Optimal Allocation of Heat Exchanger Inventory in a Serial Type Diabatic Distillation Column

Edward Steven Jimenez and Peter Salamon
Department of Mathematics and Statistics
San Diego State University
San Diego CA, 92182-7720

Ricardo Rivero and Consuelo C. Rendón
Instituto Mexicano del Petroleo
Mexico City, Mexico

Karl Heinz Hoffmann
Department of Physics
Technical University of Chemnitz
Chemnitz, Germany

Abstract

Diabatic distillation is a separation process in which heat is transferred on the trays inside the column . We have previously shown (Jimenez et al. 2003) that optimal operation of serial heat exchangers can capture most of the wasted exergy. In the present work we explore the effect of locating a fixed total heat exchanger area in different trays and calculate the optimal allocation of a given heat exchanger inventory.

Nomenclature

V_i = Moles of Vapor leaving tray i per minute

Li = Moles of liquid leaving tray i per minute

F = Moles of feed per minute

X = mole fraction of light component

x_f = x in feed mixture

x_D = x in distillate

x_B = x in bottoms

Q_D = Heat removed by t he condenser

Q_B = Heat supplied by the reboiler

B = Moles of Bottoms per minute

D = Moles of Distillate lper minute

T = Absolute temperature

T_i = Temperature on tray i

K = Number of Trays

C_s = Liquid - vapor coexistance heat capacity

C_p = Constant Pressure heat capacity

Introduction

An important way to exergy savings is through diabatic distillation. Instead of just one heat source (the reboiler) and one heat sink (the condenser); a diabatic column uses a heat exchanger at each tray. Such devices have been investigated as early as 1974 (Fonyo 1974) and have recently drawn growing interest (Schaller et al., 2002, DeKoeijer G et. Al. 2001, Rivero 1993). Spreading out the heating duties of the reboiler and the cooling duties of the condenser implies potential savings because the reboiler is adding heat at a higher temperature than needed and the condenser is removing heat at a lower temperature than needed (see Fig 1).

Optimal operation of diabatic distillation columns (see Fig 1) have been calculated before in a number of contexts. The present work goes further in a series of efforts which strive to quantify the unavoidable irreversibilities associated with different parts of the process. Here we quantify the amount of irreversibility that is associated with restricting the extra heat supplied to the column to one heat exchange fluid that moves from tray to tray in supplying heat to all the trays in the stripping section. Similarly we restrict the heat removal to one heat exchange fluid that moves from tray to tray removing heat from the rectification section (see Fig. 2). Our previous efforts in this regard found the minimum irreversibility when each tray was supplied by independently adjustable heat exchangers (Schaller 2002). Just how much extra irreversibility one has to pay for the loss of independent control of the external temperatures is quantified here for the first time.

In a steady state diabatic column, the size of the next temperature step (the temperature difference between the current tray and the next tray) can be adjusted by varying the amount of heat supplied at that tray. An early and general optimization result for columns with equilibrated trays showed that optimal operation counting only separation losses in the limit of many trays (Andresen & Salamon 2000, Salamon & Nulton 1998) adjusts these temperature steps so the thermodynamic distance between them is constant.

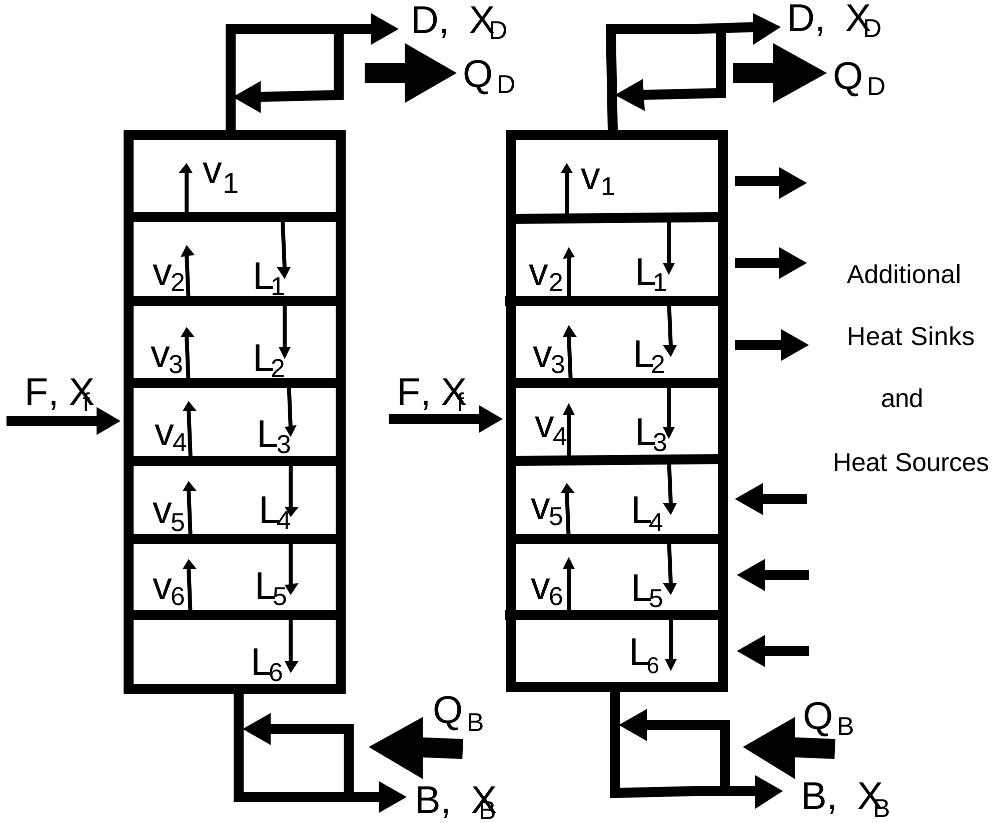

Figure 1: Comparison of an adiabatic column to a general diabatic column.

Equal thermodynamic distances mean that the temperatures should be chosen such that:

$$\int_{T_{i-1}}^{T_i} \frac{\sqrt{c_s}}{T} dT = \frac{1}{K} \int_{T_0}^{T_k} \frac{\sqrt{c_s}}{T} dT$$

where c_s is the heat capacity of the mixture under boiling conditions (Salamon and Nulton, 1998).

Recent works have improved on the Equal Thermodynamic Distance Theorem and gave further support to the assertion that diabatic distillation is a way to exergy savings. Two publications (DeKoeijer et al., 2001; Schaller et al., 2001) calculated potential savings without assuming many trays. The agreement between the numerically optimized separation losses and the losses implied by constant thermodynamic length (which provides an asymptotic result for a large number of trays) was found to be excellent down to reasonable length columns.

The next efforts (Schaller et al., 2002) characterized losses due to the inclusion of thermal resistance but still allowing the temperature of the heat exchange fluid in contact with each tray to vary freely. The findings were that the heat exchange losses were comparable to the separation losses for reasonable parameter values. Interestingly, the characteristic inverted-U-U shape (Schaller 2001) of the optimal heating profile with constant thermodynamic distance was flattened out for short columns and was even further flattened when the effect of thermal resistance was added. This suggested that the serial heat exchanger design considered here can probably be used without a large sacrifice in entropy production.

The Problem

Serial Heat Exchanger Design

This research concerns the further optimization of the diabatic design with serial heat exchangers (Rivero 1993, Jimenez et al 2003). A serial heat exchanger used for cooling is distributed throughout the rectifier and a separate serial heat exchanger used for heating is distributed throughout the stripper.

A heat exchange fluid is pumped through the serial heat exchangers to allow heat to be transferred to or from the column. This particular diabatic design will allow a conventional column to be retrofitted with serial heat exchangers. Only two piercings of the outer jacket are required for each serial heat exchanger, as shown in figure 2.

The sample calculations presented here treat the mixture of 50% benzene and 50% toluene, which is separated into the distillate containing 90% benzene and the bottoms containing 90% toluene.

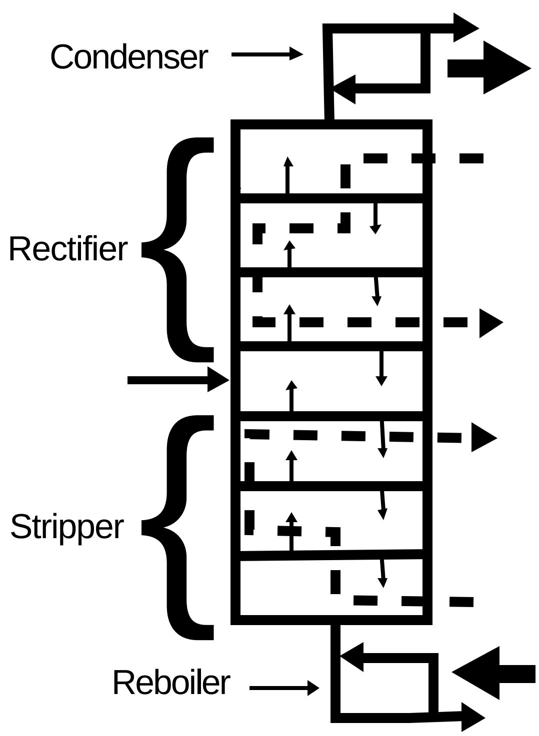

Figure 2: Conventional column retrofitted with serial heat exchangers.

Variables to be optimized

The serial heat exchanger design has 5 control variables: 1. The temperature of the serial heat exchanger fluid in the rectifier, 2. The temperature of the serial heat exchanger fluid in the stripper, 3. The flow rate of the serial heat exchanger fluid in the rectifier, 4. The flow rate of the serial heat exchanger fluid in the stripper, and 5. The amount of heat exchanger to be allotted throughout the trays in the column. The temperature profile of the distillation column is determined by the first 4 parameters. From these the total entropy production and thus the exergy losses can be calculated (Schaller 2001).

Optimization

Previous work (Jimenez et al 2003) has shown that a diabatic column with serial heat exchangers can minimize entropy production, which is the objective. To further minimize entropy production, we can vary the amount of heat exchanger that is in the trays, reboiler, and the condenser. In order to keep the comparable amount of heat exchanger as compared to previous simulations we first calculate how much heat exchanger inventory there is in a particular size diabatic column as:

$$AU_{Total} = AU_{Base} * (K - 2 + 20)$$

Where AU_{Base} is the base conductivity used in previous simulations and K is the number of trays in the column. There is no heat exchanger allotted to the feed tray or the K^{th} tray and in previous simulations the condenser and reboiler were given a heat exchanger amount of ten times that of a single tray. The amount of heat exchanger allotted to one tray is determined by AU_{Base} and AU_{Frac}, the fifth parameter in our optimization, as:

$$AU_{Tray} = AU_{Base} * AU_{Frac},$$

The remaining amount of heat exchanger is divided evenly between the reboiler and the condenser as:

$$AU_{\mathrm{Re}b} = AU_{Cond} = \frac{AU_{Total} - (K-2) * AU_{Frac} * AU_{Base}}{2}.$$

The Nelder-Mead (Simplex) method was implemented in Matlab to minimize entropy production available as fmins (Version 5.x) or fminsearch (Version 6.x) giving robust convergence.

The Heat Exchanger Ratio

In order to see what kind of allocation is optimal in a diabatic column of a particular number of trays, we introduce the Heat Exchanger Ratio (HER). We define the HER as:

$$HER = \frac{AU_{Cond}}{AU_{Tray}} .$$

This ratio gives an idea as to what the distribution between heat exchanger in the trays and external heat exchangers should be. All previous simulations had a HER value of 10, ten times the amount of heat exchanger inventory in the reboiler and condenser when compared to the amount of heat exchanger on a single tray (Jimenez et al 2003).

Figure 3 gives two examples of how the heat exchanger inventory can be distributed with the same amount of inventory but different HER values.

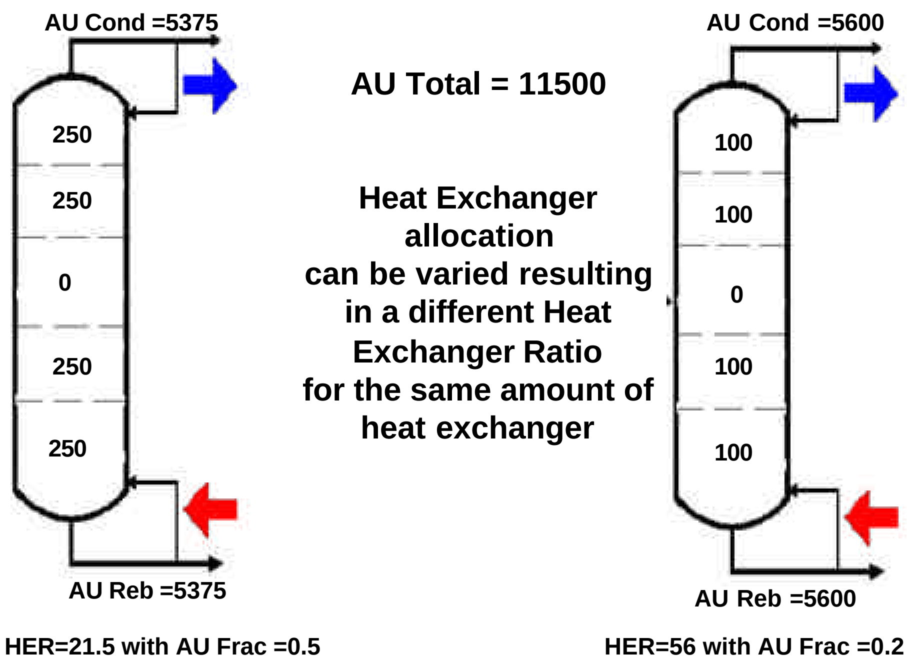

Figure 3

Results

Entropy production was further reduced when the fifth parameter, AU_{Frac}, was introduced. For smaller sized column entropy reductions were very small. However, for larger columns entropy production was reduced by approximately 9% (See Figure 4).

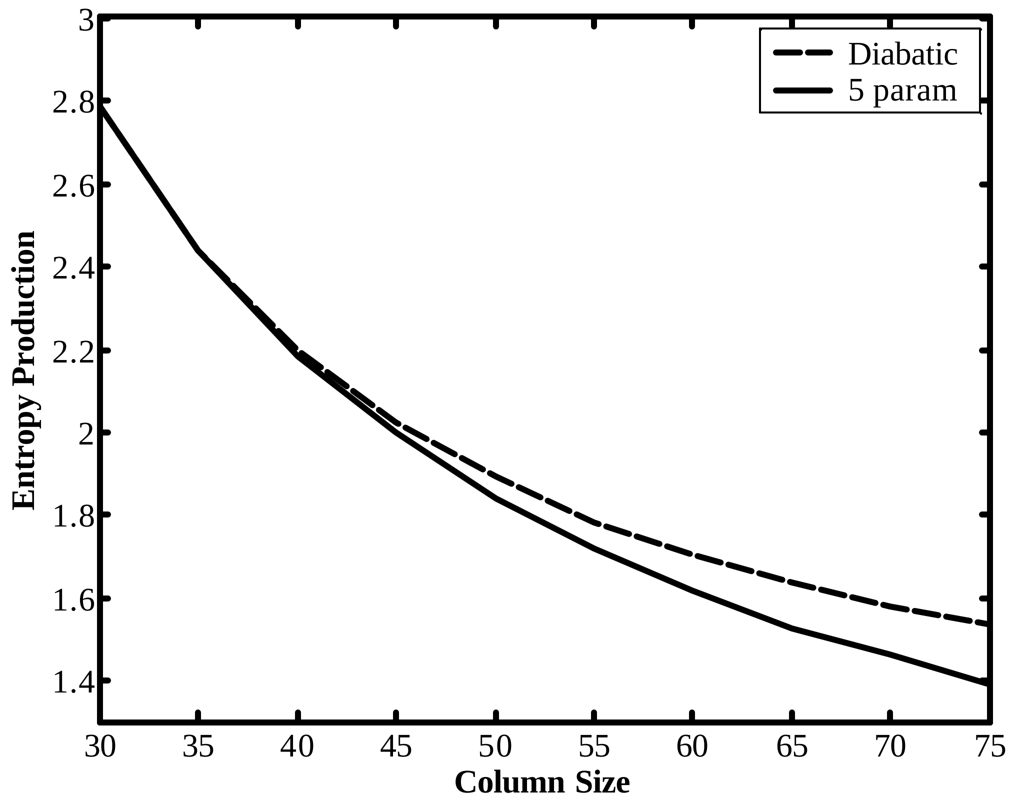

Figure 4

When analyzing the HER values for each of the column sizes, it was seen that the HER values ranged from approximately 8 to about 24, meaning for larger columns, less heat exchanger inventory should be allotted to the trays (See Figure 5).

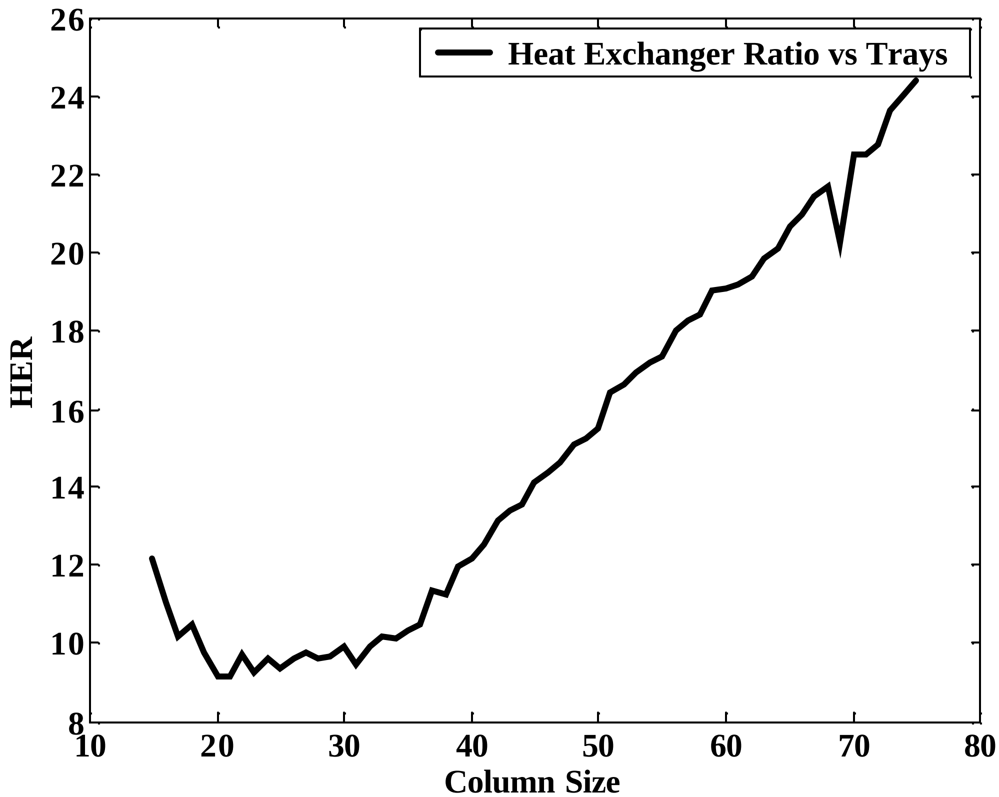

Figure 5

References

B. Andresen and P. Salamon, "Optimal Distillation Calculated by Thermodynamic Geometry", Entropie, 36, 4-10 (2000).

DeKoeijer G., Kjelstrup S., Salamon P., Siragusa G., Schaller M. & Hoffmann K.H., (2001). Comparison of Entropy Production Rate Minimization Methods for Binary Diabatic Tray Distillation. *Industrial Engineering and Chemical Research.* Retrieved August 21, 2002 from http://www-rohan.sdsu.edu/~psalamon/.

Fonyo Z., (1974). Thermodynamic analysis of rectification I and II. Reversible model of rectification, finite cascade models. *Int. Chem. Eng*., 14(1), 18 14(2), 203

Jimenez E.S, Salamon P., Rivero R., Rendon C., Hoffmann K.H, Schaller M., Andresen B. (2003) Simulation Based Optimization of a Diabatic Distillation Column. Conference Proceedings for ECOS 2003

Nulton J.D., Salamon P., Andresen B. & Admin Q., (1985), Quasistatic processes as step equilibriums. *Journal of Chemical Physics.* Vol. 83, p. 334.

Rivero R (1993). L'analyse d'exergie: application à la distillation diabatique et aux pompes à chaleur à absoprtion. Nancy: Institut National Polytechnique de Lorraine, 1993.

Salamon P. & Nulton J.D. (1998). The Geometry of Separation Processes: A Horse-Carrot Theorem for Steady Flow Systems. *Euro-Physics Letters*. Vol. 42 No. 5. p. 571-576.

P. Salamon, B. Andresen, P. D. Gait, R. S. Berry: The significance of Weinhold's length; J. Chem. Phys. 73, 1001; 5407E (1980).

Schaller M., Hoffmann K.H., Siragusa G., Salamon P. & Andresen B. (2001). Numerically Optimized Performance of Diabatic Distillation Columns. *Computers & Chemical Engineering.* Retrieved August 21, 2002 from http://www-rohan.sdsu.edu/~psalamon/.

Schaller M., Hoffmann K.H., Rivero R., Andresen B. & Salamon P. (2002). The Influence of Heat Transfer Irreversablities on the Optimal Performance of Diabatic Distillation Columns. *Journal of Non-Equilibrium Thermodynamics.* Retrieved August 21, 2002 from http://www-rohan.sdsu.edu/~psalamon/.