World Academy of Science, Engineering and Technology
International Journal of Chemical and Molecular Engineering
Vol:6, No:1, 2012

Optimization of Energy Consumption in Sequential Distillation Column

M.E. Masoumi and S. Kadkhodaie

***Abstract*—**Distillation column is one of the most common operations in process industries and is while the most expensive unit of the amount of energy consumption. Many ideas have been presented in the related literature for optimizing energy consumption in distillation columns. This paper studies the different heat integration methods in a distillation column which separate Benzene, Toluene, Xylene, and C9+. Three schemes of heat integration including, indirect sequence (IQ), indirect sequence with forward energy integration (IQF), and indirect sequence with backward energy integration (IQB) has been studied in this paper. Using shortcut method these heat integration schemes were simulated with Aspen HYSYS software and compared with each other with regarding economic considerations. The result shows that the energy consumption has been reduced 33% in IQF and 28% in IQB in comparison with IQ scheme. Also the economic result shows that the total annual cost has been reduced 12% in IQF and 8% in IQB regarding with IQ scheme. Therefore, the IQF scheme is most economic than IQB and IQ scheme.

***Keywords*—**Optimization, Distillation Column Sequence, Energy Savings

Open Science Index, Chemical and Molecular Engineering Vol:6, No:1, 2012 publications.waset.org/4316/pdf

I. Introduction

REFINERIES, petrochemical complexes, and chemical industries are major energy consumers as fuel, steam and electricity. In chemical industries, the separation process is combined with high energy consumption and distillation units among these are devoted the most used to separate the materials. Totally 90-95 percent of all separations are done for extraction and purification products, and approximately 3 percent of total energy consumption in the world are used in distillation units.

The reducing of energy consumption in the distillation process can be very effective in product cost reduction. Also increasing the global energy prices, causes the energy saving methods in distillation columns have been found double significance. Therefore, extensive research studies have been devoted on reduction of energy consumption through the overall system integration and research on new design of column with high energy efficiency. Such methods that they will be have proper energy saving are including thermal coupling, vapor recompression (heat pump) and heat integrated distillation column [1]. In this paper, three methods of heat integration in distillation columns such as conventional heat integrated distillation (IQ), heat integrated distillation with forward energy integration (IQF) and heat integrated distillation with backward energy integration (IQB) have been studied for separation of Benzene, Toluene, Xylene, and C9+. The schematics of these methods are shown in Fig. 1.

M.E. Masoumi, is with the Chemical Engineering Department, Engineering Faculty, Tehran North Branch, Islamic Azad University, P.O. Box: 19585/936 (phone: +98- 21- 887-707-42; fax: +98- 21- 887-872-04; e-mail: m_masoumi@iau-tnb.ac.ir).

S. Kadkhodaie is with the Chemical Engineering Department, Engineering Faculty, Tehran North Branch, Islamic Azad University, P.O. Box: 19585/936 (e-mail: s_kadkhodaie_64@ yahoo.com).

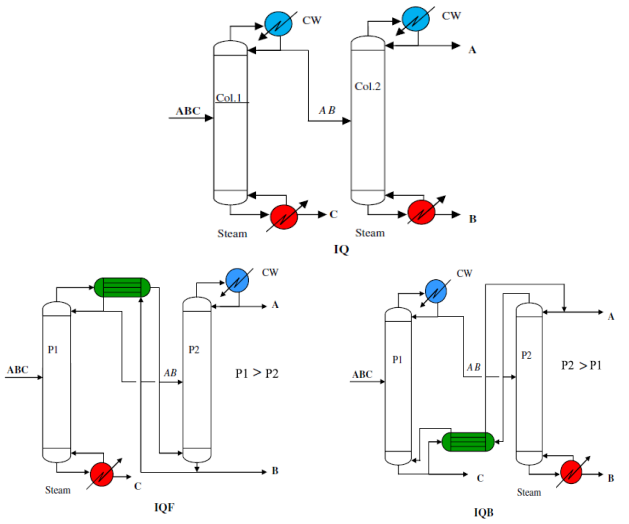


Fig. 1 Indirect sequence (ID), Indirect sequence with forward energy integration (IDF), Indirect sequence with backward energy integration (IQB)

[2] had done a comparative analysis on energy consumption and total annual cost about the separation of ternary mixtures of hydrocarbons for different feed compositions. Results refers to the sequence of heat integrated distillation columns with compared to conventional columns, between 20% - 40% can reduce their energy consumption. [3] had studied separation of ternary mixtures of Benzene, Toluene, and Xylene in heat integrated distillation columns. With survey on different feed temperature condition for conventional distillation column and other arrangements, they concluded that the best scheme for energy saving and total annual cost severely affected from feed temperature condition. In the case that feed enter into the tower at ambient temperature, the direct sequence with backward heat integration (DQB) will be considered as more energy saving scheme. [4], [5], after reviewing on food with three different combinations, discovered that the best scheme of integration depends on the composition of feed. When the feed composition percent are selected the same for all components, integrated energy schemes would be the best scheme. [6] had done a rigorous study and comparison of conventional and energy-integrated distillation schemes for the separation of ternary mixtures. They concluded that the heat-integrated columns show the best economic features over the other

Open Science Index, Chemical and Molecular Engineering Vol:6, No:1, 2012 publications.waset.org/4316/pdf

schemes except the few cases when the concentration of the middle component in the feed is high.

In first section the studied case will be introduced. In the second part the design and simulation of case study was done and result will be presented. 3rd part of this paper includes the economic studies and related results. Finally the results of different studies are compared with each other and conclusions are presented.

II. Case Study

This studied case is the separation of Benzene (A), Toluene (B), Xylene and C9 (C) components with two sequential distillation columns. After separation of C from bottom of first column, the top product of this column including A and B (Benzene and toluene - BT) is combined with other stream of BT which come from another unit and then they are entered into the second column. The schematic diagram of case study is shown in Fig. 2 and characteristics of the streams are tabulated in Table I.

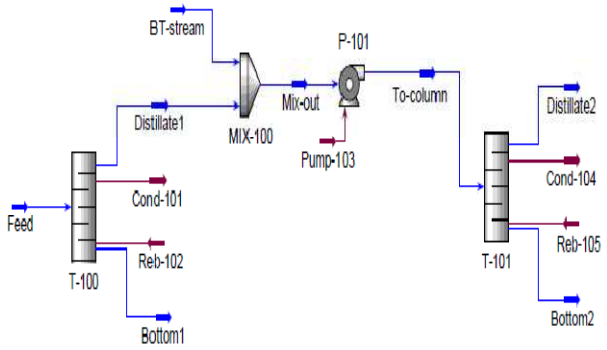


Fig. 2 Schematic diagram of case study

TABLE I
CHARACTERISTICS OF FEED AND STREAMS

Data	Feed		BT stream	
	kg/h	*wt.%*	*kg/h*	*wt.%*
Benzene	9028	8.62	13691	35.62
Toluene	40088	38.3	24648	64.14
Xylenes	33553	32.05	89	0.23
n-Nonane	21985	21.03	0	0.0
total mass flow, kg/h	104654		38428	
Operating temperature, C	153		81	
operating pressure, kpa	540		580	

BT stream = Benzene and Toluene stream, kg/h = kilogram per hour, C = Celsius degree, kpa = kilopascal, wt.% = weight percent.

III. Design And Simulation

The FUG (Fensk, Underwood, Gilliland) method that combines the total reflux Fensk equation and the minimum reflux Underwood equation with the graphical Gilliland relationship is used to preliminary design for a distillation column. In this method which is also called shortcut design, the following relations (1)-(5) are required [7].

$$N_{min} = \frac{\log\left[\frac{r_{L,D}}{1-r_{L,D}} \cdot \frac{r_{H,B}}{1-r_{H,B}}\right]}{\log \propto_{LH}} \quad (1)$$

$$d_i = \frac{\propto_{ij}{}^{N_{min}} . f_i \left(\frac{d_j}{b_j}\right)}{1 + \propto_{ij}{}^{N_{min}} \left(\frac{d_j}{b_j}\right)}, b_i = \frac{f_i}{1 + \propto_{ij}{}^{N_{min}} \left(\frac{d_j}{b_j}\right)} \quad (2)$$

$$\sum_{i=1}^{NC} \frac{\propto_{ij} x_{i,F}}{\propto_{ij} - \theta} = 1 - q, R_{min} + 1 = \sum_{i=1}^{NC} \frac{\propto_{ij} x_{i,D}}{\propto_{ij} - \theta} \quad (3)$$

$$\frac{N - N_{min}}{N+1} = 0.2788 - 1.3154\,X + 0.4114\,X^{0.2910} + 0.8268\,ln\,X + 0.9020 \ln\left(X + \frac{1}{X}\right), X = \frac{R - R_{min}}{R+1} \quad (4)$$

$$\frac{N_R}{N_S} = \left[\left(\frac{B}{D}\right)\left(\frac{x_{fHK}}{x_{fLK}}\right)\left(\frac{x_{bHK}}{x_{dHK}}\right)\right] \quad (5)$$

N_min= minimum number of stages at total reflux, r_(L,D) = recovery of light key component to top product, r_(H,B)= recovery of heavy key component to bottom product, ∝_LH= volatility of light key component relative to heavy key component, i= component i, j = reference component, d = molar flow rate in top product, b= molar flow rate in bottom product, f= molar flow rate in feed, ∝_ij= volatility of component i relative to a reference component, x_(i,F)= mole fraction of component i in feed, θ = roots of underwood equation, q = thermal condition of feed, R_min= minimum reflux ratio, x_(i,D)= mole fraction of component i in top product, N = number of theoretical stages, R = reflux ratio, X = Gilliland term to calculation N, N_R= number of stages in rectifying section, N_S= number of stages in stripping section, B = molar flow rate of bottom product (kmol/h), D = molar flow rate of top product (kmol/h), x_fHK= mole fraction of heavy key component in feed, x_fLK= mole fraction of light key component in feed, x_bLK= mole fraction of light key component in bottom product, x_dHK= mole fraction of heavy key component in top product.

These calculations are built in the part of the HYSYS simulator that is named Shortcut Distillation. Using this system, obtaining the value of reflux ratio and also the number of stages is possible. The two shortcut columns are shown in Fig. 2 that it is very similar to the arrangements IQ, IQF, IQB in order to estimate the required variables which are used for rigorous simulation. In tower T-100 initially assumed that the value of light component in the residual product is 0.1% and also the value of heavy component in the distillate product is 0.1%. Then in tower T-101, with regarding the middle component in tower T-100 as heavy component and its

Open Science Index, Chemical and Molecular Engineering Vol:6, No:1, 2012 publications.waset.org/4316/pdf

overhead component as light component, tower T-101 is simulated with above values.The rigorous simulation using HYSYS process simulation, 2006 software is done. The physical properties of feed mixture and products are calculated by the Peng Robinson model. The aim of the rigorous simulation was the decrease of number of assumptions and also this procedure is more realistic than the FUG equations [8]. For doing a simulation, components that are present in the process must be entered to the file and a proper thermodynamic model for expression the behavior of the physical properties of the phases is selected and then should be added into the simulation environment. Finally the feasibility of each project is studied and the required heat duty for economic calculations is obtained. Regarding these steps the simulation of two schemes IQF and IQB were done and are shown in Fig. 3 and 4.

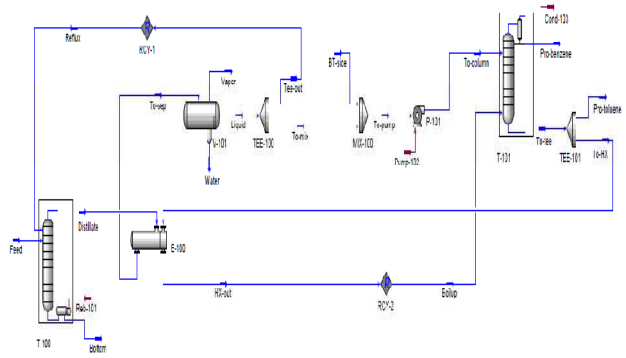


Fig. 3 Simulation of sequence distillation column with IQF method

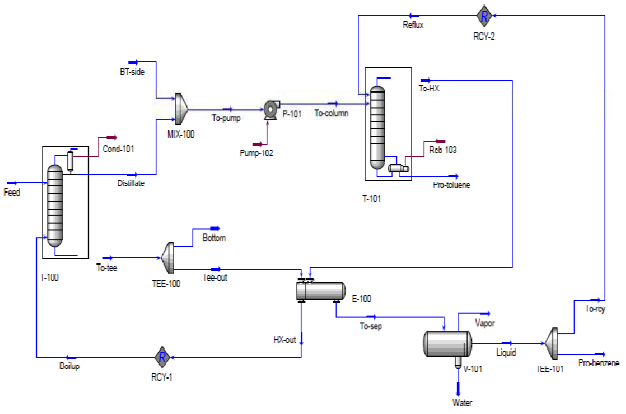


Fig. 4 Simulation of sequence distillation column with IQB method

Considering that the towers operating pressures are changed in the IQF and IQB arrangements regarding to IQ scheme then the pressure of each tower have significant effect in simulation and should be determined. The calculation results show that if the pressure of IQ scheme assumes 101 kpa then the pressure of the first tower in IQF scheme is increased to 401 kpa but the pressure of second column remain in 101 kpa while these are 101 kpa for first column and 801 kpa for second column in IQB scheme.Reflux ratio is increasing with increasing pressure, and also with increasing reflux ratio, the required number of theoretical stages for separation is reduced. Increasing of reflux ratio cause the decreasing of capital costs for distillation column and increasing the heating and cooling costs of reboiler and condenser. The optimal reflux ratio by determining the heat duty and the capital and operating costs in different reflux ratios could be calculated. This calculation for studied case was done and shown in Fig. 5. As can be seen the best reflux ratio is occurred in the point that the sum of capital and operating costs are minimized, so this amount is obtained approximately 1.1.

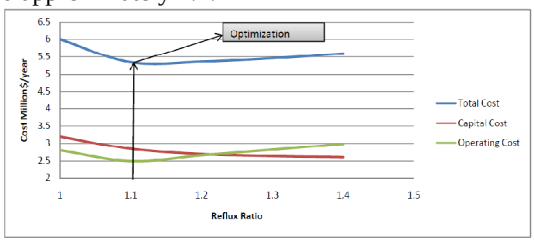


Fig. 5 The optimal reflux ratio for studied case

The design and simulation results are presented in Table II. These results are used in economic calculations.

TABLE II
DATA FROM DESIGN AND SIMULATION FOR IQ, IQF, IQB ARRANGEMENTS

	IQ		*IQF*		*IQB*	
	Col.1	Col.2	Col.1	Col.2	Col.1	Col.2
$\propto_{LK/HK}$	2.16	2.46	1.9	2.46	2.16	1.96
top temperature(C)	101.6	80.17	158.1	80.17	101.6	166.7
bottom temperature(C)	154	132.3	206	132.3	154	209.1
column pressure (kpa)	101.3	101.3	401.3	101.3	101.3	801.3
column diameter (m)	3.16	2.62	3.57	2.7	3.34	3.31
reflux ratio	1.79	3.86	2.56	4.21	2.11	6.73
actual no.of trays	74	81	77	70	59	83
no.of stripping trays	33	48	34	41	26	49
no.of rectifying trays	41	33	43	29	33	34
heating rate (kj/h)	9.31e7		6.3e7		6.88e7	
cooling rate (kj/h)	9.41e7		4.31e7		5.1e7	
HX duty(kj/h)	0		5.02e7		3.68e7	

IQ = Indirect sequence, *IQF* = Indirect sequence with forward energy integration, *IQB* = Indirect sequence with backward energy integration, Col.1 = column1, Col.2 = column2, $\propto_{LK/HK}$ = volatility of light key component relative to heavy key component, C = Celsius degree, kpa = kilopascal, m = meter, kj/h = kilojoule per hour, HX = heat exchanger.

IV. THE ECONOMIC ANALYSIS

The price of equipments is a function of some parameters

Open Science Index, Chemical and Molecular Engineering Vol:6, No:1, 2012 publications.waset.org/4316/pdf

that is related to the type of device. For example, the column price is a function of the diameter and height of the column; and heat exchanger price is a function of its surface [9]. So the needed parameters first were calculated and then the related costs were estimated. The following relations (6)-(9), are used for column sizing [10].

$$H = N_{actual} \times H_T \, , D = \left(\frac{4M_V V}{0.9 \times 0.8 \times \pi \rho_V \vartheta_T}\right)^{0.5} \quad (6)$$

$$\vartheta_T = 0.9\, K_T \left(\frac{\rho_L - \rho_V}{\rho_V}\right)^{0.5} \quad (7)$$

$$K_T = \left(\frac{\sigma}{20}\right)^{0.2} \exp(-2.979 - 0.717 lnF_{LV} - 0.0865 (lnF_{LV})^2 + 0.997\, lnH_T - 0.07973\, lnF_{LV}{}^{lnH_T} + 0.256\, (lnH_T)^2 \quad (8)$$

$$F_{LV} = \left(\frac{M_L \times L}{M_V \times V}\right)\left(\frac{\rho_V}{\rho_L}\right)^{0.5} \quad (9)$$

H= column height (m), N_actual= actual number of stages, H_T= tray spacing (m), D= column diameter (m), M_V= molecular weight of vapor (kg/kmol), V = vapor molar flow rate (kmol/s), ρ_V= vapor density (kg/m3), ϑ_T= vapor flooding velocity (m/s), K_T= terminal velocity parameter (m/s), ρ_L= liquid density (kg/m3), σ = surface tension (mN/m), F_LV= liquid-vapor flow parameter, M_L= molecular weight of liquid (kg/kmol), L = liquid molar flow rate (kmol/s).

The cost of process equipment and also the operating cost for the arrangements will be calculated using the following relationships (10)-(12) [11]. The calculation results are presented in Table III.

$$TAC = Ccap \times AF + Cop \quad (10)$$

$$Cop = (8000h/year)\left[\begin{array}{c}\left(\frac{2.6\$}{MBtu} \times Q\right) + \\ \left(0.0067\$/ton \times \frac{Q_{cond}}{c_p \Delta T}\right)\end{array}\right] \quad (11)$$

$$Ccap = \left(\begin{array}{c}\sum_{i=1}^{t} 3.18\left[101.9 {D_c}^{1.066} {H_c}^{0.802}\right] + \\ \sum_{i=1}^{t} 4.7\left(\frac{N}{E_0}\right)\left({D_c}^{1.55} H_t\right) + \sum_{i=1}^{t} 3.29\left(101.3 {A_{cond}}^{0.65}\right) \\ + \sum_{i=1}^{t} 3.29\left(101.3 {A_{reb}}^{0.65}\right) + 3.29\left(101.3 {A_{ex}}^{0.65}\right) \\ +2.27[(5.52 \times 10^3) Q^{0.85}]\end{array}\right) \times \left(\frac{M\&S}{280}\right) \quad (12)$$

TAC = total annual cost, Ccap = capital cost, AF = annualisation factor, Cop = operating cost, Q = heat duty of furnace (kj/h), Q_cond= heat duty of condenser (kj/h), c_p= heat capacity of water (kj.kg-1.k-1), ΔT = temperature difference, D_c= column diameter (m), H_c= column height (m), N = number of theoretical stages, E_o= overall stage efficiency, H_t= tray stack height (m), A_cond= area of condenser (m2), A_ex= area of heat exchanger (m2), M&S = Marshal and Swift index.

TABLE III
CALCULATION OF CAPITAL AND OPERATING COSTS FOR EACH SCHEME

costs	*IQ*	*IQF*	*IQB*
Fuel cost($/year)	2.45e6	1.65e6	1.81e6
Cooling water cost($/year)	4.50e4	2.06e4	2.44e4
operating cost($/year)	2.49e6	1.67e6	1.83e6
capital cost($/year)	2.84e6	3.01e6	3.09e6
capital cost($/year)	5.33e6	4.68e6	4.92e6

V. CONCLUSION

The optimization results for three arrangements that have been studied are presented in Table IV. As can be seen the IQF scheme is the best arrangement in term of energy saving. This scheme has 33% energy saving while that the IQB scheme has 28% in base of IQ scheme. Also the results for capital cost show that the IQF scheme needs less capital investment than IQB. Finally the total cost saving is 12% for IQF and 8% for IQB.

TABLE IV
OPTIMIZED RESULTS FOR CASE STUDY

	IQ	*IQF*	*IQB*
Capital cost saving(%)	0	-6	-9
Operating cost saving(%)	0	33	28
total saving(%)	0	12	8

Surveying in this results show that if the IQF scheme is selected for the studied case, not only the operating cost was reduced to an acceptable level, but also with consuming less fuel, the less contribution can be held in air pollution, and also to the environmental standards became near.

REFERENCES

[1] M. Gadalla, L. Jimenez, Z. Olujic, P.J. Jansens, "A thermo-hydraulic approach to conceptual design of an internally heat-integrated distillation column (i- HIDiC)," *Computers and Chemical Engineering*, vol. 31, pp. 1346-1354, 2007.

[2] C. Hernandez-Gaona, S. Hernandez, "Comparison of energy consumptions and total annual costs between heat integrated and thermally linked distillation sequences," *Chem Biochem Eng* Q, Vol. 18(2), pp. 137-143, 2004.

[3] M. Khalifa, M. Emtir, "Rigorous optimization of heat-integrated and Petlyuk column distillation configurations based on feed conditions," *Clean Technology Environment Policy*, vol. 11, pp. 107-113, 2009.

[4] E. Rev, M. Emtir, Z. Szitkai, P. Mizsey, Z. Fonyo, "Energy savings of integrated and coupled distillation systems," *Computers and Chemical Engineering*, vol. 25, pp. 119-140, 2001.

[5] M. Emtir, E. Rev, Z. Fonyo, "Rigorous simulation of energy integrated and thermally coupled distillation schemes for ternary mixture," *Applied Thermal Engineering*, vol. 21, pp. 1299-1317, 2001.
[6] O. Annakou, P. Mizsey, "Rigorous Comparative Study of Energy-Integrated Distillation Schemes," *Ind. Eng. Chem. Res*, vol. 35, pp. 1877-1885, 1996.
[7] M. Gadalla, M. Jobson, R. Smith, "Shortcut Models for Retrofit Design of Distillation Columns," *Trans IChemE*, Vol. 81, part A, pp. 971-986 2003.
[8] N.R. Corona, A.J. Gutierrez, "Optimum design of Petlyuk and divided-wall distillation systems using a shortcut model," *Chemical Engineering Research and Design*, vol. 88, pp. 1405-1418, 2010.
[9] J.M. Douglas, *Conceptual Design of Chemical Processes*. Mc Graw-Hill, 1988, pp. 32-35,667-672.
[10] R. Smith, *Chemical Process Design and Integration*. John Wiley, 1988, pp. 164-173.
[11] R. Premkumar, G.P. Rangaiah, "Retrofitting conventional column systems to dividing-wall columns," *Chemical Engineering Research and Design*, vol. 87, pp. 47-60, 2009.

Open Science Index, Chemical and Molecular Engineering Vol:6, No:1, 2012 publications.waset.org/4316/pdf