CHEMICAL ENGINEERING TRANSACTIONS, Volume 12, 2007
Edited by Jiri Klemeš
Copyright © 2007, AIDIC Servizi S.r.l., ISBN 88-901915-4-6

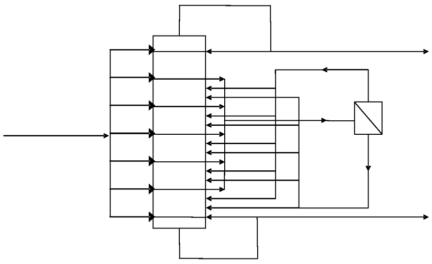
On Energy Efficiency of Hybrid Separation Processes

M.Sorin, E. Ayotte-Sauvé, Y. Azoumah, and F. Rheault.
CANMET Energy Technology Centre -Varennes, 1615 Lionel-Boulet,
P.O. Box 4800, Varennes, Quebec, J3X 1S6, Canada, Tel: (450) 652-3513,
Fax: (450) 652-0999, e-mail:msorin@nrcan.gc.ca

Distillation processes have low energy efficiency. One possible approach to improve efficiency is to combine existing distillation operations with more efficient separation processes such as membrane or adsorption separators. Generally, optimizing a hybrid process is a complex problem. A mathematical programming methodology for energy optimization of hybrid processes involving heat driven (distillation) and work driven (separator) units is presented. The objective function is the total exergy consumption for hybrid processes. Using a superstructure encoding all the alternative solutions, the problem is formulated as a Nonlinear Programming (NLP) type. The separator feed stream is taken as a side draw from the column and the permeate and retentate streams are fed back into the column. The position of feed stream to the column is also an optimization parameter encoded within the superstructure. This new approach has been applied to augmenting a distillation column for ethane/ethylene separation by a separator unit with a constant recovery. The optimization results show a potential for exergy reduction by 44 % compared to the distillation column taken alone. A thermodynamic trade-off between the position of the column feed stream and the flow rate of permeate stream has been formulated.

1. Introduction

Distillation is a highly energy intensive process. Augmenting distillation processes with a work driven separator (membrane modules or adsorption units) to form hybrid systems has been widely reported in the scientific literature (Goldblant and Gooding, 1986, Wynn, 2001, Davis et al., 1993, Ghosh et al., 1993). Significant energy savings were reported thus stirring interest for the development of systematic hybrid separation process optimization methods. Kookos, 2003, proposed a mathematical programming methodology based on a superstructure representation of alternative hybrid processes. The problem considered was the optimal design of a distillation column as well as a work driven separator (a membrane network). Since the existence of trays within the distillation column was controlled via binary variables, there resulted a mixed integer nonlinear programming problem (MINLP). The objective function to minimize was the annualized cost (Seider et al., 1999). Taking into account the non-convex nature of the problem, Kookos repeated the optimization procedure from several initial points. Aside from initial condition dependence, the results of such an optimization change with respect to the economic assumptions which have to be made for each particular system. Therefore, it may be hard to understand the general physical trade-offs governing the energy optimization of hybrid processes. This paper describes a different approach. First, retrofit of an existing distillation column is considered. In particular, the number of column trays is fixed. As a result the mathematical formulation is changed. It is of the nonlinear programming (NLP) type. Secondly a thermodynamic (and not economic) objective function is treated: the total exergy consumption of a hybrid system. For demonstration purposes the case of Ethane/Ethylene separation is considered.



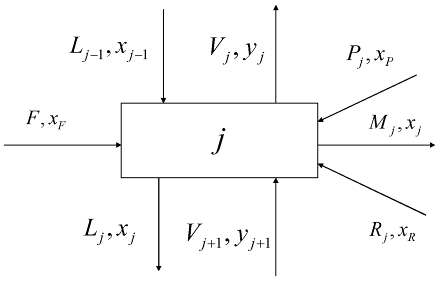


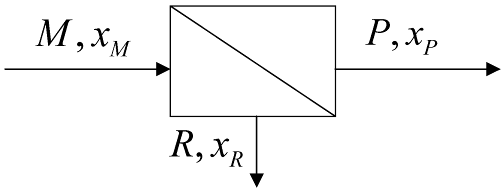
Figure 1. (left side) The superstructure for parallel hybrid configurations.
Figure 2. (right side) Inlet and outlet streams of a tray within the superstructure.

2. Mathematical Model of a Fixed Size Distillation Column/Separator Parallel Hybrid.

A distillation column and a separator module can be combined in different ways (Stephan et al., 1995). The case considered in this paper is where the work driven separator feed stream is taken as a liquid side draw from the column and the permeate and retentate streams are fed back into the column (as saturated liquids). In order to encode in a single diagram all the possible (parallel) configurations of the hybrid, the superstructure presented in figure 1 was considered. It is obtained by adapting Kookos' (2003) superstructure to the case of a fixed size distillation column for which the feed position is not fixed.

A diagram representing a single tray within the superstructure is shown in figure 2. Besides the usual vapor (Vj) and liquid (Lj) interstage streams leaving a tray (j), there are four additional streams. The first is a (saturated liquid) feed stream (Fj), the second stream Mj represents a fraction of the liquid leaving the tray drawn to enter a work driven separator. The third stream Pj is the permeate from the separator which is fed back to tray j via a compressor. The role of the compressor is to restore the permeate pressure to the pressure on the tray j. Finally the retentate stream Rj from the separator is also fed back to the tray j. The permeate and retentate are assumed to enter the column as saturated liquids. It is also assumed that there is no pressure loss associated with the retentate Rj. The distillation column is modeled using the MESH equations (Taylor and Krishna, 1993), which are a combination of mass balances, enthalpy balances and equilibrium relations involving the Murphree (vapor) efficiency for each tray.

The simplified model of a work driven separator is presented in figure 3 (CHEMCAD). The model includes two mass balances and a relation defining a constant recovery ratio, α (the ratio between the flow rates of the light component in the permeate and the separator feed). The link between the distillation column and the separator is expressed by appropriate mass balances around the mixers and splitters illustrated in figure 1.



$$M = P + R$$
$$Mx_M = Px_P + Rx_R$$
$$Px_P = \alpha M x_M$$

Figure 3. Simplified model of work driven separator.

3. Optimization Problem.

It is well known that the results of any economical optimization strongly depend on the cost assumptions which have to be made for each particular process. Given that these assumptions widely differ from case to case, the results of such an economical optimization for a particular process could be very restrictive. In contrast, the results of the thermodynamic optimization may allow for conclusions that reach a broader range of cases. Moreover as will be demonstrated, the thermodynamic optimization allows one to better understand the physical trade-offs governing the energy optimization of hybrid processes. The simplified model of a work driven separator allows one to target the potential energy savings of the hybrid systems without focusing on the design of the separator. Only after getting attractive energy savings opportunities can a designer choose and check the options, which will allow to achieve the targets in practice. These options may be, for example, different types of membranes or adsorbents. Since the distillation column is a heat driven separator and the additional process unit is a work driven separator, the total exergy consumption (Ex) of the hybrid is chosen as objective function. The form of Ex depends on the temperature conditions in the reboiler and condenser. For example for the sub-environmental distillation of ethane/ethylene mixture the supply and withdrawal of heat both require work spending and Ex takes the form:

$$Ex = Q_B\left|\theta_B\right| + Q_D\left|\theta_D\right| + \frac{R_g T_M P}{\eta}\ln\frac{PR}{PP} \qquad (1)$$

where θ_B and θ_D denote the value of the Carnot function for the temperature conditions of the bottom product and distillate respectively; Q_B and Q_D are heat flows to the reboiler and from the condenser correspondingly; η is the isothermal efficiency of the compressor; PR and PP are the inlet and outlet pressures of a compressor installed on the permeate flow; T_M is the temperature within the separator and R_g is the ideal gas constant. Using an enthalpy balance around the condenser, we can express the condenser duty (Q_D) as a function of the reflux ratio (RR) and the distillate flow rate (D):

$$Q_D = (RR + 1)D\Delta H\,, \qquad (2)$$

where ΔH is the (positive) difference in molar enthalpy between the vapor entering the condenser and the liquid leaving it. By combining the overall enthalpy balance around the hybrid process with equation (2), the objective function takes the form:

$$Ex = K_1(RR+1) + K_2 + K_3 T_M P \tag{3}$$

where

$$K_1 = D\Delta H(|\theta_B| + |\theta_D|)\,;\, K_2 = (DH_D + BH_B - FH_F)|\theta_B| \text{ and}$$

$$K_3 = \frac{R_g}{\eta} \ln \frac{PR}{PP} \quad .$$

Given that the pressures (PR and PP) and the specifications (flow rates, compositions and pressures) of the column feed, distillate and bottoms are fixed, K_1, K_2 and K_3 are constant and the exergy consumption (Ex) is a function of only three variables: the reflux ratio (RR), the permeate flow rate (P) and the temperature associated to the separator (T_M). The minimum of Ex corresponds to a trade-off between these three variables. The combination of the nonlinear objective function (3) and nonlinear constraints results in a nonlinear programming problem (NLP). The GAMS modeling interface and the CONOPT solver were chosen as the numerical tools to be used in the optimization.

The thermodynamic analysis of the objective function (1) gives a necessary condition for optimality. For a hybrid system to have minimal exergy consumption (Ex) the following conditions must be satisfied:

i) the exergy losses due to mixing between side streams entering the column and internal column streams must be zero;

ii) the exergy losses due to mixing between the side streams leaving the column must be zero.

Configurations where either of these exergy losses is non-zero are sub-optimal, i.e. the function Ex cannot attain a minimal value. In particular, configurations where there is splitting of side streams entering the column or mixing between side streams exiting the column should be discarded. This criterion can be useful in identifying (and discarding) sub-optimal optimization results.

4. Optimization Results: Ethane/Ethylene Separation.

As a case study, optimization of a hybrid process for ethane/ethylene separation is considered. This example is based on the data given in (Chang and Chuang, 2001). The column feed consists of 416.7 mol/s of a saturated liquid mixture containing 63% of ethylene that is to be separated into a top product composition of 99% in ethylene and a bottom product composition of 98% in ethane. The distillation column contains 40 trays with a feed location at tray 17 (counting from the top); the reflux ratio is 11.9. While the separator's recovery ratio is fixed, the flow rates and composition of its feed and outlet streams are allowed to vary. In particular, an upper-bound of 90 % was chosen for the concentration x_P.

Figures 4 and 5 summarize the results of the optimization for different restrictions on the column feed position. The hybrid in figure 4 is obtained when the column feed position is allowed to vary during the optimization. The column operates with a reflux ratio of 6, which is half the reflux ratio of the column taken alone. Note also that the column feed tray is changed from tray 17 to tray 25.

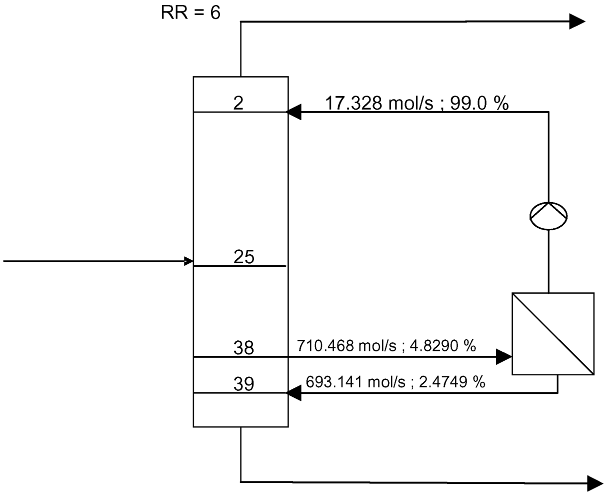


Figure 4. Optimization result: Variable Column Feed Position.

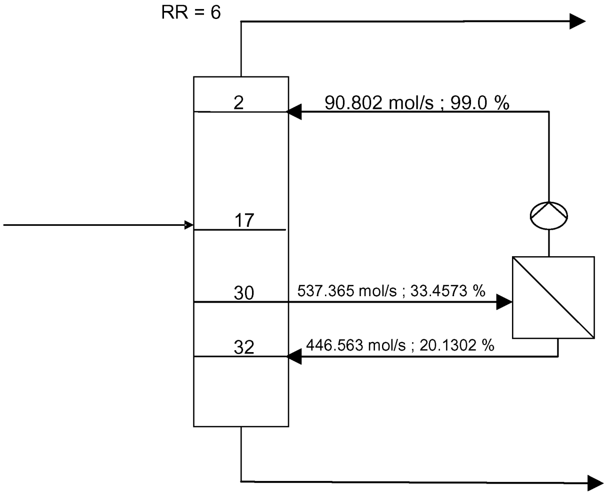


Figure 5. Optimization result: Fixed Column Feed Position.

Figure 5 illustrates a scenario where the index of the column feed tray is fixed at 17. The reflux ratio is also 6. It is interesting to note that despite the fact that both scenarios account for the same amount of heat energy (and exergy) for the distillation process, the scenario in figure 4 requires less electrical power to pump back the permeate flow than the scenario in figure 5. This is due to the fact that P has its lowest value in the case presented in figure 4 (17.3 vs. 90.8 mol/s) and because the temperature within the separator varies little (only a 2.9% difference between figure 4 and figure 5). When comparing the exergy consumption of the hybrid to the exergy consumption of the column taken alone (base case), we see a 43.7% reduction in exergy consumption for figure 4 and a 36.2% reduction in exergy consumption for figure 5. The thermodynamic explanation of this phenomenon is linked to higher exergy losses due to mixing between the feed stream and the internal column streams in the case of the hybrid structure presented in figure 5. Moreover it can be observed that the separator's stage cut (P/M) is smallest in the scenario in figure 4, where the column feed position varies during the optimization. This gives useful directions to choose when designing an appropriate separator.

Conclusion

The optimization results show an important exergy (energy) savings potential for using hybrid processes compared to distillation taken alone. A trade-off between the position of the column feed stream and the flow rate of permeate stream is observed. The reduction in exergy losses caused by mixing of the column feed stream and internal column streams leads to reduction in flow rate of the permeate stream and as a result, to lower energy consumption to drive the separator's compressor.

References

Chang, H. and S.-C. Chuang, 2003, Process analysis using the concept of intrinsic and extrinsic exergy losses, Energy, 28, 1203-1228.

CHEMCAD, Chemstations, Inc, 2901 Wilcrest Dr., Suite 305 Houston, TX 77042 USA.

Davis J.C., R.J Valus, R.Eshragniand and A.E.Velikoff, 1993, Facilitated transport membrane systems for olegin purification, Sep. Sci. Technol., 28, 463-476.

Ghosh T.K., H.D.Lin and A.L. Hines, Hybrid adsoption-distillation process for separating propane and propylene, Ind.Eng.Chem.Res., 32(1993), 2390-2399.

Goldblatt, M.E. and C.E. Gooding, 1986, An engineering analysis of membrane aided distillation, Indust. Membrane Processes, AIChE Symp. Ser., 248, 51-70.

Kookos I., 2003, Optimal design of membrane/distillation column hybrid processes, Ind.Eng.Chem.Res., 42, 1731-1738.

Seider, W.D., Seader, J. D. and Lewin, D. R., 1999 , Process Design Principles, John Wiley & Sons, New York.

Stephan W., R.D.Noble and C.A.Koval., 1995, Design methodology for membrane/distillation column hybrid process, Journal of Membrane Science, 99, 259-272.

Taylor, R.and R. Krishna, 1993, Multicomponent mass transfer, John Wiley & Sons, New York,.

Wynn N., 2001, Pervaporation comes of age, Chem. Eng. Prog, 97, 10, 66.