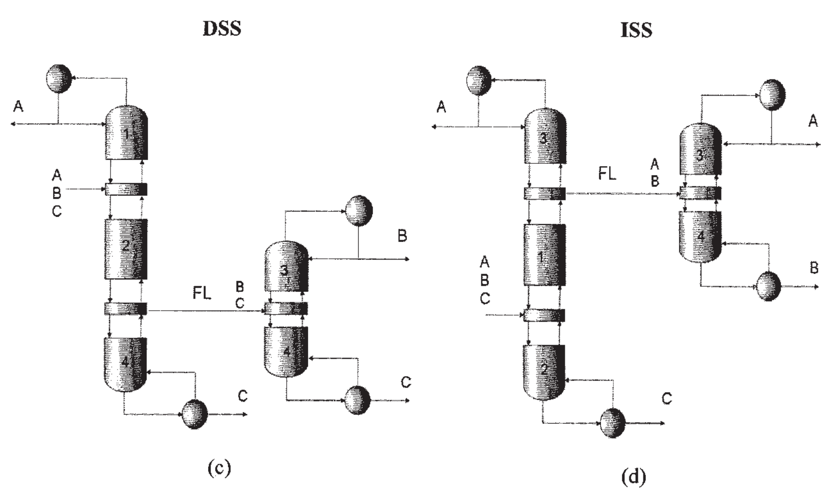

Figure 2. Modified arrangements to the coupled sequences with side columns.

(a) Modification to TCDS-SR; (b) modification to TCDS-SS.

Table 1. Mixtures Analyzed

Mixture	Components A/B/C	ESI (α_{AB}/α_{BC})	Pressure (bar)
M1	n-pentane/n-hexane/n-heptane	1.04	2.068
M2	n-butane/i-pentane/n-pentane	1.86	4.826
M3	i-pentane/n-pentane/n-hexane	0.47	2.068

cases. Interestingly, when ESI differs from 1, the best sequence from the new arrangements performs the most difficult split in the last column. When this heuristic rule is not followed, the new sequence diminishes the energy savings provided by the thermally coupled options, although even in those cases they still provide some energy savings with respect to the conventional direct and indirect sequences.

The reason for the thermal efficiency of the new arrangements has to do with the elimination (or reduction) of the remixing of the intermediate component that is typically observed in the operation of conventional sequences for ternary mixtures. Figure 3 shows, for instance, the composition profile of the intermediate component for the case of the DSS structure separating mixture M2 with feed F2. The extraction of the side stream from the first column is performed at the tray where the composition of component B reaches a maximum, thus avoiding the remixing of such component. This situation corresponds to the best energy-efficient separation of the ternary mixture. For the cases in which a lower energy efficiency was observed for the new arrangements, the best operation that could be achieved, given the tray structures provided by the thermally coupled schemes, was such that the composition of component B at the interconnecting tray did not correspond to a maximum value. One such case can be seen in Figure 4, where the composition profile of the intermediate component is shown for the operation of the DSS structure with mixture M3, feed F2. After the optimization procedure was carried out, the most efficient operation was such that some remixing was unavoidable, which affected the energy consumption with respect to the thermally coupled systems; such a remixing effect, however, was reduced with respect to the conventional sequences.

Table 2. Feed Composition

Feed	Composition (mol %)
F1	40/20/40
F2	33/33/33
F3	15/70/15

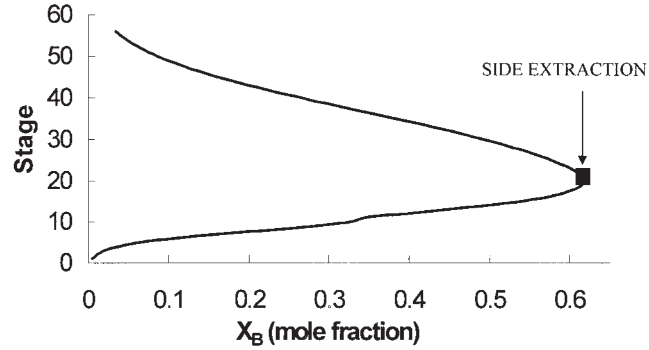

Figure 3. Composition profile of component B for the DSS system, mixture M2–F2

We have shown that the new arrangements can provide potential energy savings for the separation of ternary mixtures. The incentive for further consideration of the new sequences clearly improves when one includes the expected improvement in operation properties of the new sequences with respect to the TCDS with side columns.

There is, however, one additional issue worth discussing. The optimization curves for each type of arrangement show interesting features. Figure 5, for instance, shows the response curves obtained during the optimization for energy consumption of the TCDS-SR and the DSS options for mixture M2. Although the energy efficiency of the new structure is similar to or better than that of the TCDS, the response surfaces of the TCDS-SR structure show smoother behavior than those of the new sequence. That means that variations in operating conditions will more noticeably affect the new design, which implies that such a design will very likely be more difficult to control. The results for the other mixtures showed that, for feeds with low or medium content of the intermediate component, the design with no recycle stream is more sensitive to changes in operating conditions.

The response curves for mixture M2 for the other two structures under analysis are shown in Figure 6. It can be noticed how the system with the recycle stream clearly provides a more stable performance, with respect to potential changes in operating conditions, than that of the alternative arrangement with no recycle stream for feeds with low or

Table 3. Minimum Heat Duties for Thermally Coupled Systems with Side Columns (kW)

	M1		M2		M3	
Feed	TCDS-SR	TCDS-SS	TCDS-SR	TCDS-SS	TCDS-SR	TCDS-SS
F1	606.99	579.76	1344.25	1255.39	1209.37	1185.57
F2	731.76	669.47	1563.22	1460.95	1295.64	1299.59
F3	1026.79	915.63	2304.85	2173.67	1759.59	1737.56

Table 4. Minimum Heat Duties for New Systems without Vapor Interconnection (kW)

	M1		M2		M3	
Feed	DSS	ISS	DSS	ISS	DSS	ISS
F1	607.07	582.59	1316.27	1421.07	1367.57	1192.96
F2	723.17	659.41	1439.25	1646.10	1442.07	1257.48
F3	964.19	890.16	2191.23	2481.35	1954.46	1749.23

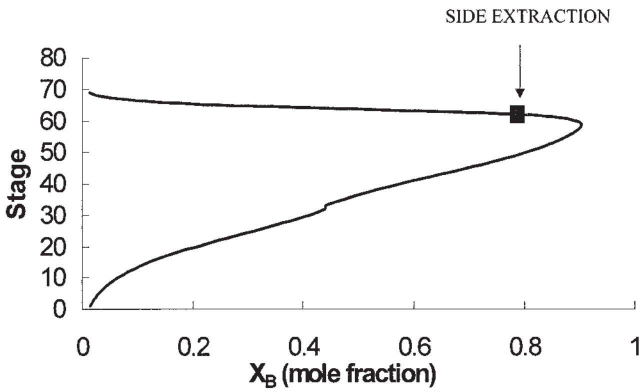

Figure 4. Composition profile of component B for the DSS system, mixture M3–F2.

medium content of component B. For feeds with high content of component B, the difference is not as sharp. That trend was also observed for the other mixtures.

In general, the new systems, which were proposed as alternatives with better operational properties than those of the TCDS with side columns, show a higher sensitivity to small changes in operating conditions than that of the integrated schemes. Although a formal method of dynamic analysis, such as that shown by Jiménez et al. (2001), would still be needed, these results seem to indicate that, contrary to the original expectation, the new systems might be more difficult to control than the integrated arrangements.

Conclusions

An analysis on energy consumption of two new sequences that arise from modifications to the thermally coupled systems with side columns has been presented. It has been shown that the new systems can perform the separations tasks with energy

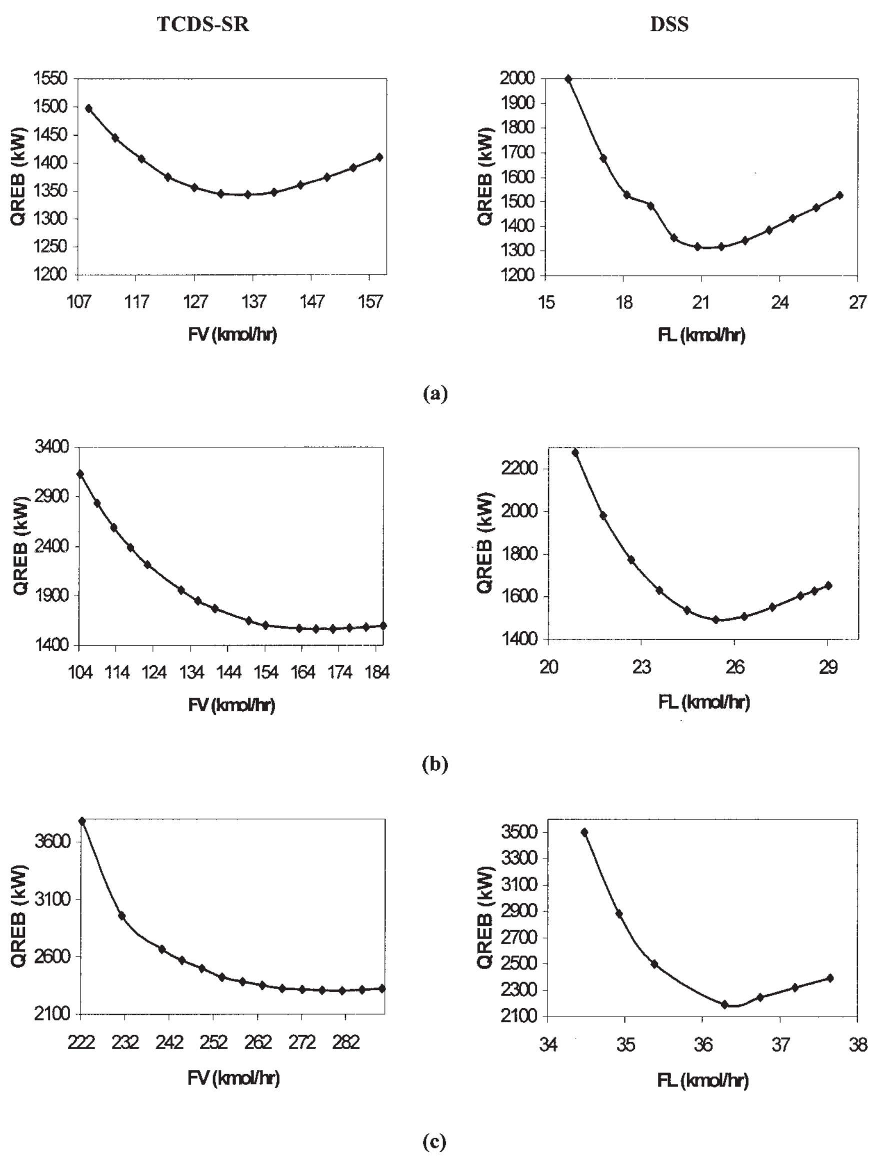

Figure 5. Response curves for TCDS-SR and DSS, mixtures M2–F1 (a), M2–F2 (b), and M2–F3 (c).

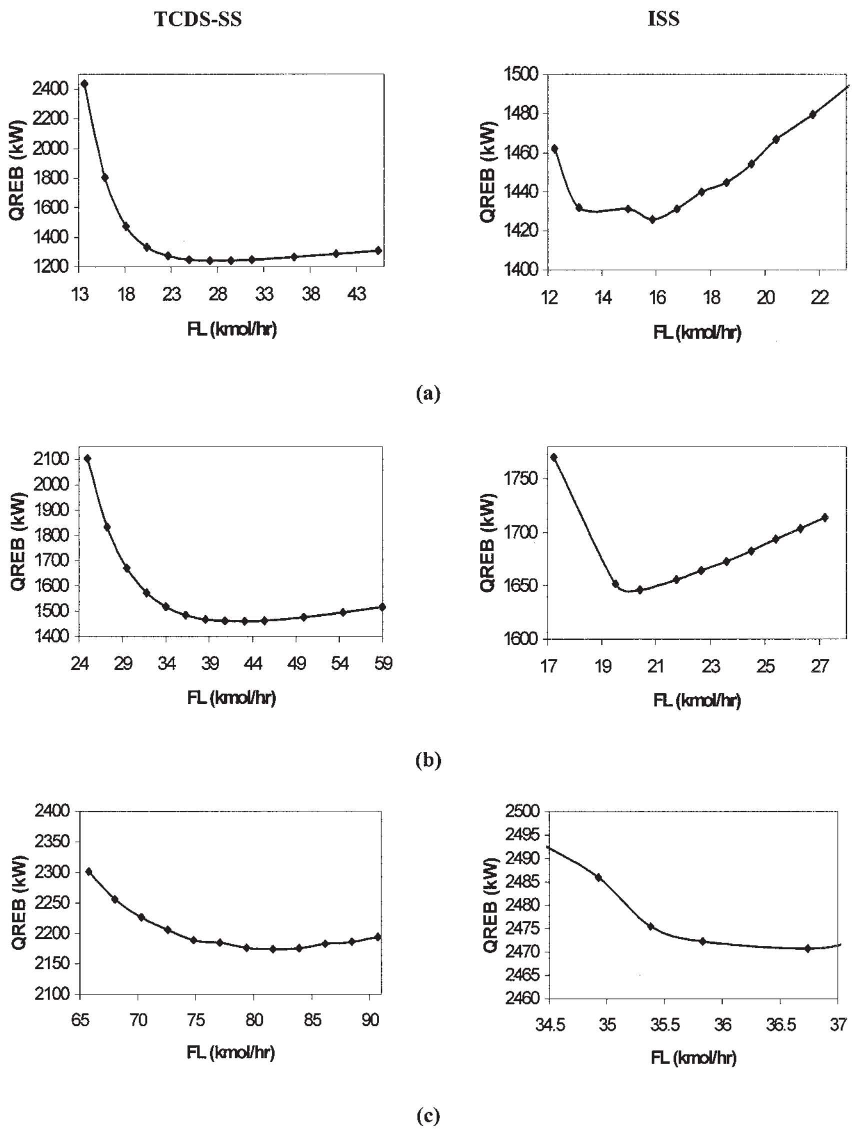

Figure 6. Response curves for TCDS-SS and ISS, mixtures M2–F1 (a), M2–F2 (b), and M2–F3 (c).

efficiency that is similar to or better than that of thermally coupled systems. Given the simpler structure, the new systems were conceived as more operable options to the integrated schemes. However, the results obtained for the response curves of each type of system show that the new designs are more sensitive to changes around the optimal operating point; therefore, the new systems with no recycle streams may offer more operational problems than the thermally coupled sequences with side columns.

Acknowledgments

N. Ramírez was supported by a scholarship from Consejo Nacional de Ciencia y Tecnología (CONACyT), Mexico.

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Manuscript received Oct. 21, 2003, and revision received Feb. 13, 2004.