Graphical Design and Analysis of Thermally Coupled Sidestream Columns Using Column Profile Maps and Temperature Collocation

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A systematical procedure is presented to design thermally coupled sidestream units like side rectifiers and side strippers are presented in this article. The method combines the column profile map technique to assess topological characteristics of the specific configuration with temperature collocation to rigorously ensure a realizable column design, without making assumptions with regard to the phase equilibrium or product specifications. The proposed methodology offers a unique graphical insight into the challenging problem of thermally coupled column synthesis. Techniques are presented for highlighting superior designs or eliminating inferior ones, based on vapor flow rate, number of stages, and thermodynamic efficiency. Design parameters such as the feed and side-draw trays that may require insight or experience are products of the procedure. Design solutions obtained using this methodology can be used to initialize the state of the art process flow sheeting tool, AspenPlus®, which typically leads to fast convergence to the desired product purities without further adjustments. © 2010 American Institute of Chemical Engineers AIChE J, 57: 2406–2420, 2011

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Introduction

Distillation is the most widely used method in modern chemical industries to separate liquid mixtures into pure components. Despite its wide use and functionality, it is a very energy intensive method of separation, accounting for about 40% of the total energy used in the chemical and petroleum refining industries. With the price of energy and environmental concerns expected to increase even further, researchers and process engineers have set out to find new and creative ways to operate and design separation units. To this end, the notion of coupling individual columns through transferring heat between them has received considerable attention, with reports that up to 50% average savings on the energy demand may be achieved, when compared with the traditional approach, where simple columns are used in series to achieve the desired product purities. These savings arise partly due to the fact that the number of reboilers and condensers are reduced, but it should be noted that these savings are dependant on numerous factors including the...
compositions and volatilities of the feed stream. Additionally, because thermally coupled arrangements reduce the number of reboilers and/or condensers required to affect the separation, significant capital savings can also be achieved.

The simplest method of thermal coupling is a large main column that preseparates the light and heavy components in the feed, linked to a side unit which removes one or more intermediate components. These units, called side rectifiers or strippers or more generally thermally coupled sidestream units, have found considerable use in practice. The side stripping column has been extensively used in petroleum refineries, whereas the side rectifier columns have found application in air separation as well as replacing entrainer regeneration columns in extractive distillation operations.

Other, more complex arrangements such as the fully thermally coupled Petlyuk or Kaibel column arrangements have also been proposed, with even greater potential for energy and capital investments. Although thermally coupled structures promise significant cost reductions, their widespread implementation has been hampered somewhat by control and operational problems. The energy integration increases the control loop coupling in the system, so that the operating strategy for the columns is no longer apparent. This could lead to irregular startup and shutdown procedures and may therefore offset any potential savings due to noncontinuous production. However, numerous advances have been made in the operability of coupled columns in recent years, so much so that large companies like BASF (and others) now have fully functioning Petlyuk and Kaibel columns.

Numerous techniques have been proposed to design thermally coupled side rectifiers and strippers. Several of these methods deploy the Underwood equations, but this method is reliable only for nearly ideal andzeotropic systems and also assumes sharp product specifications. The vapor rate and the minimum reflux ratio, both of which are imperative for the column design and cost, will therefore be idealized using the Underwood methods. Another, more recent approach using the shortest stripping line shows a robust energy targeting strategy that provides a continuously differentiable description of column sequences. This approach can account for any phase equilibrium behavior (including azeotropes) and has the ability to find column sequences that contain nonpinched, minimum energy columns within a sequence as well as accounting for heat integration and capital/operational cost trade-offs, using numerical optimization techniques. Rigorous models using tray-by-tray computations which account for nonidealities have also been suggested, but global optimization methods of synthesis problems involving both structural and parametric degrees of freedom is still a challenge for existing math programming algorithms. Furthermore, black box solutions also permit limited insight the designer can derive from the final solution.

Recently, a column profile map technique has been proposed and was shown to be an efficient tool to synthesize distillation columns, including simple and thermally coupled columns. The graphical and general nature of this technique mean that the designer is able to achieve considerable insight and flexibility in the design. However, the graphical aspect of this approach has a drawback that it involves trial-and-error for determining parameters to construct and validate composition profiles repeatedly until a suitable design is found.

A temperature collocation approach proposed by Zhang and Linnenger transformed the governing equations in the work of Tapp et al. thermodynamically to rigorously synthesize simple columns. More recently, an expansion of temperature collocation has been shown to entire networks of simple and complex column configurations. The advantages of combining the two design approaches are (1) nonideal mixtures may be easily modeled, (2) multicomponent problems can be designed semiautomatically, (3) any network configuration may be designed and tested for feasibility, and (4) design variables such as the feed tray, side-draw tray and total number of stages can be determined reasonably without much computational effort. Furthermore, they showed that the column specifications obtained from this methodology for entire separation networks can be validated with AspenPlus.

This article aims to combine the advantages of the column profile map and temperature collocation techniques, for the rational design of thermally coupled side stripper and rectifier columns. This article does not attempt to find globally optimal solutions to the problem of thermally coupled sidestream column, but instead presents a systematic and rigorous design strategy that offers design engineers clear insight into the behavior of these configurations. This article is structured in the following manner. A “Methodology” section discusses the design methodology and general properties of the column profile map and temperature collocation techniques. The following section highlights the procedure for side stripper/rectifier design including its structural properties, a degree of freedom analysis, mass balance properties, feasibility criteria, and informed choices of design variables. The “Design Trade-Offs” section presents the spectrum of feasible designs for a methanol/ethanol/p-xylene case study and specifically methods are proposed to direct one to superior designs based on the reboiler duty, the number of stages, and energy efficiency. This article closes with conclusions summarizing significant results from this work and suggesting areas of future work and applicability of the methods.

**Methodology**

**Column profile maps**

Continuous column profile equations were originally proposed by Van Dongen and Doherty for conventional rectifying and stripping sections. These continuous equations were expanded to the difference point equation for a generalized column section (CS), from which a column profile map may be constructed, by setting parameters such as the reflux ratio and net compositional flows. The general nature of the column profile map method has the advantage that it is not specific to any configuration, which consequently lends itself to model any structure, irrespective of its complexity. The equations have been developed by defining a CS as a length of column between points of material addition or removal, as shown in Figure 1.

The equation describing the liquid compositional change along the CS may then be derived through a steady-state mass balance over a CS, assuming constant molar overflow followed by a Taylor expansion, which yields: